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FISHES AND AQUATIC HABITATS OF THE UPPER SAN PEDRO RIVER SYSTEM, ARIZONA AND SONORA

by

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INTRODUCTION

Acquisition of much of the upper San Pedro River in the United States by the Bureau of Land Management (USBLM; Rosenkrance 1986) and its proposed designation as a "San Pedro Riparian National Conservation Area" (hereafter Conservation Area; USBLM 1986) presents a possibility for protection and management of a Southwestern stream and its plant and animal resources. Part of those resources are fishes, which due to their absolute dependence on surface water are sorely endangered. If existing populations can be maintained and former inhabitants reintroduced it will be a major contribution to native fish conservation in the region.

Of 18 kinds of native fishes originally known from the Gila River system (Miller 1959; Minckley 1973, 1985), one is extinct and 10 are rare enough to be Federally or State listed as Threatened, Endangered, or of Special Concern (Deacon et al. 1979; Minckley 1985). The San Pedro River supported at least 13 of these fishes in historic time (Table 1), of which eight persist as remnant populations.

Objectives

The present report details the fish fauna of the San Pedro River basin, traces and documents changes, assess problems associated with maintenance of native fishes in the area, including those pertaining to adequacy of present and future stream flows, and suggest possibilities for re-establishment of natural habitats and the native ichthyofauna. Specific topics include:

1. history of the San Pedro River native fish populations, the cause for their decline;
2. present species and relative abundance of fishes that inhabit San Pedro River in the study area;

Table 1. Common and scientific names of native and introduced fishes from the San Pedro River basin, Arizona, United States, and Sonora, Mexico.

Common name	Scientific name
NATIVE TAXA	
Family CYPRINIDAE (minnows)	
Roundtail chub	*Gila robusta* Baird and Girard
Gila chub	*G. intermedia* (Girard)
Spikedace	*Meda fulgida* Girard
Colorado squawfish	*Ptychocheilus lucius* Girard
Longfin dace	*Agosia chrysogaster* (Girard)
Speckled dace	*Rhinichthys osculus* (Girard)
Loach minnow	*Tiaroga cobitis* Girard
Family CATOSTOMIDAE (suckers)	
Flannelmouth sucker	*Catostomus latipinnnis* Baird and Girard
Sonoran sucker	*C. insignis* Baird and Girard
Desert sucker	*Pantosteus clarki* (Baird and Girard)
Razorback sucker	*Xyrauchen texanus* (Abbott)
Family CYPRINODONTIDAE (killi- and pupfishes)	
Desert pupfish	*Cyprinodon macularius* Baird and Girard
Family POECILIIDAE (livebearers)	
Sonoran topminnow	*Poeciliopsis o. occidentalis* (Baird and Girard)
INTRODUCED TAXA	
Family SALMONIDAE (trouts, chars, salmons, and graylings)	
Rainbow trout	*Salmo gairdneri* Richardson
Brook trout	*Salvelinus fontinalis* (Mitchill)
Family CLUPEIDAE (shads, herrings)	
Threadfin shad	*Dorosoma petenense* (Gunther)
Family CYPRINIDAE (minnows)	
Common carp	*Cyprinus carpio* Linnaeus
Goldfish	*Carassius auratus* (Linneaus)
Fathead minnow	*Pimephales promelas* Rafinesque
Red shiner	*Notropis lutrensis* (Baird and Girard)
Family ICTALURIDAE (North American freshwater catfishes)	
Black bullhead	*Ameiurus melas* (Rafinesque)
Yellow bullhead	*A. natalis* (Lesueur)
Channel catfish	*Ictalurus punctatus* (Rafinesque)
Family POECILIIDAE (livebearers)	
Mosquitofish	*Gambusia affinis* (Baird and Girard)
Family CENTRARCHIDAE (sunfishes)	
Largemouth bass	*Micropterus salmoides* (Lacepede)
Green sunfish	*Lepomis cyanellus* (Rafinesque)
Bluegill	*L. macrochirus* Rafinesque

3. water flow regimen and water quality that affect the life history of fish species such as flooding, low flow, and intermittent flow;
4. the effect of upstream mining activities on stream water quality and fish populations;
5. instream flow management strategy that would enhance fish habitat conditions in the river; and
6. possibilities for reintroduction and survival of federally listed threatened or endangered fish species that historically inhabited San Pedro River.

DESCRIPTION OF THE STUDY AREA

The San Pedro River originates in desert grasslands of northern Sonora, Mexico, and flows about 240 km north to enter the Gila River near Winkleman, Arizona. Its watershed of 11,635 Km^2 includes most major vegetational life zones of North America, ranging from coniferous forests on mountains higher than 2300 m above mean sea level to Sonoran desertscrub at 588 m elevation near the river's mouth (Lowe 1964; Brown and Lowe 1978; Brown 1982). Much of the mainstream flows through structural basins over valley fill approaching or exceeding 300 m thick (Roeske and Werrel 1973). Its floodplain is usually a kilometer or more wide, except where bedrock outcrops approach the stream near Charleston, at the "Narrows," near Redington, and again as it approaches the Gila River (Wilson et al. 1960). These restrictions result in unequal depths of valley fill and increased slope between each successive subbasin (Haynes 1968; Cooke and Reeves 1976). Bedrock near the surface also promotes emergence of subterranean water, insuring sections of perennial flow. Zones of strong artesian pressure are in the vicinity of Palominas and Herford, St. David and Benson, and Mammoth (Roeske and Werrel 1973). Average gradient of the overall channel is about 4.0 m/km.

As detailed below, the San Pedro River mainstream prior to 1890 consisted of marshlands, called <u>cienegas</u> in the American Southwest, alternating with short reaches of incised channel (Hastings 1959, 1962; Hastings and Turner 1965; Cooke and Reeves 1976; Hendrickson and Minckley 1985). Then, unusually severe arroyo cutting devastated the stream (Hastings and Turner 1965):

> "Where the San Pedro River of southeastern Arizona formerly wound its sluggish course northward through a marshy, largely unchanneled valley, in August, 1890, it began carving a steep-walled trench through which it thereafter emptied rapidly and torrentially into the Gila. Where it formerly ran more or less consistently throughout the year, after 1890 its flow became intermittent, leaving the new channel dry over much of its length for most of the time."

This hydrologic shift occurred at about the same time along all major watercourses in southern Arizona, and constituted a major catastrophe. Economic loss to farmers and ranchers was severe. Irrigation ditches were left high above water levels, valley floors were dissected, and much developed land was rendered unusable. Ecological conditions were changed so that whole communities of plants and animals disappeared and others began to develop in their places (Hastings and Turner 1965). Causes for these vast changes are still debated, but there is little doubt that a combination of factors resulted in the geologic event of arroyo cutting (Hendrickson and Minckley 1985).

Most of the San Pedro River mainstream remains incised. Downcutting is greater than 3 or 4 m where floodplains are narrow, but erosion progressed laterally in wider places to create a broad channel occupied by a relatively small wetted area during drought, and filled in flood by a turbid, erosive river. Discharge near the mouth has averaged 1.62 m^3/sec over 13 years (1966 to 1979; median, 1.08), varying from no flow to 476 m^3/sec (U.S.

Geological Survey [USGS], publ. periodically). Flow patterns are sharply bimodal, with flooding in winter and summer separated by spring and autumn droughts (Anderson and White 1979; Putman et al. 1985). A large percentage of total water yield occurs during infrequent flooding events, as characteristic of most lower elevation Southwestern streams (Fisher and Minckley 1978; Minckley and Meffe 1987).

Substrate in the channel is comprised mostly of sand, with much of the bottom consisting of bedload in transport. Some armoring by gravel and cobble occurs in swifter areas, especially near points of input of such materials from ephemeral tributaries. Such a system provides little fish habitat in the form of pools, cover, or resting space. Most of the stream consists of riffles alternating with braided, shallow runs. Shifting sand bottoms are notoriously deficient in production of algae or benthic invertebrates (Hynes 1970), and the stream is further exposed to full sunlight, with minor exceptions where channels approach cutbanks or are shaded by riparian plants, so temperatures fluctuate radically on both diel and seasonal bases.

Incision also resulted in declines in local water tables and drying of floodplain features like oxbow lakes and marshes not fed by springs. Areas classed as dense riparian vegetation, marshland, river channel, and streambed all have been substantially reduced in the past five decades (Table 2), and as documented below were even more extensive a century ago. Yet, some parts of the river remain relatively unincised, and riparian vegetation grows as a dense and viable corridor where not cleared for agriculture (McNatt 1979a; Brady et al. 1985). Only a few cienegas, floodplain lakes, and springfed marshlands persist (Smith and Bender 1973, 1974a-d; Hendrickson and Minckley 1985).

Table 2. Percentages of 31,590 hectares under various types of land use and in different vegetation types along San Pedro River, 1935 to 1978 (modified from Riechardt et al. 1978).

Types	1935	1966	1978
Dense Riparian[1]	22	39	45
Agricultural	11	19	28
Cultural-Industrial	1	12	9
Other[2]	66	40	18

1 Cottonwood (Populus fremontii), willow (Salix spp.), mesquite (Prosopis spp.), and saltcedar (Tamarix chinensis).
2 Marshland, mesquite-scrub, river channel, and streambed thickets of annual and/or immature riparian species.

HISTORIC AQUATIC CONDITIONS

Hastings (1959, 1962), Hastings and Turner (1965), Cooke and Reeves (1976), and Hendrickson and Minckley (1985) cited much of the historic literature on the upper San Pedro River. In all cases their intention was to document past geomorphic and vegetational status of the region or stream channel and its surroundings. None specifically addressed description and interpretation of past status of aquatic habitats and, in turn, fishes.

Data for such a reconstruction are sparse. Ecological conditions before arrival of man are indicated by studies of fossil plants and animals within and adjacent to the upper San Pedro River valley (e.g., Martin 1963). However, such data are fragmentary and necessitate too much speculation for other than description of the broadest kinds of ecological change. Historic records are also fragmentary, and unlike scientific information may be biased, partial, or even fictional based on the author's training, thoroughness, or intent. Habitat reconstruction from such documents is fraught with danger of misinterpretation (Forman and Russell 1983).

However, a baseline must be established for comparison with present conditions, and despite their drawbacks, historic documents present first-hand and otherwise unavailable information.

One must first delimit a period of time to be emphasized for the baseline, then outline basic assumptions for reconstruction. For present purposes, the period of initial archaeological record (ca. 1500 A.D.) through discovery, exploration, and early exploitation by Western man (ca. 1850) is emphasized. Conditions in this period are compared with post-1900 trends that resulted in habitats seen today. Assumptions are those of a continuity in space and time of basic physical processes like erosion and deposition, biological responses of vegetation to greater or lesser water supplies, and species' habitat preferences, which are presumed not to have changed in the past few hundreds of years.

Man in the Upper San Pedro Valley

Influence of man on aquatic habitats in the Southwest obviously predates historic records. Indian harvesting of fishes must have influenced their populations, and presence of bones in archaeological sites (Miller 1955) attests to their use as food. Irrigation development in the San Pedro basin (Kino 1919; Bryan 1929, 1941; Di Peso 1951, 1953), although apparently not as extensive as those in central Arizona (Gladwin et al. 1937; Haury 1976; Masse 1981), must have negatively impacted the stream. Indian diversions from the Gila River for floodplain irrigation in the 18th and 19th centuries were seasonally sufficient to dry long downflow reaches (Emory 1848; Clarke 1852; Bartlett 1854; Sweeny 1856; Sedelmayr 1955; Russell 1908; Rea 1983). On the other hand, Dobyns (1978, 1981) proposed that spreading of floodwaters by agricultural terraces in headwaters along with downstream diversion dams aided in minimizing erosion in earliest times. Human population crashes from devastating epidemic disease (Crosby 1976) and later Apache depredations may have allowed these structures to deteriorate, contributing to erosion cycles. Dobyns (1981) also considered it possible that broader Indian use of fire for hunting, affects of food and firewood gathering, and impacts of aboriginal livestock herding practices all contributed to habitat change.

Other than use by hunters and gatherers, man's occupation of the San Pedro valley dates from sometime before 1500, when peoples with cultural affinities to Sonora established and maintained at least four agricultural rancherias east of the Huachuca Mountains. Their ancestry to the Sobaipuri Indians, who inhabited San Pedro valley when Spaniards arrived, is ambiguous (Di Peso 1951, 1953). Spaniards visited the region beginning with the westward wandering of Alvar Nunez Cabeza de Vaca in 1536 (1542, translated by Covey 1986; see also Hodge 1984a), and certainly by Frey Marcos de Niza in 1539 and Francisco Vazquez de Coronado in 1540 (Bolton 1980; Hodge 1984b); both the last traveled northward down the San Pedro River in the first organized penetration of the Southwest by European man.

The Sobaipuris were again visited by Padre Eusebio Kino and other missionaries in the later 1600s, and were census as 2000 "souls" in 14 villages (Kino 1919). They subsisted by irrigated agriculture, confirmed by mention of extensive acequias (ditches), lived in houses built of poles and "reeds," and were provided livestock by Padre Kino. The largest villages were Quiburi, about 2.0 km north of present day Fairbank and occupied from 1150 to about 1760 A.D., and La Victoria de Ojio near Aravaipa Creek. They remained as farmers until fleeing Apache attacks in 1762 (Guiteras 1894). A comprehensive report on Quiburi was published by Di Peso (1953)

For the next seven decades, Apache raids allowed only sporadic development of Spanish cattle ranching. Mexican land grants in 1822 deeded most of the San Pedro valley to cattlemen, who commenced heavy stocking of ranges (Mattison 1946). Apache hostilities from 1828 to 1843 caused most to abandon operations (Haskett 1935), and Clarke (1852) described abandoned irrigated farming, ruined haciendas, and plentiful wild cattle. Cooke (1938) documented extensive trampling of the valley by feral cattle and horses in 1846. These herds dwindled quickly, possibly due to hunting by the Apache, military expeditions, and "49ers" traveling west in search of gold (Browne 1869; Bell 1932).

Attempts at cattle ranching again commenced in the late 1860s, but Apaches continued to raid until the late 1870s, when J. H. ("Texas John") Slaughter brought a major herd to Herford. Cattle populations grew to peak at an average of perhaps 400,000 head in the period 1888 to 1893 in what is now Cochise, Santa Cruz, Pima, and Graham counties, Arizona (see Hendrickson and Minckley 1985), just before and during a disasterous drought (Haskett 1935). By comparison, the average for 1977 through 1981 in the same area (Arizona Crop and Livestock Reporting Service 1981) was only 180,000 cattle. The drought resulted in loss to hunger or thirst of more than half, or perhaps as many as 75%, of all livestock in the region by 1895 (Wagoner 1951, 1952, 1960; Hastings and Turner 1965).

At about this same time, irrigation was again being developed near St. David (McClintock 1921) and elsewhere along the river; 1400 ha irrigated by surface water were under production by 1899 (Roeske and Werrel 1973). Mining also emerged as a major industry, especially near Tombstone by 1878, and the short lived "boom" stimulated construction of a riprap dam across the San Pedro in 1879 and diversion of water through a 2.4 km channel to an ore mill at Charleston in 1881 (Hamilton 1881; Gilluly 1956). Charleston was deserted and Tombstone nearly so by 1890, but irrigated agriculture and livestock ranching persisted and expanded despite drastic reductions in the local economy. Irrigation was largely by pumpage from floodplain aquifers as electrical power became available, and amount of land under production in the San Pedro valley increased to 5000 irrigated hectares by 1966, which had declined to 3900 by 1970 (Roeske and Werrel 1973), and was estimated at 5950 ha in 1979, excluding an unknown area in Mexico (USGS, publ. periodically).

Aquatic Habitats of the Past

Upper parts of streams in southeastern Arizona formerly supported a habitat termed cienegas, described in detail by Hendrickson and Minckley (1985) as:

> "a marshland community associated with perennial springs and headwater streams...Cienegas are perpetuated by permanent, scarcely-fluctuating sources of water, yet are rarely subject to harsh winter conditions. They are near enough to headwaters that the probability of scouring flood is minimal. The system is controlled by permanently saturated hydrosoils..."

Based on historic evidence, as noted before, a large proportion of the upper San Pedro River supported cienegas in the four centuries prior to technological development, and long before.

Unfortunately, Spaniards as the earliest explorers scarcely mentioned ecological conditions, rivers, or local terrain except in journal comments on difficulty or ease in travel. Coronado's party, for example, passed near the site of Cananea, Sonora, down the San Pedro River to perhaps what is now Benson, Arizona, and scarcely mentioned the stream. They turned east and back north to reach a "deep arroyo and a ravine," the Gila River near Geronimo (Bolton 1980), described as a "..deep and reedy stream"

(Calvin 1946) where they crossed about 16 km west near Bylas, Arizona. Padre Kino (1919) described the upper San Pedro valley in the late 17th Century as lush and heavily irrigated, but essentially ignored the river.

The Mormon Battalion in 1846 provided the first specific comments on the San Pedro Valley. Cooke (1938) described their camp "..in a marshy bottom with plenty of grass and water" and the stream as a "beautiful little river." For two days travel downstream, conditions remained the same. Tyler (1881), on the same expedition, considered the stream "boggy" near Bull Run (the present Lewis Springs) and stated: "A kind of cane grass grew in this region, from 4 to 6 feet high, being very profuse and luxuriant in the bottom near the stream." Cooke (1938) likely referred to stands of sacaton grass (Sporobolus airoides) when describing the bottoms (floodplain) as "..having very high grass and being lumpy" near Lewis Springs. He also related "..the bottom grass is very tall and sometimes difficult to pass through. These bottoms average above a mile and are good land." Leach (1858) similarly reported broad, dense sacaton "bottoms" downstream from Tres Alamos, with cottonwood, ash, and willow lining the river. Eccleston (1950) described the San Pedro near the mouth of Tres Alamos Wash below Benson as:

> "...extremely boggy and has to be crossed by making a brush bridge...I was obliged, in order to manage my team, to jump in beside them, and get wet above the waist...Here it is lined with a poor growth of swamp willow and other brush, so it cannot be seen till you come within a few feet of it, and then the bank is perpendicular, not affording an easy access of its water, which though not very clear, is good. The banks and bed are extremely boggy, and it is the worst place for cattle and horses we have yet been, being obliged to watch them very close."

Parke (1857) described what appeared to be similarly extensive marshlands above the San Pedro "Narrows", as follows:

> "In the gorge below, and in some of the meadows, the stream approaches more nearly the surface, and often spreads itself on a wide area, producing a dense growth of cotton-wood, willows and underbrush, which forced us to ascend."

Evans (1945) described a "..road winding through miry bottoms of a small stream which was kept alive by the water of marsh and springs," as his party crossed the San Pedro River near the International Boundary before going south of the Huachuca Mountains to the Santa Cruz River valley in 1849. A few years later, Emory (1857) provided a broader picture of the stream and its valley near the same place:

> "At this point, approaching from the east, the traveller comes within a mile of the river before any indications of a stream are apparent. Its bed is marked by trees and bushes, but it is some sixty or one hundred feet below the prairie, and the descent is made by a succession of terraces. Though affording no great quantity of water, this river is backed up into a series of large pools by beaver-dams, and is full of fishes. West of the river there are no steep banks or terraces, the prairie presenting a gentle ascent."

Beaver (Castor canadensis) attracted fur trapper James Ohio Pattie (1833) to the San Pedro River in 1824 and Etz (1938) remembered extensive marshlands and beaver dams in the 36-km reach downstream from Benson in the late 1800s. Dobyns (1981) and Davis (1982) provided other references to an abundance of beaver along the length of the stream. Hastings (1959, 1962) confirmed presence of marshlands along the river from Benson to Tres Alamos from other sources, such as 1889 court records, and cited epidemic malaria at streamside communities and military installations (Bell 1869; McClintock 1916, 1921; Granger 1960; Bennett 1977) as further evidence of swamps along the river. It is notable that malaria disappeared as a major regional disease with arroyo cutting (Hastings and Turner 1965).

Clear indications of extensive cienega conditions are tempered by other references to contemporaneous, incised arroyos almost in the same areas. In 1851, banks 2 to 3 m in height near St. David had to be leveled before wagons could be lowered by hand (Graham 1852; Bartlett 1854). The river was reported as incised almost 4.0 m near present day Benson about that same time (Parke 1857), and Bartlett (1854) wrote that downcutting was great enough to preclude floodplain irrigation. Hutton (1859) encountered incised channel upstream from the "Narrows," but marshlands below. Cooke and Reeves (1976) examined surveyor's reports that similarly indicated eroded banks along some stream reaches and lack of incision elsewhere. Entrenchment, although obviously present, appears to have been discontinuous and local, perhaps a "normal" state in streams with developed cienegas (Hendrickson and Minckley 1985), and in sharp contrast to the broadening, erosive channels of today.

Permanence

Most historic accounts indicate perennial surface flow in the San Pedro River wherever it was crossed. Lee (1904) described surface flow as continuous, although small in volume during dry seasons, as late as turn of the present Century. Hastings and Turner (1965) cited two references for discontinuous flow, and one intermittent reach: Leach (1858) and Hutton (1859) both mentioned ephemeral flow in the river below Tres Alamos. Significant permanent surface discharge persists in tributaries (Aravaipa Creek, Babocomari River, and Hot Springs and Redfield canyons). Some tributary streams now or in the recent past used for irrigation must have formerly been larger. As typical in the region, most tributaries infiltrate when flowing onto San Pedro valley fill, with connection to the mainstream in flood (Hendrickson and Minckley 1985).

FISHES OF THE SAN PEDRO BASIN

History of Study

A large percentage of the Gila River basin fish fauna was first made known to science from collections in the upper San Pedro basin by personnel of the U.S. and Mexican Boundary Survey (Emory 1857). Major sampling sites were in the mainstream near the present International Boundary and mouth of Babocomari River, and in Babocomari River itself. Specimens were shipped via various means and routes to the east, and ultimately studied and described by Spencer F. Baird and Charles F. Girard. Baird later brought an early and vigorous beginning to the U.S. Fish Commission (in 1871), which led to the Bureau of Fisheries and ultimately to the U.S. Fish and Wildlife Service (USFWS). Girard had come from France to study with Professor Louis Agassiz, and became prominent in American science in part beause of his work (Girard 1859) on fishes of the U.S. and Mexican Boundary Survey (Hubbs 1964).

Collections were not again made in the basin until Philip H. Kirsch, a former Indiana State Fish Commissioner, volunteered to report on aquatic resources of the Arizona Territory to the U.S. Bureau of Fisheries (Jennings 1987). However, he died in 1900 after surveying only the San Pedro River (Smith 1900), and Frederic M. Chamberlain was assigned the job. Smith's notes are in the National Archives in Washington (Jennings 1987), but I have not yet obtained a copy.

Chamberlain was a prominent field assistant in the Bureau of Fisheries who spent three months in Arizona in 1904 (Evermann 1905), results of which included both early fish collections and an insightful, 52-page manuscript (Chamberlain 1904). It was never published, but fortunately was deposited along with his field diary in the Smithsonian Institution Archives. His observations on failing springs, drying cienegas, lowering water tables, eroding streambanks, and loss of fishery resources (Jennings 1987) were later corroborated by a number of workers (Bryan 1925, et seq.; Antevs 1952; Hastings 1959, 1962; Hastings and Turner 1965; Cooke and Reeves 1976; Hendrickson and Minckley 1985). He hypothesized changes to have resulted from a combination of overgrazing, removal of tree cover, climatic change, and poor farming practices.

The next series of samples and observations in the San Pedro basin were by Carl L. Hubbs in 1938, James R. Simon in 1943, and Robert R. MIller in 1950 and 1961. All their specimens are housed in the University of Michigan Museum of Zoology (UMMZ), which, largely through efforts of Hubbs and Miller, remains the major repository for Western American fishes. Simon never published on his collections, but Hubbs did as a coauthor with Miller, and Miller's field data and information on specimens appeared in numerous papers by himself, students, and colleagues. Subjects included new records (Miller and Winn 1951), Arizona drainages (Miller 1954), larval fish identification (Winn and Miller 1954), archaeology (Miller 1955), faunal change (Miller 1961), and reviews of species groups (Hubbs and MIller 1941; Miller and Hubbs 1960; Smith 1966) and of Arizona fishes in general (Miller and Lowe 1964).

Studies of Southwestern fishes were commenced by W. L. Minckley of Arizona State University (ASU) in 1963 (Minckley 1973, 1985), including frequent collections from the San Pedro basin by himself, his students, and collegues, beginning in 1964 and extending to present. Representative specimens are deposited in the ASU Collection of Fishes, and most papers and reports including data from those collections are cited elsewhere in text of the present document.

Patterns of Ichthyofaunal Change

Faunal change with time in the San Pedro River mainstream includes a gradual depletion of native species accompanied by appearance of ever-increasing numbers of non-native, introduced fishes (Table 3). There seemed little immediate response to the 1890 incision event, unless reflected in the initial disappearance of large fishes (Colorado squawfish, razorback sucker, flannelmouth sucker). These were followed by species characteristic of cienegas (Gila chub) and of streams with pool-riffle development (roundtail chub). Some fishes of permanent, gravel-bottomed creeks (loach minnow, speckled dace, spikedace, Sonoran sucker) remained for 50 years after arroyo cutting, as did kinds depending on river margins or river-associated floodplain habitats like oxbows, springs, and marshes (desert pupfish, Sonoran topminnow). Significantly, the pupfish was last caught in headwaters of the San Pedro in Mexico (Miller and Winn 1951) above a dam that may have protected them from channel erosion, and topminnow was last recorded in the outflow of an artesian well (McNatt 1979a-b). Only those fishes tolerant of erosive, shallow, sandy-bottomed desert streams (longfin dace, desert sucker) persist today. More details on biology of these species are given below.

Native fishes in some tributaries, especially those like Aravaipa Creek and Redfield Canyon that must have been of an erosive nature for millinea, fared better than those of the mainstream. Aravaipa Creek fishes, for example, have proven remarkably stable in species composition and population structure over time, in spite of major flooding and drought (Meffe and

Table 3. Records verified by specimens (X) and probable occurrences due to existance of later records (0) of native and introduced fishes in the San Pedro River mainstream from the late 1800s through 1986. A question mark (?) indicates the estimated, approximate time of extirpation of a native species due to documented habitat change, or probable time of first introduction of a non-native species based on patterns of appearance elsewhere in Arizona (Minckley, 1973, unpubl. data). Tributaries such as Aravaipa Creek, Redfield Canyon, and parts of the Babocomari River system that still support a largely native fauna are excluded, but are discussed elsewhere in text. This compilation is based on literature cited in text, specimens deposited at UMMZ and ASU, and unpublished field notes of W. L. Minckley and associates.

	YEARS OF OCCURRENCE OR COLLECTION													
Species	1700s	1851	1880s	1904	1938	1943	1950	1961	1964	66-8	70-4	76-9	80-3	85-6
							NATIVE TAXA							
Colorado squawfish	X	0	?	-	-	-	-	-	-	-	-	-	-	-
Razorback sucker	X	X	?	-	-	-	-	-	-	-	-	-	-	-
Flannelmouth sucker	0	X	0(?)	-	-	-	-	-	-	-	-	-	-	-
Roundtail chub	0	X	0(?)	-	-	-	-	-	-	-	-	-	-	-
Gila chub	0	0	0(?)	-	-	-	-	-	-	-	-	-	-	-
Speckled dace	0	0	0	0(?)	-	-	-	-	-	-	-	-	-	-
Loach minnow	0	X	0	0	0	0	X(?)	-	-	-	-	-	-	-
Desert pupfish	0	X	0	0	0	0	X(?)	-	-	-	-	-	-	-
Spikedace	0	X	0	0	X	0	X	0	X(?)	-	-	-	-	-
Sonoran topminnow	0	0	0	0	0	X(?)	0	0	0	0	0	X(?)	-	-
Sonoran sucker	0	X	0	X	X	X	X	X	X	X	0	0	X(?)	-
Longfin dace	0	X	0	X	X	X	X	X	X	X	X	X	X	X
Desert sucker	0	X	0	X	X	X	X	X	X	X	X	X	X	X
							NON-NATIVE TAXA							
Common carp	-	-	X	0	0	0	0	0	X	0	0	0	X	0
Rainbow trout	-	-	?	0	0	0	0	0	X	0	0	X	0	0
Black bullhead	-	-	-	-	X	0	0	0	0	0	0	0	0	0
Green sunfish	-	-	-	-	X	0	0	0	X	X	0	0	X	0
Mosquitofish	-	-	-	-	?	X	0	0	X	X	X	0	X	X
Goldfish	-	-	-	-	?	-	-	-	X	0	0	0	0	0
Fathead minnow	-	-	-	-	?	-	-	-	X	X	0	0	X	X
Yellow bullhead	-	-	-	-	?	-	-	-	X	0	X	0	X	0
Channel catfish	-	-	-	-	?	-	-	-	X	0	X	0	0	0
Bluegill	-	-	-	-	?	-	-	-	X	0	X	X	0	0
Largemouth bass	-	-	-	-	?	-	-	-	-	X	0	0	0	0
Brook trout	-	-	-	-	-	-	-	-	-	X	0	0	0	0
Threadfin shad	-	-	-	-	-	-	-	-	-	?	X	0	0	0
Red shiner	-	-	-	-	-	-	-	-	-	-	?	-	-	X

Minckley 1986). Seven of the original San Pedro fauna of 13 fish species remain there. It is therefore possible that apparent persistance of some species in the San Pedro mainstream actually reflected movements from tributaries in the United States or from unknown populations that remained for a time in Mexico. Tributary streams that underwent downcutting like that of the San Pedro (e.g., lower Babocomari River) had similar depletions in their fish faunas (unpubl. data).

Of the 14 recorded introduced species, common carp was first stocked into Arizona in ponds near St. David (Taggart 1885; Rule 1885), and almost immediately appeared in Arizona's rivers (Evermann and Rutter 1895; Gilbert and Scofield 1898). Rainbow trout followed closely, according to local testimony (unpubl. data) being stocked in the Huachuca Mountains near the turn of this Century. Black bullhead and green sunfish were taken from the San Pedro mainstream in 1938, and mosquitofish in 1943. All three (Miller and Lowe 1964), and probably yellow bullhead and channel catfish, were stocked in Arizona by the 1920s. Bluegill and largemouth bass also appeared in cattle-watering tanks and reservoirs far earlier than indicated by collections from the San Pedro River (Minckley 1973). Their absence in older samples probably reflects lack of suitable habitat. Brook trout appeared late, stocked as a put-and-take fishery in the Huachuca Mountains (unpubl. data). Threadfin shad has entered the stream only at its mouth, presumably as stragglers from San Carlos Reservoir on the Gila River, and the late appearance of red shiner reflects its slow, inexorable spread through the Gila River basin from bait releases in the Colorado River mainstream and near Phoenix (Hubbs 1954; Koehn 1965; Minckley 1973).

Past Habitats and Fish Communities

Existance of populations of large species like Colorado squawfish and flannelmouth and razorback suckers in the San Pedro River (Table 1) demands presence of habitats substantially different than those of today. However, these fishes were extirpated from the Gila River and its tributaries before species' habitat requirements were studied, and interpretations can only be based on historic records and ecological relations where they persist in the upper Colorado River basin. Desert pupfish is even nearer extinction throughout its range (USDI 1986c), so definitions of its habitat and role in the San Pedro are clearly problematic. Other species also gone from the river, roundtail chub, spikedace, loach minnow, speckled dace, Sonoran sucker, and Sonoran topminnow, persist elsewhere in the Gila basin. All but the last remain in Aravaipa Creek (Barber and Minckley, 1966; Minckley 1981), which must therefore retain some of the ecological conditions once typifying the upper mainstream. Sonoran topminnow, although federally-listed as endangered (USFWS 1984c), is locally represented by populations in the adjacent Santa Cruz River basin. Longfin dace and desert sucker persist in the San Pedro itself (Table 3).

These species fall into four broad categories with regards general ecological requirements throughout their native ranges, and thus presumably in the pre-disturbance San Pedro River:

I. tending to live in large, eroding rivers and associated floodplain habitats (squawfish, flannelmouth and razorback sucker);

II. tending to inhabit perennial, moderate- or small-sized streams of variable erosiveness (spikedace, roundtail chub, loach minnow);

III. occupying spring-fed or river-associated, aggrading habitats such as backwaters, cutoff pools, or stream margins (Gila chub, desert pupfish, Sonoran topminnow); and

IV. ubiquitous and/or variable in habitat use, including occurrences in spatially intermittent systems (longfin and speckled daces, Sonoran sucker, desert sucker)

Past aquatic habitats, delineated in part from historic literature, may be further defined by the known ecological requirements of each of these fishes, and three basic conclusions may be reached. Fishes of Category I required larger habitats than are presently available. Greater stability in the sense of perennial flow and a presence of stream-associated habitats must have been characteristic for the stream and its environs to support fishes of categories II and III. And, the system must have been more heterogenous than now to support such a diversity of species (all categories).

Habitat Size. -- The San Pedro River was never "large" in the sense of the Colorado River mainstream, or even Arizona's Salt or Gila rivers. Those watercourses command far larger watersheds, originating in tributary nets that accumulate winter snow at high elevations, the major source of runoff for master streams of the Sonoran Desert region. They also flow through heterogenous terrain, alternating between canyon-bound and erosive in mountains, and broad, aggrading, and meandering when crossing intermontane basins. Precipitation in the San Pedro watershed is relatively high due to its overall elevation and proximity of high mountains. However, with exception of a few places where resistant strata constrain the channel (e.g., the "Narrows"), most of its course passes over alluviated floors of structural basins.

A pattern in southeastern Arizona of anticyclonic, summer monsoons and more general and protacted winter rainfall (Martin 1963; Fogel 1981) has not changed markedly in the past few centuries, despite some indications of increased aridity (Hastings and Turner 1965; Cooke and Reeves 1976; Brown and Henry 1981). Thus, assuming gross precipitation has remained about the same, greater "size" of the San Pedro River in the past resulted from: 1) factors that influenced runoff through dampening and attenuating flood peaks and spreading seasonal discharge variation more evenly over the year; and 2) altering channel morphology to create greater dimensions and lower speed-of-flow through larger cross-sectional areas.

Dense vegetative cover of ungrazed desert grasslands, deep, porous soils, and relatively low gradients of rolling hills of the watershed all tended to reduce rates of runoff. Sheet flow was retarded, minimizing channel discharge in ephemeral arroyos, maximizing infiltration to storage in water tables, and increasing base flow. Percolation occurred slowly to stream channels, leveling discharge peaks. Cienegas and beaver ponds provided additional buffering. Marshlands increased "roughness" in the channel, retarding speed of flow and erosion and promoting deposition. Alluvial fans from inputs from side slopes and ephemeral arroyos (Melton 1965) onto cienega surfaces also formed partial dams. The few centimeters of water temporarily stored in these and in beaver ponds during spates spread to infiltrate or at least was slowed in passage (Hair et al. 1979; Parker et al. 1985). Accumulations of organic debris interbedded with inorganic materials created alternatively spongy and highly porous, underground reservoirs, collecting and storing flood waters that were "leaked" to the channel during drought. Willow and cottonwood trees germinated and grew on streamsides that became elevated above water.

Development of woody vegetation enhanced beaver, which added to formation of ponds and even greater water storage and sediment entrapment through their activities.

Nick points formed at breached beaver dams, accumulated debris piles and fallen trees, stream bends, and inputs of sediment from tributaries all induced local cutting, and pools formed downstream from concentration, diversion, or abrupt changes in direction of flow. Volume of water stored and its retention times were vastly increased, and the river was far "larger" as a result.

Measures of Stability. -- Stability in the sense of reduced variability must have been greater in the upper San Pedro River in the past than at present. Slow release of water from streamside and instream aquifers ameliorated low flow conditions. Reduced speeds and volumes of discharge moderated flooding from the limited watershed due to interception and impedence by vegetation and infiltration into deep, porous soils and other storage. Hendrickson and Minckley (1985) further reviewed conditions leading to development of extensive cienegas, all of which hinge upon a balance between aggradation and degradation (Curry 1972; Bull 1979, 1981) that must have existed in the watershed.

Heterogeneity. -- Marshlands can be ecologically monotonous, especially when in advanced stages of succession where decomposition of accumulated organic materials influence chemical environments. Cienegas, however, are stream channel phenomena, and as such are far more dynamic than might be expected. As noted above, channel constraints inducing locally increased gradient and flow concentration promoted local incision. Local downcutting often persisted as deep, slit-like pools until filled by succession and deposition back to cienega conditions (Hendrickson and Minckley 1985). However, local nick points also migrate upstream until an equilibrium is reached, forming reaches of swift, turbulent flow, few pools, and harder bottoms of sand, gravel, and cobble, alternating with large, deep pools, and soft substrates in cienega reaches.

Features of local channels and floodplains provided other kinds of aquatic habitats due to a tendency in Southwestern streams for alternating, concave-convex longitudinal profiles. Coarse sediments carried from tributaries by flood can impound a receiving channel, as can coarse material dropped by energy dissipation of short-term, high intensity, but low volume discharges (Schumm and Hadley 1957; Patton and Schumm 1981). Cienegas alternating with zones of downcutting obviously created such patterns, as did beaver dams alternating with undammed reaches (Hair et al. 1979).

Coarse bedloads of degrading reaches further result in high porosity and substantial underflow of water. Points of underflow emergence into concave segments, across stream meanders, or behind natural levees formed spring-like or ponded situations that provide substantial fish habitat. Cutoff meanders (oxbow lakes or pools) or areas of scour where major flooding crossed alluvial terraces, also were served by underflow so long as they remained deep enough to intersect the water table. Springs rising along faults at valley edges provided additional water to the river and fed streamside depressions.

Species' Ecologies Relevant to Available Habitats

Category I. -- Unlike some other fishes, "big river" species recorded from the San Pedro River should have been restricted to the mainstream. Tributaries, with possible exception of Babocomari River, would have provided little habitat conceivably suitable for completion of life cycles of Colorado squawfish, razorback sucker, or flannelmouth sucker. In fact, depths and other dimensions of pools and other larger habitats on the upper San Pedro mainstream must have been comparable, at best, to minima occupied by squawfish and razorback in the Salt, Gila, and especially the Colorado rivers. The San Pedro undoubtedly included habitats comparable to those now occupied by flannelmouth sucker in other parts of its range.

Both Colorado squawfish and razorback sucker occupy deep, quiet, eddying or slowly-flowing water as adults, and even young are rarely taken other than along margins of large rivers, in backwaters and oxbows associated with major streams, or even more rarely in mouths of tributaries (Vanicek 1967; Vanicek and Kramer 1969; Vanicek et al. 1970; Holden and Stalnaker 1975a-b; Tyus et al. 1982a-b; Valdez et al. 1982). Colorado squawfish feed on zooplankton and benthic invertebrates until about 75 mm total length (TL), then shift to a diet of other fishes (Seethaler 1978). Razorback sucker feed on benthic invertebrates, zooplankton, detritus, and algae throughout life (Marsh 1987; Marsh and Langhorst 1987).

Spawning by both species occurs in current on gravel bars associated with riffles under riverine conditions (Seethaler 1978; McAda and Wydoski 1980; Tyus et al. 1982b; Tyus 1985, 1987). There is evidence that wild squawfish return to the same area of river to spawn (Tyus 1985). Colorado squawfish achieves sexual maturity at about six years of age at less than 20 cm TL under hatchery conditions (Hamman 1981). Razorback sucker reproduces along wave-washed shorelines over clean cobble bottoms in Colorado River reservoirs (Douglas 1952; Minckley 1983). This species matures at 35 to 39 cm long at 2 (males) or 3 (females) years old under optimal hatchery conditions (Hamman 1985). Young razorback produced in hatcheries and stocked in backwaters and upper parts of small streams in Arizona grow rapidly and appear competitive with other native fishes (Brooks et al., in prep.); however, no stocked population has been in place long enough to evaluate possibilities for natural re-establishment.

Colorado squawfish ("salmon-trout") 3.0 feet (0.9 m) long from at or Fairbank in 1846 (Cooke 1938), similar-sized fish reported at Tres Alamos in 1849 (Eccleston 1950), and squawfish vertebrae from fish near 5.0 feet (1.5 m) in length from Sopaipuri trash middens at Quiburi dated between 1707 and 1763 (Miller 1955) document presence of adults, if not a reproductive population, in the upper San Pedro River. The single vertebra of a razorback sucker identified by Miller (1955) from Quiburi was from a fish perhaps 3.0 feet (0.9 m) long, which is near maximum for the species (McCarthy 1986; McCarthy and Minckley 1987). Chamberlain's (1904) report that razorback sucker was formerly marketed at Tombstone as "buffalo,' so called from the hump" further attests to occurrence of large individuals in the river.

Razorback sucker live to great age and Colorado squawfish must get even older. Razorback are approaching 50 years old in Lake Mohave, Arizona-Nevada, based on 24- to 44-year-old individuals sacrificed for study in 1981 and 1983 (McCarthy and Minckley 1987). No comparable data are available for squawfish, but growth is slow under presumably optimal hatchery conditions (Rinne et al. 1986), and hatchery fish 9 years old achieved less than 50 cm TL. Individuals a meter long must have been living for 50 or more years.

Annual reproduction in such a long-lived species may not be necessary, so individual fish or year classes could have occupied deep pools of the San Pedro River for decades, periodically reproducing to maintain populations. An alternative exists, however, that occasional upstream movement could have been a source of San Pedro "big river" fishes. Colorado squawfish make remarkably long annual movements, often exceeding 150 km in the upper Colorado River basin (Tyus et al. 1982b; Tyus 1985), so migration from the Gila River would not have been surprising. No such data are available for razorback sucker, although they apparently made spring migrations, presumably to spawn (Minckley 1983). However, a San Pedro River repeatedly blocked by beaver dams and cienegas might not have allowed upstream movement except during flood. Historic records for both squawfish and razorback sucker extend far upstream past the mouth of the San Pedro River on the Gila River to near Safford, Arizona (Chamberlain 1904). Thus, although habitat was almost certainly present in the San Pedro River, there is no present way to falsify the hypothesis that both these species were migrants as opposed to representives of reproducing populations.

Flannelmouth sucker is known from the San Pedro River only from the type specimens (Minckley 1980g). In fact, it was rarely taken anywhere in the Gila River basin by early or later collectors, and if still present, is expected only in the Salt River above Roosevelt Reservoir (Minckley 1985). Flannelmouth also attain large sizes as adults, to more than 60 cm TL. Unlike fishes just discussed, this species often enters tributaries, becoming abundant over soft bottoms in creek mouths and sometimes ascending small streams for considerable distance (Carothers and Minckley 1981). Its habitat in large rivers includes riffles and runs as well as deeper, quiet or eddying water (Minckley 1973, 1985). It feeds on algae, detritus, and b... ic invertebrates. Reproduction was in spring and early summer in ...hs of tributaries to the Colorado River in Grand Canyon National Park ...hers and Minckley 1981). Mainstream reproduction is typically over ...ottoms in moderate current.

Populations of flannelmouth sucker in the San Pedro River must have been small, and little can be said about its probable ecology. This species presently occupies habitats that seem comparable, or even smaller and less stable, than those which must have existed in the San Pedro River in times past. Reasons for its rarity and apparently early extirpation from the Gila River basin are unknown (Minckley 1985).

Category II. -- Greater stability in discharge and instream flow volumes allowing spikedace, loach minnow, and roundtail chub to live in the upper San Pedro River were insured by ungrazed watersheds and cienega formation. However, it seems likely that none of these fishes, with possible exception of the last, would have remained for long in under fully developed cienega conditions. Both spikedace and loach minnow are small, rarely exceeding 75 mm TL, and are invariably associated with currents and hard bottoms in streams (Barber et al. 1970; Anderson 1978; Britt 1982; Propst et al. 1985a-b). Both are endemic to the Gila River basin (Minckley 1973, 1980b, 1985; Rhode 1980). Roundtail chub is similarly restricted to streams, but often occupies pool habitat.

Spikedace is an active, visual, midwater consumer of drifting benthic and terrestrial invertebrates (Schreiber 1978; Schreiber and Minckley 1982; Barber and Minckley 1983). It spawns in shallow, flowing water over coarse sand or fine gravel. There is evidence that larger (older) females spawn earlier in the year and perhaps twice, once in spring and again in midsummer. Females in their first summer of life spawn once in late spring. Sexual maturation occurs the second summer of life and individuals live only to their third summer (Barber et al. 1970; Anderson 1978).

Loach minnow prefers streams of moderate gradient that form turbulent riffles with moderate- to high-velocity current over cobble-rubble substrate seasonally covered by filamentous algae (Minckley 1981; Britt 1982; Propst et al. 1985a). The species is benthic and feeds on simuliid dipterans and mayflies (Schreiber and Minckley 1982). Spawning is beneath stones on or lateral to swift riffles in spring and early summer (Britt 1982). Maturation is in the second summer, and few individuals survive through a third.

Roundtail chub is potentially large, achieving more than 40 cm long in larger rivers. As with many Western fishes, smaller habitats are usually occupied by smaller roundtail (Smith 1981). The species can reproduce its second or third summer, and presumably lives to a relatively great age. It is silvery in color, elongate, and large finned, and a strong swimmer capable of long distance movements when so disposed (Siebert 1980). It has a large mouth and strong pharyngeal teeth (Minckley 1973). Considering this last morphology, roundtail foods consist of a surprisingly high percentage of filamentous algae. They also feed on large and small invertebrates and other vertebrates including fishes and even lizards (Neve 1976; Schreiber and Minckley 1982). Young frequent flowing margins of pools and runs, but adults prefer shaded, deep pools, especially those with cover such as overhanging vegetation, undercut banks, boulders, or large debris. Adults also often occupy eddies downstream from boulders in rapids or the downstream ends of riffles (Vanicek and Kramer 1969; Minckley 1973; Neve 1976). The species tends to avoid creeks in the upper Colorado River basin (H. M. Tyus, USFWS, pers. comm.), but commonly lives in small creeks in the Gila River system (Minckley 1973, 1985) and within its extensive range in Mexico (Hendrickson et al. 1981; Minckley et al. 1986).

Under pre-disturbance conditions, all three of these species were most likely exclusive, or at least most abundant, in reaches characterized by incision. As noted before, soft bottoms and relatively quiet waters of cienegas would exclude both spikedace and loach minnow. Beaver ponds or deeply cut pools of cienegas should be suitable for roundtail chub, but I know of no recent records for the species from such habitat.

Category III. -- Deep pools in cienegas are, however, characteristic environments for Gila chub, a formerly common and widespread species in southeastern Arizona that persists in the upper San Pedro basin as local, remnant populations (DeMarais 1986). This fish is thicker bodied than roundtail chub, with smaller, more rounded fins, larger scales, and darker coloration. Gila chub is most abundant in deep pools of small streams, ciengas, and springs, where extremely secretive, hiding under cut banks and debris and seldom venturing from deeply shadowed areas. No detailed life history data are available, but based on general observations (Minckley 1969a, 1973, 1985) the species is omnivorous, tending toward carnivory. Reproduction seems protracted since tiny young are present from early spring through autumn.

There is no doubt that Gila chub was more abundant when cienegas were common in the upper San Pedro basin, nor that re-establishment of cienega conditions would enhance this species. It seems likely this fish also became common in oxbow lakes, marshes behind natural levees, along floodplains, and in springs. It presently inhabits oxbows along upper Bonita Creek, Arizona (Minckley and Clarkson 1979). Records from eroding streams seem to represent remnants of former cienega stocks or stragglers that find local conditions suitable for establishing peripheral enclaves. Such populations are highly localized and typically small in number.

A second species of special habitats, desert pupfish, is known from two collections in the upper San Pedro basin: the type specimens, obtained by U.S. and Mexican Boundary Survey collectors in 1851 (Baird and Girard 1853) and a 1950 sample from Sonora, Mexico, 12.8 km south of the International Boundary (Miller and Lowe 1964). The species otherwise was recorded from the Santa Cruz, Salt, mainstream Gila, and lower Colorado rivers and Salton Sea in United States, Rio Sonoyta, United States and Mexico, and Colorado River Delta and isolated springs in Sonora and Baja California del Norte, Mexico (Miller 1943; Minckley 1980e, 1985).

Pupfish are often described as characterizing severe habitats, tolerating waters too saline, hot in summer, deoxygenated, or otherwise unsuitable for fishes (Cowles 1934; Barlow 1958a-b, 1961). They are also typically thought restricted to springs, perhaps because they often occupy oases that comprise the last available surface water in arid zones. However, a number of species are, in fact, widespread in major rivers, where they live along margins in habitats that other fishes cannot attain, sometimes because of severe conditions, but often simply due to shallowness. Examples in Western North America are the Red River and Pecos pupfishes (_Cyprinodon_ _rubrofluviatilis_, _C_. _pecosensis_) of the high Plains, United States, Conchos pupfish (_C_. _eximius_) of the Rio Conchos, Mexico, and (formerly) the desert pupfish of the lower Colorado River basin (Miller 1981).

It is true that pupfishes are among the most resistant animals known to high temperatures and salinities. Some live in water warmer than 40° C and salt concentrations greater than five times that of seawater. Yet, they also live in places with more "normal" temperature and salinity regimes. With few exceptions, however, they do not flourish in community settings. They appear unable to persist under pressures of competition for space or food, predation, and other interspecific interactions.

Pupfishes are omnivores, with strong tendencies toward detritivory or herbivory. They are active over wide ranges of temperature, beginning to reproduce in early spring and continuing well into autumn or early winter at lower elevations. Males are brightly colored and highly and aggressively territorial, females are drab and spend most of their time feeding, and young resemble females. Sexual maturation is a few months after hatching, so populations can build rapidly from a few mature individuals, and life span in nature is probably less than a year. Adults rarely achieve more than 2 or 3 cm TL.

Desert pupfish was likely throughout the Gila River basin in the past, occurring locally and abundantly where habitat was suitable for seasonal reproduction by otherwise scattered individuals. A reach might support a few tens of fish per kilometer except in a warm, shallow, isolated backwater, slough, or oxbow, where populations could build to hundreds of fish in a month or so. As the habitat dried, or was inundated and disrupted by flood, pupfish moved along stream margins to persist until another suitable place was formed. Desert pupfish are likely not very flood resistant, so as channels incise and concentrate flow they may be displaced downstream. If isolated habitat was not available on the floodplain, such as pools maintained by underflow or springs, net downstream displacement would deplete upstream populations. As water tables dropped, floodplain habitats dried, and intermittency began to prevail, repopulation of headwaters by upstream movement was precluded and the species disappeared.

Sonoran topminnow presents an enigma for the upper San Pedro River basin. It was not represented in early or later collections except near the river's mouth, once near the confluence with Aravaipa Creek in 1943 and in outflow of an isolated artesian well in 1978 (McNatt 1979a-b); both these populations were extirpated.

Reasons for absence of topminnow from apparently suitable habitats of the upper basin are unknown. The species was abundantly represented throughout the adjacent Santa Cruz watershed, from which it was described by Baird and Girard (1853), occupied the San Francisco River upstream to Frisco Hot Spring in New Mexico (Koster 1957), and was recorded from the mainstream Gila River and its tributaries in Arizona from the lowermost San Simon to Yuma (Hubbs and Miller 1941; Minckley 1973, 1980f; Minckley et al. 1977; Meffe et al. 1983). It is now rare, persisting in numbers only in places that remain free of introduced mosquitofish, an aggressive species that feeds on young and attacks and shreds fins of adult topminnow. Mosquitofish depredations appear the major factor in disappearance of this native species from most of its formerly extensive range (Schoenherr 1974, 1977, 1981; Minckley et al. 1977; Meffe 1983a-b, 1984, 1985; Meffe et al. 1983).

Sonoran topminnow is a livebearer. Males have an intromittent organ, a modified anal fin or gonopodium that delivers sperm packets to the female, and young develop inside the female's body. Young are born at 5 to 7 mm long and grow to maturity in a few weeks. Reproduction is mostly in spring through autumn, but populations in constant-temperature springs reproduce in winter as well (Schoehnerr 1974, 1977). As with pupfishes, this species can develop large populations quickly in isolated, warm margins of streams or floodplain habitats. They feed mostly on detritus, but are predaceous on insect larvae or other invertebrates when such resources are abundant

(Gerking and Plantz 1980). They are almost as resistant to environmental extremes as pupfishes, living in places with dark, malodorous water, or where summer temeperatures exceed 38° C (Minckley 1973). Their resistance to salinity has yet to be thoroughly tested. The species is currently being managed toward recovery from Endangered Status, and is maintained under hatchery conditions by the USFWS (Rinne et al. 1986). The species has also been widely reintroduced, with variable success, in attempts to re-establish it in nature (Minckley 1969b; Brooks 1985, 1986; Minckley and Brooks 1986).

Category IV. -- Of fishes in this category, only speckled dace has suffered devastating reductions in range in southeastern Arizona. Sonoran sucker persists so long as pools are present for occupation by large adults, but undoubtedly has become rarer as streams incised. Longfin dace and desert sucker are likely as abundant or more so per unit area now than in the past in the remaining surface waters.

Speckled dace is the most widespread, abundant, and morphologically variable cyprinid fish in Western North America, ranging west of the Rocky Mountains from the Gila River north to southern Canada, and west to coastal California (Hubbs et al. 1974). Type locality for the species is Babocomari River, Arizona (Girard 1857), from which it has disappeared (Minckley 1973). Although tending to live at higher elevations, some populations exist below sea level in springs of Death Valley (Soltz and Naiman 1978). Local populations are often differentiated, and many have been described as unique subspecies. A number of stocks probably represent distinct species that are yet to be described.

In Arizona, this species lives in hard-bottomed, flowing waters ranging in size from the Colorado River mainstream to small headwater creeks of high mountains (John 1964; Minckley 1973, 1985). It is a bottom-dwelling carnivore, feeding on benthic invertebrates (Schreiber and Minckley 1982), and spawns in spring and summer on riffles, where males congregate over clean gravel to wait for receptive females. There is evidence that summer monsoons stimulate reproduction by the species (John 1963), perhaps due to sorting and cleaning of stream gravels by spates (Mueller 1984). Young grow rapidly to mature their second year, and based on size-frequency distributions, live through 3 or 4 summers.

Speckled dace was recorded in the San Pedro basin from the mainstream, Babocomari River, Redfield Canyon, and Aravaipa Creek; they persist in the last two (Minckley 1973, 1985). As with spikedace and loach minnow, most speckled dace in the undisturbed San Pedro River were likely in incised segments, although the species might be expected to colonize pools in cienegas or beaver ponds as large adults.

Sonoran sucker, described from the upper San Pedro near the mouth of Babocomari River (Baird and Girard 1854), was formerly widespread and abundant in the watershed. It remains common in suitable habitat in tributaries, but is now absent from the mainstream. This is a large species, often exceeding 35 cm TL even in small creeks and approaching 60 cm in rivers of the Gila and Bill Williams basins, to which it is endemic (Minckley 1980d). Adults and juveniles live in pools and young are typically along margins or in moderately-swift riffles. They feed throughout life on bottom-dwelling invertebrates gleaned from benthic substrates, with variable amounts of detritus and algal materials that may be ingested incidental to animal foods (Clarkson 1982; Schreiber and Minckley 1982). Spawning is on gravel riffles, usually of moderate velocity and turbulence (Minckley 1973). Sexual maturity is achieved the second or third summer of life and longevity is unknown.

Pool habitat seems critical to maintenance of large populations of Sonoran sucker, although habitats scarcely qualifying as "pools," undercut banks, depressions beneath logs, or scoured areas along cliff faces, often seem adequate in Aravaipa Creek (Minckley 1981). Adults concentrate in such areas in daytime, dispersing to feed at night in other parts of the stream and often to riffles. It maintained large populations under cienega conditions in Babocomari River prior to introduction of largemouth bass. That non-native piscivore seemed to decimate the sucker, which persists as small numbers of large individuals (unpubl. data). Sonoran sucker must have been abundant prior to downcutting. When present since 1964 (Table 3), it comprised only a few percent of the fish population.

Longfin dace is naturally distributed west of the Continental Divide from the Rio Sinaloa of Mexico northward to the Bill Williams River of Arizona (Minckley 1980a). As noted above, the species was probably enhanced in the upper San Pedro basin by cutting of cienegas and creation of a degrading system. It becomes most abundant in hot, shallow, sandy-bottomed desert streams, although also penetrating to relatively high elevations (Minckley and Deacon 1968; Minckley and Barber 1971). The species rarely occupies deep pools, and only as large adults, and prefers slow to moderate current and smooth flow. It seeks cover only when disturbed.

Longfin dace is omnivorous, tending to feed on both algae and invertebrates, or whichever is most abundant (Fisher et al. 1981; Schreiber and Minckley 1982). Eggs are laid in circular pits dug in fine sand by action of a spawning pair. Eggs and larvae develop rapidly, and young grow to reproductive size in a few weeks. Reproduction has been recorded throughout the year, but is most pronounced in spring and early summer (Kepner 1982).

Under undisturbed conditions, longfin dace were likely uncommon except in sections of downcutting or in eroding tributaries to the San Pedro River. The fish is so ubiquitous, however, that populations would be expected in any flowing segment, such as in shallows over "deltas" of inorganic bedload that form at heads of pools and ponds, or even in channels flowing over cienega deposits. In collections since 1964 (Table 3), longfin dace has comprised 70 to 100% of all fishes taken from the San Pedro River mainstream (unpubl. data).

Desert sucker, consisting of a complex of populations that may represent more than a single species (Minckley 1973, 1985), is distributed from the Gila River basin, northwest through the Bill Williams and Virgin rivers, to the now-disrupted White River of south-central Nevada (Minckley 1980c). It also lives in hard-bottomed, shallow streams, but tends to occupy turbulent water far more than longfin dace. Young and smaller adults remain in current, but large adults move from resting areas in pools to riffles to feed. All life history stages scrape diatoms, algae, and adhering detritus from stones with specialized, cartilage-covered jaws. Invertebrates are rarely eaten, and then perhaps incidental to plant material (Fisher et al. 1981; Clarkson 1982; Schreiber and Minckley 1982). The species achieves ralatively large size in rivers, to 33 cm TL, but often remains less than 25 cm in smaller creeks (Minckley 1973, 1980c, 1985). Breeding is on riffles in late winter through spring and young grow to mature their second summer.

Desert sucker would have been even less abundant than longfin dace under pre-disturbance conditions, except where pool habitat for adults was associated with harder bottoms productive of diatoms and other encrusting organic materials, and where flowing water and gravel provided suitable spawning habitat. This species made up less than 30% of all fishes collected from the San Pedro River since 1964 (unpubl. data).

FACTORS AFFECTING LIFE HISTORIES OF NATIVE FISHES

The present flow regimen of the San Pedro River consists of winter and summer floods separated by low flow in spring and autumn, and reflecting a bimodal pattern of local, monsoon-like summer rains and more regional winter precipitation (Fogel 1981). This pattern is consistent and predictable over the period of record, and as already noted has persisted for millenia (Martin 1963).

There are indications that native fishes of the region are adapted to this pattern; i.e., a number of workers have discussed apparent stimulation of spawning by summer floods. Koster (1957) implied late summer spawning by longfin dace and Rio Grande sucker (Pantosteus plebeius) in New Mexico a response to floods. Deacon and Minckley (1974) noted longfin dace spawning immediately following a flash flood, and Rinne (1975) demonstrated that drastic population reduction, either by natural or unnatural means (i.e., ichthyocide), stimulated reproduction in that species at any time of year. Annual spawning by speckled dace in the Chiricahua Mountains, Arizona, occurred twice, after spring freshets and following summer rains, with the second deleted if flooding did not occur (John 1963). Mueller (1984) hypothesized postflood spawning by speckled dace a response to mixing and cleaning of stream gravels rather than to flooding itself.

Short-term and local impacts of major floods on native fishes include only an infrequent record of faunal destruction (Deacon and Minckley 1974).

Young are sometimes removed from a system (John 1964), and adult populations may be displaced downstream, slightly depleted, or changed in species composition (Barber et al. 1970; Deacon and Minckley 1974). However, in the long-term, native Southwestern fishes are scarcely influenced by even the largest, most violent discharges (Deacon and Minckley 1974; Harrell 1978; Meffe and Minckley 1986). Meffe (1984) demonstrated Sonoran topminnow to be flood resistant from newborn to large adults, remaining in place through behavioral defensive response to onset, pulsations, and duration of flood flows. Minckley and Meffe (1987) further documented relationships between persistence of native faunas and occurrence of scouring discharges. Diversity of native fishes was inversely related to number of non-native species, and flooding differentially removed the latter, which appeared to enhance the indigenous fauna.

Indirect effects during flood (Fisher and Minckley 1978) may be more important than increases in water volume, velocity, and turbulence. Shifting bedloads produce not only tremendous molar action dangerous to organisms, but also fill pools with sand and rock. Loss of deepwater habitats excludes large fishes or those requiring quiet pools for rest or feeding, and formation of long reaches of riffle and run seem to enhance species like longfin dace to the possible detriment of other small kinds. Suspended solids may also clog branchial chambers and suffocate fishes, and water-carried sediments can abraid gills and other body tissues (Deacon and Minckley 1974).

Drought conditions are far more dangerous to fishes than flood. Crowding may be extreme in habitats reduced by drought, and epizootic disease or starvation may obtain. Low water conditions appeared to inhibit spawning in Chiricahua Mountain speckled dace (John 1963), perhaps due to nutritional deficiencies when crowded in intermittent pools. Predation or cannibalism on young or adults may be major factors in such situations (Deacon and Minckley 1974). Chemical features, typically resulting from variation in dissolved gasses, can also result in population depletion during drought. Accumulation of organic material or crowding in pools isolated from underflow of water may result in oxygen depletion or other chemical factor that causes mortality (Lowe et al. 1967). Shallow, low-volume habitats vary greatly in temperature, which may exceed tolerances of some species (John 1964; Deacon and Minckley 1974). Skin damage from sunburn can occur when fishes are exposed to full sun in clear, shallow water. Severe damage may also accrue from a combination of drying and sunlight when water depth is insufficient (Minckley and Barber 1971). Salinity changes sufficient to kill native fishes are rarely recorded in streams. However, in one instance, a surge of "black alkali" carried by spate from the Gila River in the late 1880s is said to have killed fish in the mainstream Colorado River for >125 km downstream (Sykes 1937).

Long-term changes in pattern of discharge of the San Pedro River had profound impacts on native fishes. Alterations in flow regimen resulted in equilibrium adjustments from a channel characterized by high storage and slow release of water, to one that has little storage and rapid runoff depletion. The first state resulted in greater permanency and larger habitat size, enhancing larger fish species, promoting high species diversity due to greater heterogeneity, and allowing development of large population sizes. Intermittency due to reduced storage and rapid runoff resulted in shifts to small species and far lower diversity, but may not have changed numbers per unit area. Longfin dace and desert sucker that persist in the stream, under the correct conditions, attain some of the largest populations known in Southwestern fishes (Minckley 1981).

There are found no evidences from historic or other records that natural water quality in the San Pedro River exercised constraints on fish population, except, as speculated on above, under severe drought conditions. It is obvious, however, that input of mine wastes or other toxic materials can decimate a fauna, and that the presence of copper mines in headwaters of the San Pedro River (Eberhardt 1981) is a pervasive threat to the system, as discussed elsewhere.

Presence of non-native fishes may be considered another type of pollution, which may be even more difficult to deal with than chemical wastes. Introduced fishes are detrimental to native species (Miller 1961; Minckley and Deacon 1968; Minckley 1973, 1985; Moyle 1986; Moyle et al. 1986; Herbold and Moyle 1987; many others). Where introduced species become abundant, native fishes decline in number of species and population sizes, and often disappear. In most instances, non-native fishes introduced in Western United States are characteristic of quiet-water habitats (Herbold and Moyle 1987), and therefore flourish where natural stream environments include large pools, where rivers have been impounded, channelized, or otherwise altered, or in artificial ponds and lakes. As noted earlier, few introduced fishes occupy the mainstream San Pedro River due to its incised, erosive nature. However, pools of Babocomari River are infested with largemouth bass, goldfish, catfishes, and mosquitofish, and stock-watering tanks provide additional sources of sunfishes, fathead minnow, and other species, available to invade and colonize stream environments as they become suitable for occupation. A major problem in re-establishing habitat and native fishes in the upper San Pedro River will be invasion by non-native fishes into developed or reconstructed environments.

Modes of interaction between native and non-native fishes that result in disappearance of the latter have rarely been defined. However, the pattern of disappearance of native forms is consistent, and enhancement of native fishes after removal of non-native species by flooding (Minckley and Meffe 1987) provided a "natural" experiment that documented a cause and effect relationship. Minckley and Deacon (1968), Schoenherr (1981), Moyle (1986) and Herbold and Moyle (1987), among others, advocated competition for food and/or space as major concerns in such interaction, but most evidence was inferential. Meffe (1983a, 1985) demonstrated direct predation by mosquitofish on young and adults of Sonoran topminnow that resulted in extirpation of the native species under both field and laboratory conditions. Whatever the case, either removal of non-native species or placing native fishes in habitats isolated from potential predators and competitors both result in successful completion of life cycles by the native forms (Minckley 1985; Rinne et al. 1986; unpubl. data). The most dangerous non-native species appear to be unbiquitous forms with strong colonizing capabilities, flexible reproductive habits, and broad tolerance to habitat extremes and available foods.

ACTUAL AND POTENTIAL IMPACTS OF UPSTREAM MINING OPERATIONS

Presence of extensive, open-pit copper mining in headwaters of the San Pedro River in Sonora, Mexico (Eberhardt 1981), presents unique problems for creation and management of the Conservation Area. Despite possibilities for controls and cooperative management of wastes, potentials for decimation of the biota and alteration of habitat necessitate planning both for worst case scenarios of acute toxicity or sedimentation and chronic conditions of heavy metal or other chemical-physical pollution.

Major sources of pollution from mining of copper, iron, zinc, and other metals consist of effluents from refining processes. Water and contained wastes are typically stored in tailings ponds, where evaporation and sedimentation concentrate heavy metals and suspended solids. Seepage or discharge from such ponds may be continuous and in low amounts, or may occur in a "slug" due to intentional or accidental release. In the Southwest, streams receiving such wastes may be intermittent or ephemeral, with little diluting capability, and either type of release may create severely toxic conditions.

Regional problems with wastes from mining operations have long existed in Arizona. Chamberlain (1904) noted that razorback sucker, squawfish, and "other suckers" disappeared from near Safford, Arizona about 1902, on the basis of local testimony that "minerals and concentrate-wash from the mines and works at Morenci and Clifton have killed the fish." Suspended solids were observed of detriment to crops a bit later: "Tailings carried in suspension by the Gila River settled on the land and formed a hardened substance rendering the growing of crops and alfalfa impervious to the fullest benefit of the irrigation water [Anonymous 1913]." Relatively low concentrations of heavy metals, especially copper and zinc, are toxic to fishes, and mixtures are even more toxic (U.S. Environmental Protection Agency [USEPA] 1973, 1976). Such metals are less toxic to invertebrates, but instances are known where they killed all aquatic life (LaBounty et al. 1975; Lewis 1977; Jamail and Ullery 1979; Eberhardt 1981).

Few specific data are available on impacts of copper-mine pollution on Southwestern stream biotas. Lewis (1977) studied effects of a newly-opened copper mine on Pinto Creek, Arizona, a stream populated by species similar to those living in the San Pedro system. The creek was intermittent during low flow, and its aquatic biota depended on refuge areas for survival during drought. Most species were eliminated near incoming mine effluents. Suspended solids altered stream geomorphology from gravelly-bottomed, alternating pools and riffles, to fine-grained-bottomed, long runs. Primary production was reduced 36% and biotic diversity declined in silted areas. Metal concentrations were nontoxic except during times of large effluent discharges, but copper and zinc (alone or combined) exceeded toxic levels to fishes in 25% of water samples. Fish kills were observed two times in the period 1975 and 1976, and desert sucker was eliminated from a long reach of Pinto Creek soon after the mine began operations, which was attributed to low oxygen concentrations in the presence of high temperatures and heavy metal toxicity. Zinc was the most lethal single ion to longfin dace (LC 50 [concentration lethal to 50% of the test animals] = 0.79 mg/l), while copper-zinc mixture was the most lethal combination (LC 50 = 0.21 copper and 0.28 mg/l zinc). These concentrations did not differ significantly from those reported as lethal for other species of minnows (Lewis 1977). Metal residues in the biota were better indicators of heavy metal pollution than mean water quality. Iron, manganese, and copper were more concentrated in lower food chain elements, while zinc concentrated in upper elements.

Minckley and Constantz (1974) reported comparable copper and zinc concentrations in water samples from Cocio Wash, Arizona, an intermittent stream also fed in by seepage effluent from copper mining operations and occupied by longfin dace and Sonoran topminnow. Neither fish showed effects of sublethal or lethal heavy metals except in their absence from (avoidance of[?]) immediate areas of effluent input. Effects of potentially toxic levels of heavy metals on biotas of both streams may have been mitigated by relatively high levels of hardness and complexation with organic and inorganic materials (i.e., Lewis 1977).

Toxicity and other features of pollution in the upper San Pedro River has resembled these other systems, but has often been more acute. Extreme pollutional conditions in the San Pedro River in 1977-1979 were attributed to overflow or leakage of improperly located leaching ponds associated with excessive runoff in Mexico (Eberhardt 1981). The most detail was obtained during a spill in 1979, when water was brick-red in color, pH as low as 3.1 and dissolved oxygen as low as 2.0 mg/l were recorded, along with high iron, copper, manganese, zinc, and suspended solids. Concentrations of copper and zinc alone and in combination far exceeded those lethal to longfin dace (Lewis 1977). Aquatic life was killed for at least 100 km north of the International Boundary (Arizona Game and Fish Department [AGFD] 1979, 1980), and water quality for irrigation, livestock, and wildlife was impaired both in the stream and potentially in area groundwater. Similar pollutional events were noted in December 1977 and January through March 1978 (Eberhardt 1981). Longer-term pollution from seepage or minor releases of mine wastes almost certainly occurred prior to 1977 (University of Arizona 1978), but was not evident in samples from 1973 (U.R.S. Company et al. 1976).

Recovery from the 1979 event was surprisingly rapid. Invertebrates, fish (longfin dace), and acceptable water quality all were recorded four months after the mine spill subsided. According to Eberhardt (1981) problems associated with the event were corrected at the Cananea, Sonora, Mine, and no additional problems have arisen to date (Edward K. Swanson, Arizona Water Quality Board, pers. comm.).

Existance of potentially severe pollution of the upper San Pedro River nonetheless remains a major concern, and merits additional discussion. As already noted, major impacts may especially be expected if pollutants enter the system during low flow when dilution potential is minimal and toxicity can quickly develop. Such a situation will result in decimation of aquatic life, and, as noted in the 1979 incident, in possible loss of terrestrial wildlife and other values of the system. Spills of chemical or physical pollutants diluted during high discharge should pass quickly through the presently incised San Pedro River and have minimal local influence. On the other hand, if incision can be reversed in the San Pedro River and cienega conditions re-created, floods will pass far more slowly and sedimentation will be far greater in pools and in a roughened, heterogenous channel. Toxic or sedimenting wastes would be retained and their impacts exascerbated by longer exposure times and greater local concentrations in both the longer and shorter term. If foreign materials in toxic quantities enter groundwaters then pass to the stream or into wells another problem will be created. Greater storage of groundwater might be paralleled by greater storage of waste materials, a trend that would be somewhat countered by dilution and complexation by organic and inorganic materials.

Development of a monitoring system that provides early warning of pollutional input, and facilities for diversion and holding for disposal of toxic materials through evaporation, sedimentation, treatment, or other means, could be applicable to short-term and perhaps accidental inputs that occur under low or moderate discharges (see later). Chronic pollution can only be alleviated through negotiated agreement or infusion of assistance, advice, or funds to assure its abatement.

ENHANCEMENT OF SAN PEDRO RIVER FISH HABITATS

Suggestions in this section are based on the assumption that annual water yield from the San Pedro River watershed will remain its present volume or will increase as land-use practices improve (see, however, USBLM 1986), and that water will continue to be of a quality to support fish, wildlife, and other uses. A further assumption is that goals of management of the Conservation Area is to re-establish and maintain an historic and dynamic plant and animal community in perpetuity.

The process of environmental reconstruction must begin in the watershed outside the Conservation Area, which may only be rejuvenated by protection of soils through control of both sheet and channel erosion, most realistically through enhancement of native grasses. Sub-basins should be evaluated and the most erosive ones identified for initial action toward erosion control, reduction in grazing, and revegetation if necessary. Control should be exercised over developments that involve removal or alteration of natural vegetation, such as construction projects that channelize or otherwise concentrate water flow. Cooperation among Federal, State, and Private agencies and individuals should be of the highest priority, which obviously necessitates an active program of education and information dissemination to define goals and operating criteria of the Conservation Area at National, International, Regional, and Local levels.

The mainstream San Pedro River will likely continue to incise and transport large quantities of bedload until the watershed and floodplain are improved. Use of erosion-control devices like rip-rap or armoring of the channel will scarcely promote aggradation, and if designed to inhibit or restrict channel migration, will stimulate incision and create a greater problem. Manipulations in the natural channel should be essentially the reverse of those typically applied in channelization and containment of rivers. Points, obstructions, and constraints that accelerate local flow and thus stimulate erosion should be removed and smoothed to slow movement of water and sediment transport as much as possible, until a broad, heterogenous waterway is formed. Rehabilitation of the mainstream will likely be a long-term operation.

In the shorter-term, development of off-river fish habitat to provide for immediate re-establishment of native fishes in the Conservation Area and as an adjunct to rebuilding of the mainstream seems a viable alternative. Developments are possible at different levels, each of which will enhance fishes, and at increasing levels of committment would further contribute to abatement of potential pollution, healing of erosion scars, and maintenance of riparian and terrestrial plant and animal communities of the floodplain.

Semi-natural Habitats

Basically, I suggest three possible levels of aggressive construction of semi-natural habitats. The proposal hinges on excavation of an array of off-river channels paralleling the mainstream to provide habitats that will:

1. at a minimal level of development provide managable units for re-establishment and maintenance of native fishes;
2. be used when appropriate for entrapment of pollution inflow for disposal or diversion of such materials from the Conservation Area.
3. if fully implemented, will provide fish habitat, pollution abatement, and avenues for dispersion and infiltration of flood flows to minimize scour, promote aggradation in the natural channel, and re-establish manageable ecological conditions similar to those present in pre-disturbance times.

Channels constructed for fish habitat alone would consist of simple, semi-natural, oxbow-like depressions a few meters wide and 100 m or more in length. Variations in depth and configuration would provide relatively large size and marked heterogeneity, and the habitats would be excavated deeply enough to intersect the water table, (which is relatively high in the area [USBLM 1986]) and/or fed by a gravity-flow intake or pumped water to insure permanency. Seepage would maintain minimum water levels and provide flow through such a depression. Isolation from the natural channel would preclude or minimize invasion of non-native species of fishes, and also would allow for management such as their removal should they invade. Such habitats could be of various sizes and patterns, and minimal construction costs would allow development of habitat for essentially all native fishes known from the upper San Pedro system.

Substantial ancillary benefits would accrue from development of these off-river aquatic habitats. Semi-lentic conditions would attract waterfowl, and after development of riparian vegetation, beaver and other aquatic and semi-aquatic vertebrates could be reintroduced or expected to establish. Riparian vegetation along semi-isolated habitats would attract greater diversity and density of song birds and other, smaller vertebrats, providing greater forage for raptors and predatory mammalian species.

The second possibility, use of lateral channels to isolate and/or divert pollutional inputs, would in part be incompatible with maintenance of native fishes in channels so used, but would serve to preclude major environmental damage and thus be a major enhancement of fish habitat. Eberhardt (1981) recommended diversion or ponding and treatment with lime and precipitating agents to reduce acidity and trace metal concentration as near the source of pollution as possible. If such a system cannot be devised in Mexico, near the point of entry of the San Pedro River in the United States would be a more acceptable alternative than allowing passage of lethal wastes through the Conservation Area. Fishes established in channels designated for such use should be considered expendible, or used for stocking other, more reliable habitats, and terrestrial communities developing in association with aquatic habitats of such channels would obviously also be in jeopardy when pollutional conditions occurred.

Use of excavated channels for minimizing impacts of flood flows, promoting alluviation of the San Pedro mainstream, pollution abatement, and creation of fish habitat is a third alternative. This last, most ambitious proposal is justified by position of the Conservation Area near headwaters of the river system, the good possibilities for improvement in land-use practices that will increase probability of success of the venture, and an availability of historic and technological background that allows for a comprehensive, holistic approach to area management.

Natural floodplains resist incision by developing sheet flow or multiple channels, both of which buffer velocity, turbulence, and thus the erosional competence of floods, and promote aggradation. Acequias, the hand-dug intake ditches leading to fields from brush and earthen dams of Indian communities, must have performed such a function along streams in prehistoric times, so this proposal is certainly not unique.

Series of relatively large channels may be excavated to lead from the mainstream to infiltration zones or broad sumps on the floodplain distant from the river. Channels should be elongate, perhaps many kilometers long in fact, and sporadically widened places would act as intermediary infiltration basins. Intake elevations could be arranged so that progressively higher mainstream discharges moved into consecutive channels.

Abrupt decrease in water velocities at intake points would promote deposition both in the natural and artificial channels, so each intake should be broad to accomodate this phenomenon and insure diversion of a substantial proportion of floodflow. For maintenance of water spreading and infiltration, the system would be monitored after each event for volume and permeability, and channels and infiltration zones and sumps re-excavated or new ones built. Maintenance would also be required to preclude downcutting and occupation by the river of new channels in such a system, which might require excavation of secondary spreading channels. With correct design and computation of capacity and infiltration rates, such a system should be able to behead all but the most severe flood flows and promote aggradation both on the floodplain and in the mainstream channel. Discharges like the maximum recorded (2780 m^3/sec at Charleston in 1926; USGS, publ. periodically), or even less, would be expected to overrun and bypass the system; however, such events may be of only statistical, 50- or 100-year recurrences.

Such a system should partially alleviate the trend toward continued incision. Presence of a lowered base level, a degraded Gila River channel in the case of the San Pedro, portends great difficulty for rebuilding the alluvial floodplain. Degradation in the Gila River canyon downstream from San Carlos Reservoir has, however, apparently aggraded the mouth of the San Pedro, which allowed sedimentation to migrate upstream, counteracting incision and allowing re-establishment of extensive riparian cottonwood forests (Brady, et al. 1985). Constrained areas along the San Pedro channel result in local adjustments in grade (Cooke and Reeves 1976), each of which developed into secondary nick points. Alterations of flow at such places should constitute the key to healing of erosion scars, so lowering of flood crests and increasing time-of-flow of river output, for example at the "Narrows," would in turn stimulate alluviation in the Conservation Area.

Semi-natural fish habitat like those described as a first alternative would be developed in combination with a water-spreading system, although management of a combined system would necessarily be more intense than in one designed only for one or the other function. Flood inputs would result in sedimentation and introduction of alien fishes from the surrounding watershed, even though some channels in a series would be preserved as intact fish habitat except under highest discharge conditions (when an entire system might take in water or be over-ridden). From the perspective of maintaining fish habitat, alluviated channels could be drag-lined, but perhaps best would be replaced by parallel excavations; succession to dryland plant and animal communities would proceed in older habitats, thus increasing diversity in the Conservation Area. Non-native fishes would be removed by ichthyocides or simply allowed to desiccate following removal and transfer of native forms to new or renovated areas.

Selected artificial channels near the International Boundary could as readily be used for diversion of pollutional imputs, if the occasion arose, as in the second proposal discussed above.

Rehabilitation of the Natural Channel

Enhancement of fish habitats in the natural mainstream of the San Pedro River will only occur when incision is reversed and water tables elevated. If this occurs, succession in the channel should proceed naturally toward a pre-disturbance state. However, this may be anticipated to require many decades. A major priority should be to maintain at least the present minimum and median discharges in permanent reaches (e.g, 1.42 m^3/sec, median at Charleston; USGS, publ. periodically), and attempt to increase these parameters by active watershed and groundwater management. Doubling of median discharge and increasing minimum flow (equivalent to "no flow" each year at some gauging stations) to a level of at least 0.28 m^3/sec would maintain the present fish fauna (see later) and further be adequate to accomodate reintroduction of most of the indigenous fauna. Major goals should be to insure high quality fish habitat by increasing minimum flow and decreasing flood peaks through watershed management. However, as noted above, flood control as such in these systems may be undesirable, since native fishes are scarcely impacted and introduced forms are removed or at least reduced in numbers by flood.

Under active management such as development of recharge and water-spreading channels and sumps, permanence of the system and progressive alluviation of the natural channel should occur far more quickly. Adequate material is undoubtedly transported through the Conservation Area as bedload to effect rapid filling of existing incisions, assuming its transfer can be intercepted. Use of brush barriers, diversions, and smoothing of lateral cutbanks and other points of degradation by use of heavy equipment should be applied to augment and enhance aggradation and stabilization. Riparian vegetation should occur naturally or be encouraged by plantings, and beaver should colonize or be transferred from adjacent habitats.

As fish habitat develops in the aggrading, natural channel of the San Pedro River, native fishes available from artificial channels, hatchery stocks, or local populations may be stocked and monitoried. Kinds to be re-established depend on development of habitat and on biological factors such as the presence of introduced fishes, as discussed below.

REINTRODUCTIONS AND MANAGEMENT OF NATIVE FISHES

Assuming adequate amount and quality surface waters can be maintained and altered back toward their former (pre-1880) states, and additional habitat can be developed, there seems little doubt that a number of native fishes would find the upper San Pedro River suitable for occupation and maintenance of viable populations. Simple creation of suitable habitat and reintroduction of native species will not suffice, however, since the presence of non-native fishes will necessitate active management.

Philosophies, Problems, and Realisms

Re-establishment of native fishes within their native ranges is being widely attempted in Southwestern United States (Minckley 1969b; Johnson 1985; Minckley and Brooks 1986; USFWS 1986a; Brooks et al., in prep.), and meeting with limited success. Such programs are also tending to evolve from a single-species orientation to one of multiple-species management (Minckley 1985), e.g., attempts are being made to re-establish fishes and other biotic components that co-occurred naturally into viable, self-perpetuating communities (USFWS 1984a, 1986a-b, 1987). This approach is appropriate in the upper San Pedro River basin. However, this necessitates agency recognition of the values of all species, rather than emphasis only on those under protection of Federal laws such as the Endangered Species Act of 1973 (as amended). In the case of the San Pedro area, spikedace and loach minnow are Federally listed as Threatened (U.S. Department of Interior [USDI] 1985a-b, 1986a-b), Colorado squawfish (USFWS 1984b), Sonoran topminnow (USFWS 1984c), and desert pupfish (USDI 1986c) as Endangered, and Gila chub and razorback sucker are considered "candidates" for listing (USDI 1985c).

All federally listed species are similarly recognized by AGFD, and Gila chub, razorback sucker, and the San Pedro population of roundtail chub (which was considered an invalid subspecies [Gila robusta grahami] by DeMarais 1986) are listed of special concern by that agency (Terry B. Johnson, AGFD, pers. comm.). Thus, eight species have legal or quasi-legal "justifications" for management, and the remaining five are protected or otherwise influenced only by legislation such as exclusion from use as bait, general prohibition of transport of fishes, illegal methods of take, and so on (Minckley 1985).

Dealing with Endangered or otherwise threatened species carries a substantial responsibility. Methods of handling and manipulation are subject to regulation, public use of the species is often prohibited, and presence of an endangered fish may influence other uses of a given habitat. This has been circumvented somewhat by initiation of an "experimental" classification applied to some introduced populations, which may be designated "essential" and thus fall under legislative protection as about the same level as a species (or population) listed as Threatened, or "nonessential," which is essentially exempt from the Endangered Species Act (James E. Johnson, USFWS, pers. comm.). Many populations of endangered fishes are currently being reintroduced under Memoranda of Agreement designating them as "experimental, nonessential." I am concerned that this application will become general in usage, and consider it essentially an abrogation of responsibility on the part of Federal agencies to insist on such a classification prior to participating in an Endangered Species recovery effort.

I consider any population of a species that is biologically endangered is "essential," notwithstanding its natural or introduced status, and urge that species reintroduced into the Conservation Area be considered as such. Note that there are levels of endangerment, as with any series of categories, and that I used the term "biologically endangered" rather than adhering to the legal designations.

A number of criteria should be considered in selecting species for reintroduction to any area. First should be the biological assessment of probability for re-establishment of viable, self-sustaining populations and thus of the probability for contribution to recovery of a species from the verge of extinction. In the case of some critically endangered forms, however, the simple presence of natural or semi-natural populations that may be expected to maintain themselves for even a short period of time may justify a stocking. Small, peripheral stocks of endangered forms like desert pupfish and Sonoran topminnow provide sources for additional reintroductions, buffers against extirpation of other natural and introduced populations, or sources for natural dispersal into other habitats as rehabilitation occurs intentionally through direct action or indirectly as improvements of land-use become reflected in runoff and thus in stream habitats.

Secondly, one may consider the potential contribution of Endangered fishes to management of other aspects of a resource or resource area. For example, exclusion of introduced mosquitofish will be necessary if a native fish program is undertaken, rehabilitation of marshlands will almost certainly be part of any management plan for the San Pedro floodplain, and pestiferous insects such as mosquitos are an automatic and historic problem to be anticipated. Stocking of desert pupfish and Sonoran topminnow should serve to alleviate local mosquito problems. Further, efforts to attract and re-establish populations of raptors, some of which fed on native fishes under pre-disturbance conditions, should be augmented by formation of additional food sources provided by fish populations. Lastly, rehabilitation of natural riverine habitats, those on the floodplain, and even excavation of semi-natural, oxbow-like reaches, will contributed not only to fishes, but also to other aquatic and semi-aquatic vertebrates, most of which are typically of greater interest than fishes to laymen and managers alike.

A third consideration should relate to contributions of a fish reintroduction to other programs. Efforts to recover razorback sucker and Colorado squawfish are ongoing in the Gila, Salt, and Verde rivers (Brooks et al., in prep.; Dean A. Hendrickson, AGFD, pers. comm.), so stocking of those species in the Conservation Area would be a positive aspects of that effort. Colorado squawfish is technically classed as Endangered, yet it reproduces successfully in a substantial proportion of the upper Colorado River basin (Seethaler 1978; Tyus et al. 1982a-b, 1985) and has been successfully cultured under hatchery conditions (Rinne et al. 1986). Its perpetuation seems assured due to the volume of research directed toward recovery and public and agency interest, so it is no longer "biologically endangered." Razorback sucker, which is far less secure in nature (Minckley 1983, 1985; Tyus 1987), but also has been successfully brought into hatchery conditions, is not yet listed due to agreements between agencies that allow attempted recovery in lieu of listing (Brooks et al., in prep.). Both these species are excellent candidates for reintroduction and manipulation in appropriate habitats.

A fourth consideration is the potential National Showcase aspect of such a Conservation Area, which will best be served by presence of a diverse, natural fauna and flora that can and should include native fishes.

Educational values of fishes in such a system include demonstration of natural community relations such as interdependence of more visible animals like raptorial birds and their food supplies, aspects of habitat diversity and heterogeneity to be demonstrated by presence of a diversity of fishes, and the timely, historic perspective of natural conditions, followed by vast ecologic change, then the kinds of management required to create and perpetuate earlier communities as a National Resource.

Recommendations for Reintroduction and Management

A reiteration of the status of San Pedro River native fishes is appropriate. Only two common and widespread species, longfin dace and desert sucker, persist in the mainstream. Among the few major tributaries of the system, seven species are in Aravaipa Creek (spikedace, loach minnow, longfin and speckled dace, roundtail chub, desert and Sonoran sucker). That stream is under protection by USBLM (Aravaipa Canyon Wilderness Area; USBLM 1987) and the George Whittell Wildlife Reserve (Smith and Bender 1974d; Minckley 1981). Redfield Canyon, occupied by Gila chub, speckled dace, desert sucker, and Sonoran sucker, is largely controlled by The Nature Conservancy. Gila chub, longfin dace, and desert and Sonoran suckers persist in the Babocomari River basin, of which a part of O'Donnell Creek is set aside on The Nature Conservancy's Canelo Hills Cienega (Smith and Bender 1974d). Thus, 8 of 13 native fishes are under some kind of physical protection in the basin and the remainder (Colorado squawfish, razorback and flannelmouth sucker, desert pupfish, Sonoran topminnow) is extirpated. Enhancement of fish habitats in the upper San Pedro River will allow reintroduction and probably re-establishment of all native species, with variable committment of time and funds.

A first priority should be to insure perpetuation of species which persist in the basin in their natural settings. Thus, the watersheds of Aravaipa Creek and Redfield Canyon, and the part of O'Donnell Creek that flows through the Canelo Hills Cienega Preserve, should receive a first consideration in management toward maintaining a natural state. No introductions of additional species should be considered in these habitats without careful evaluation and analysis of benefits versus possibly detrimental impacts. Tributary populations provide for natural dispersal to the mainstream should that habitat be enhanced for support of native fishes, and furthermore represent the natural genetic stocks indigenous to the region that can be transferred to newly-rehabilitated habitats. The same consideration should be given any populations of native fishes, viz., desert sucker and longfin dace in the San Pedro River mainstream should be perpetuated and enhanced by maintenance of median discharges the same or greater than those of periods of records (see above). Both species are resistant to intermittent conditions, but are enhanced by permanence. Thus, goals for minimum flows should be near 0.28^3/sec, or more, similar to minima in Aravaipa Creek (Minckley 1981). Such would undoubtedly enhance the present, resident species, and insure their perpetuation.

On the other hand, other streams already damaged by habitat change or introductions of non-native fishes, such as Babocomari River, should be considered as high priorities for renovation and rehabilitation toward a natural state. In fact, the most realistic way to perpetuate native fishes is to secure natural habitats in which they still occur or can be expected to establish if reintroduced. Therefore, a strong recommendation is to secure the Babocomari River watershed, part of which already is already on Federal lands (most headwaters) or in ownership by The Natural Conservancy, which will insure perpetuation of existing fish populations, and just as importantly, some of the most physically undisturbed cienega habitats that remain in the Southwest (Smith and Bender 1974b, d; Hendrickson and Minckley, 1985). Watershed and channel enhancement of this and other tributaries would also result in positive flow alterations in the mainstream San Pedro. Addition of Babocomari River to the Conservation Area is furthermore appropriate due to historic significance as a U.S. and Mexican Boundary Survey collection site and its confluence with the San Pedro River within the Area near Fairbank.

As already noted, introduced fishes are common in Babocomari River, which would necessitate renovation and active, ongoing management to preclude their re-establishment. The stream is incised downstream from an old dam constructed on a stony dike that crosses the channel near the river's headwaters. That dam, and likely the dike before it, protected an extensive cienega that includes water to 3.0 m, or deeper, plus extensive marginal, sedge-filled marshlands. Habitats in and associated with the cienega would obviously support species still persisting or recently recorded there (see above), and a number of others. Desert pupfish would almost certainly establish in cienega margins, along with Sonoran topminnow. The main pool of the cienega is certainly large enough to support razorback sucker, stocking of which is recommended, and perhaps Colorado squawfish, should their reintroduction to the area if deemed appropriate. With reconstruction of stream habitat downstream from the cienega, principally a retardation of incision, speckled dace, spikedace, and loach minnow would be appropriately transferred from other parts of the basin with reasonable expectations of success.

A third priority should be assigned to establishing native fishes in semi-natural habitats, if such are excavated on the San Pedro River floodplain. These habitats also should be stocked with fishes genetically as similar as possible to original inhabitants of the basin. However, in the case of a number of species, this is not possible. Brood stocks for hatchery Colorado squawfish are from the upper Colorado River basin in Utah and Colorado (Rinne et al. 1986). Those for razorback sucker are from Lake Mohave, mainstream Colorado River, Arizona and Nevada (Minckley 1983, 1985; Brooks et al., in prep.). Desert pupfish available for reintroduction originate from the Colorado River delta in Sonora, Mexico (unpubl. data). And, stocks of Sonoran topminnow from the San Pedro River basin are extirpated, with the nearest geographic source being populations that persist in springs along the Gila River near Bylas, Arizona (Meffe et al. 1983; Minckley 1985). Hatchery populations of Sonoran topminnow originated from the upper Santa Cruz River basin (James E. Brooks, USFWS, pers. comm.). No flannelmouth sucker stock has yet been held in hatcheries, so any reintroduction would necessarily be from wild populations, of which that in the Virgin River, Nevada-Arizona-Utah is morphologically most similar to original inhabitants of the San Pedro River (Minckley 1980g), and abundant enough to merit such an effort.

Kinds of fishes to be placed in excavated, semi-natural habitats will depend upon kinds of habitats developed. Quiet, deep waters will support large fishes, Colorado squawfish, roundtail chub, and razorback and flannelmouth suckers, along with small desert pupfish and Sonoran topminnow along margins. Reproduction by the larger fishes would only be expected if suitable substrates, gravel and cobble, were provided in areas where underflow or input of surface waters through intake structures produce currents. Hatchery experience indicates, however, that some riverine fishes can and do reproduce under pond conditions, and at least razorback and flannelmouth suckers might be anticipated to form self-sustaining populations. The long lives of these species should be kept in mind, and an initial stocking may well establish a population that has the potential to persist longer than a given habitat will remain suitable. Vegetative succession from marginal marshland to closed swamp, and then to a willow-cottonwood riparian community may well occur in less than 50 years (Minckley and Brown 1982), which is the minimum probably longevity of either razorback sucker or squawfish. Reproduction by large fishes may necessarily be discouraged to prevent overpopulation in limited habitat, then encouraged once a decade, or so, to maintain the stock. As with the whole project, active management will be the key to maintaining fishes as well as the overall habitat, vegetative, and faunal aspects of the Conservation Area.

All attempts should be made to encourage development of self-perpetuating populations of native fishes in the San Pedro mainstream, mostly from natural dispersal of native and reintroduced stocks and continuing habitat enhancement. Hatchery fish, if available, should be used for initial establishment and supplementation of stocks if other, native populations are unavailable. Progressive re-establishment of the fauna should first involve species characteristic of relatively stable, yet erosive habitats, next those requiring pool habitats, then species of margins and floodplain habitats, and last, if habitat conditions warrent, big river species.

Control measures for non-native fishes will be necessary along with attempts to enhance native forms. Since floods tend to selectively remove introduced fishes (Meffe 1984; Minckley and Meffe 1987), stocking of non-native species in the basin should be curtailed insofar as possible. Quiet-water, non-native forms occupying reservoirs or stock-watering tanks are the sources for undesirable re-colonizations of mainstreams after floods. Sport fishing should be encouraged for predatory species like catfish, sunfishes, and largemouth bass, to minimize their populations. Use of live bait should be strictly prohibited to attempt to avoid accidental introductions of additional problem fishes such as red shiner. Stocking of mosquitofish by State and County vector control agencies (Minckley 1985) should also be discouraged, with its role pre-empted by native pupfish and topminnow.

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