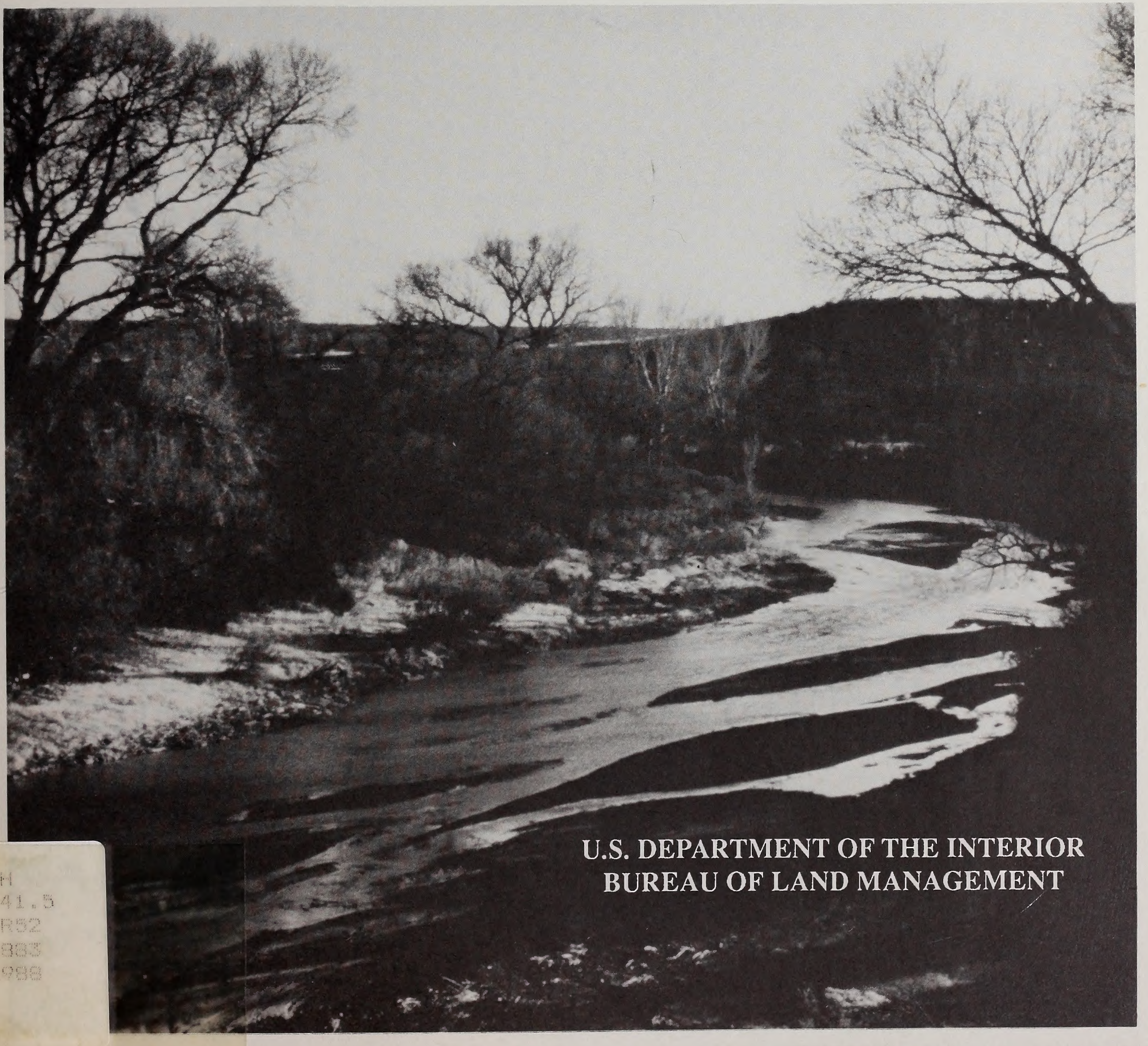
ASSESSMENT OF WATER CONDITIONS AND MANAGEMENT OPPORTUNITIES IN SUPPORT OF RIPARIAN VALUES:

BLM San Pedro River Properties, Arizona

Project Completion Report



U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF LAND MANAGEMENT

United States Department of the Interior

BUREAU OF LAND MANAGEMENT
DENVER SERVICE CENTER
DENVER FEDERAL CENTER, BUILDING 50
P.O. BOX 25047
DENVER, COLORADO 80225-0047

IN REPLY
REFER TO:
7250 (D-471)

June 28, 1988

Information Bulletin No. DSC-88- 161

To: All Field Offices

From: Service Center Director

Subject: San Pedro River Water Resources Assessment Project
Completion Report

The attached report summarizes a recently completed assessment of water resource conditions in the BLM San Pedro River Properties, Safford District, Arizona. It was prepared to provide information for the Safford District's San Pedro River Land Use Plan.

The Report describes relationships between water conditions and riparian resource values and evaluates water resource management opportunities, including water rights. The assessment was performed by an interdisciplinary team in response to a request from the Arizona State Director to the Service Center.

Questions regarding management of the San Pedro River should be directed to the District Manager in Safford, 602/428-4040. Questions about the status of instream flow protection should be addressed to Dan McGlothlin, Arizona State Office, 602/241-5512. Questions about the Report's technical content may be directed to Bill Jackson at the BLM Service Center, 303/236-0148. Additional copies of the Report are available from the BLM Printed Materials Distribution Center (D-558B), Building 50, Denver Federal Center, Denver, Colorado 80225, phone 303/236-7637. The stock number is P-259.

Associate

1 Attachment
  1 - Project Completion Report (180 pp)

Distribution
WO 102, MIB, Room 5646 - 1
WO 200, MIB, Room 5626 - 1
WO 222, Premier, Room 909 - 2
WO 240, Premier, Room 903 - 1
San Pedro Project Manager - 2
D-553A - 13
D-140 - 1

ASSESSMENT OF WATER CONDITIONS AND MANAGEMENT OPPORTUNITIES IN SUPPORT OF RIPARIAN VALUES:

BLM San Pedro River Properties, Arizona

Project Completion Report

by

William Jackson, 1
Tony Martinez, 2
Paul Cuplin, 3
W.L. Minkley, 4
Bo Shelby, 5
Paul Summers, 6
Dan McGlothlin, 7
Bruce Van Haveren, 8

BLM/YA/PT-88/004+7200

May 1987

U.S. Department of Interior
Bureau of Land Management
Service Center
P.O. Box 25047
Denver, CO 80225-0047

1. Hydrologist, Project Leader, Bureau of Land Management Service Center
2. Attorney and Water Rights Specialist, Bureau of Land Management Colorado State Office
3. Fisheries Biologist and Riparian Specialist, Bureau of Land Management Service Center
4. Professor of Zoology, Arizona State University
5. Associate Professor of Resource Recreation, Oregon State University
6. Hydrogeologist, Bureau of Land Management Service Center
7. Hydrologist, Bureau of Land Management Arizona State Office
8. Hydrologist, Bureau of Land Management Service Center

March 3, 1849

United States Department of the Interior

TAKE PRIDE IN AMERICA

BUREAU OF LAND MANAGEMENT
ARIZONA STATE OFFICE
P.O. Box 16563
3707 N. 7th Street
Phoenix, Arizona 85011

IN REPLY REFER TO:

This document is the final report of a project prepared by the Bureau of Land Management's (BLM) Denver Service Center for the Safford District Office in Arizona. The project, initiated by the Arizona State Office, was designed and implemented by the San Pedro River Study Team, a group of multidisciplinary professionals specializing in hydrology, geomorphology, hydrogeology, fisheries biology, riparian ecology, water rights and natural resource recreation.

This report: (a) presents information on the condition of water resources in the San Pedro River Management Area, (b) justifies the quantification of instream dependent uses identified in the area and (c) examines and recommends strategies for protecting or enhancing the identified water-related values.

The report provides a basis for BLM's resource management planning for the San Pedro area. It is not, however, a decision document. The information in the report will be utilized by the Safford District in developing resource management objectives for the San Pedro River Management Area.

The project team's findings were presented to the Arizona State Office and Safford District Office in June 1987. A draft project report was sent to various interest groups and organizations for their technical review. The study was fully coordinated with the Arizona Congressional Delegation to ensure its consistency with pending legislation for the San Pedro River Management Area.

The report satisfies fully the intent and purpose for which this study was commissioned. I accept the water right recommendations and approve the implementation of strategies for protecting flows in the San Pedro River.

Sincerely,

D. Dean Bibles
State Director

PREFACE

The Bureau of Land Management (BLM) Service Center was requested in July, 1986, by the Arizona State Office to organize a project team and prepare a proposal for a water resources assessment and water rights quantification project for recently acquired properties on the San Pedro River in southeast Arizona. The project proposal was accepted in October, 1986. The project purpose is to assist the BLM Safford District by providing water resources information for land use planning, and by providing a strategy and quantification for the acquisition of an instream flow water right. Whereas water resources in the San Pedro River properties provide a useful focal point for many resource values and management issues, the report by no means reflects all of the issues and concerns involved in land use planning and management. The ultimate acceptance and implementation of recommendations in the report is subject to further analyses as part of the resource management planning process.

ACKNOWLEDGEMENTS

This project involved the help and cooperation of a number of BLM organizational units, individuals and other agencies. In particular, we would like to acknowledge the help of Larry Humphrey, Del Molitor, Steve Knox, Pete Zwaneveld, Mike Meusel, Joe Fisher, Erick Campbell, Lyle Rolston, Ray Brady, and Les Rosenkrance—all from the BLM Safford District; Don Henderson, Ed Lehner, Richard Mathews, John Maynard, Dr. L. G. Wilson, Dr. D. F. Post, and Dr. K. G. Renard of the San Pedro River soil and water advisory committee; Bill Kepner of the U.S. Fish and Wildlife Service; Herb Dishlip and the hydrology staff at the Arizona Department of Water Resources; Bill Swan, Interior Department solicitor; John Leshy, Arizona State University; Catherine Rovey, Ground-Water Hydrologist; Norma Reitsma, Shirley Hudson, Shirley McCulloch, Peter Doran, Hans Stuart, Herman Weiss, Jennifer Reese, June Johnson, Marge Trujillo, and Marilyn Chatterton of the BLM Service Center; and to the many other individuals who contributed to the acquisition of information and discussion of ideas. In addition, we would like to thank the BLM Arizona State Office for its cooperation and support throughout the project.

TABLE OF CONTENTS

Page

List of Figures

Page

List of Tables

EXECUTIVE SUMMARY

The natural values of the San Pedro River are inextricably linked to water resources. Riparian vegetation, wildlife, fisheries, recreation and other water-related natural values depend on instream flows (including floods and related ground-water conditions). Baseflows and riparian zone water tables are maintained almost entirely by inflows from the regional ground-water aquifer. Either regional ground-water depletions or localized (near-stream) drawdowns in the floodplain aquifer can reduce instream flows and concurrently lower riparian zone water tables. The cottonwood stands along the San Pedro River are especially sensitive to water table declines. Periodic floodflows are required for vegetation reproduction, floodplain development, and channel maintenance and evolution.

The Federal Land Policy and Management Act (FLPMA) affords the BLM a wide range of land management alternatives, but does not guarantee that water resources will be available to achieve land management objectives. Alternatives available to the BLM for the protection of instream flows and related ground-water tables are founded in concepts of water law—both State and Federal.

The viability of any mechanism (legal, administrative, or technical) which serves to protect the water-dependent natural values of the San Pedro River relies on a thorough scientific analysis of the interrelationships between natural characteristics of the area and water availability. This report provides that scientific analysis in addition to an analysis of legal, administrative, and technical mechanisms available to BLM for the management and protection of San Pedro River water resources.

The following tasks were completed:

1. **Quantify Hydrology:**
   a) to serve as the basis for a water right quantification, and
   b) to identify and evaluate interrelationships between surface flow conditions, riparian area water conditions, and regional ground-water conditions.

2. **Describe Water-Dependent Values, Processes, and Conditions:**
   a) to provide the justification for a water right, and
   b) to identify other water-dependent management issues.

3. **Develop Legal Strategy:** develop and analyze alternative available water rights approaches, and translate water requirements into a legally cognizable water right.

4. **Develop Management Strategy:** identify other administrative and technical approaches which will support the purposes of a water right.

The following key issues were identified:

1. **Federal Reserved Water Right vs. State of Arizona Water Right:** A Federal Reserved Water Right is created independently of State law as of the date land is set aside for a Federal purpose, but only in amounts required to satisfy the primary purpose(s) of the Federal reservation. The argument could be made that, the setting aside of the San Pedro properties as a National Riparian Conservation Area by Congress will create a reserved water right.

Borrowing from recent wilderness reserved water right litigation, the United States may not have to assert a reserved water right merely because one exists, if there are more appropriate mechanisms available to protect the resource values associated with the reserved water right. Arizona recognizes instream flow water rights. Although legal issues are unsettled, the United States may have a great deal to gain and very little to lose by pursuing an Arizona instream flow water right for the San Pedro River.

2. **Possible Designation of the Upper San Pedro River Basin as an Active Management Area:** Under the Arizona Groundwater Management Act BLM is one of the major affected parties in this pending decision. Designation as an AMA affects water rights strategies and alternatives available for protecting instream flows and riparian area water conditions from excessive ground-water pumping. In absence of AMA designation, BLM will have to work to achieve legal recognition of the physical connection between ground-water and surface flows in the San Pedro River. Maintenance of water tables is probably the key issue in protecting instream flows and associated riparian zone water conditions.

3. **Resource Management Philosophy** (as distinguished from resource management objectives): There are opportunities to protect and enhance water-dependent values in the Conservation Area using both passive management concepts (restrictive land use and natural processes) or active management concepts (structures, habitat enhancement projects). Both philosophies involve water rights considerations, as well as economic, scientific, and aesthetic considerations.

4. **International Problems and Opportunities:** From 35-87 percent of the San Pedro River watershed at the BLM properties is in Mexico. Surface water and ground-water development in Mexico could greatly influence water resource conditions in the study area.

SUMMARY OF FINDINGS (Resources)

General: The BLM San Pedro River properties represent an important and unique resource. However, by most accounts the properties are degraded both in terms of historic hydrologic condition and habitat diversity. That degradation is associated closely with the episode of river entrenchment (described later in this report) which occurred between about 1880-1926 and resulted in the loss of cienega reaches and further incised already existing entrenched reaches. Entrenchment set into motion a number of important adjustment processes—geomorphic, hydrologic, and biologic. Most of those adjustments are continuing today and if permitted to proceed more or less naturally may have profound influences on resource conditions along the San Pedro River.

Successful management of the BLM San Pedro River properties will be based upon the recognition that the current geomorphic-hydrologic-riparian system is undergoing change, and management needs to consider protecting and enhancing long-term processes as well as existing or existing potential conditions.

Riparian Vegetation: Cottonwood, Goodding willow, and seepwillow are the major species providing the structure of the riparian gallery forests. Seepwillow is the pioneer species that establishes a foothold for other species to begin the stream terrace building process. Seepwillow is confined to very shallow ground-water sites and requires sustained flow for seedling establishment. Cottonwood colonization occurs after seepwillow pioneering on stream bars. Seed drop and moderately high stream flows must coincide for cottonwood reproduction. Seedlings require moist sites such as stream banks and overflow channels. Moist soil conditions must prevail until roots grow to depths where moisture is continuously available (roughly the water table). Cottonwood is not tolerant to lowering of water tables. The other riparian species may tolerate moderate drought conditions. All riparian species induce sedimentation during flooding. Presently 5-27 feet of sediment has accumulated around the larger cottonwoods.

Fishes: Two common and widespread fish species persist in the San Pedro River mainstem—longfin dace and desert sucker. The mainstem of the San Pedro River is a habitat-limited system for fishes. The present fishery could be maintained under the present flow regime, and likely enhanced for existing fish species if median monthly flows were elevated to long-term norms. However, meaningful enhancement of fishery resources requires enhanced habitat diversity and quality which can be achieved when geomorphic processes (aided or unaided by man) allow parts of the river to evolve to a pre-incision state with certain features characteristic of former cienega habitats. This would permit an increase in species diversity. High flood flows do not appear to be directly detrimental to longfin dace or desert sucker.

Wildlife: Wildlife uses the riparian zone for habitat, food, and water. Forty-seven species of reptiles use the San Pedro River riparian zone; eight of these species are entirely dependent on its existence. Of the 52 species of mammals in the riparian zone, roughly 7 species are entirely dependent upon its existence. Over 275 bird species have been documented along the corridor; 45 are directly dependent upon the riparian conditions. Necessary riparian conditions include viable and diverse riparian vegetation and open water for drinking or feeding.

Recreation: Possible recreational uses of the riparian area include wildlife observation, hiking, backpacking, picnicking, wading, camping, hunting, horseback riding, and photography. Interpretation of cultural and archeological resources is also an important possibility. All of these activities are closely tied to the integrity of the area's water-dependent resources, and in particular to the riparian vegetation, presence of open water, and maintenance of geomorphic processes and alluvial landforms.

Fluvial Geomorphology: Following the rapid sequence of entrenchment, which occurred between 1880 and 1926, the San Pedro River has—and is continuing—to undergo an evolution to a new dynamic equilibrium condition. That evolution consists primarily of widening, bar development, and the creation of floodplains. Whether or not certain reaches of the San Pedro River might now or someday aggrade to pre-entrenchment levels is a matter of conjecture. There is evidence, however, that conditions may favor this evolution in some reaches.

Surface Water Hydrology: Surface flows in the San Pedro River occur as both rainfall runoff and ground-water discharge. The highest flows occur in July and August in response to intense rainfall. A secondary period of high flow occurs from December to March. May and June are the lowest-flow months. A secondary period of low flows occurs in the fall. Distributions of daily flows are highly skewed. Thus, median daily flows are a better descriptor of normal monthly flow conditions than mean daily flows. Annual low flows and spring and fall period flows (predominantly influenced by regional ground-water discharges) have declined significantly over the past 50 years, whereas mean annual flows (predominantly influenced by rainfall-surface runoff events) have not declined over that period. In general, the 10-year flood is adequate to inundate the entrenched river bottom. Floods in excess of the 10-year flood are handled by deeper and faster flows more than by increased width of flows.

Ground-water Hydrology: Ground-water elevations in the riparian zone are roughly at the level of the stream due to the generally permeable nature of floodplain sediments. The floodplain aquifer is recharged by lateral inflow from the regional aquifer and by surface recharge during high stream flow events. Regional ground water sustains base flows in the river throughout the year. The effects of flood flows on base flows is short-lived. While ground-water data are spotty, indications are that ground-water levels in the floodplain aquifer have generally declined over time and that these declines correspond to the lower base flows observed in the river. The main factor influencing ground water in the floodplain aquifer are direct pumping of the aquifer and changes in lateral inflow due to pumping in the regional aquifer. Recharge due to high surface water flows has probably remained constant over the past 50 years.

RECOMMENDATIONS (Water Rights)

To maintain sufficient water supplies to sustain the natural values of the San Pedro River, the BLM must perfect a water right recognized under Arizona law. Whether that right is based on Federal law (reserved water right) or State law (instream flow appropriation), the BLM must have some cognizable right to the waters of the San Pedro River.

The basic components of the recommended water rights strategy are

(1) to amend the BLM Application to Appropriate No. 33-90103 to reflect the instream flow values recommended by this Project, and

(2) the continued assertion of the St. David Irrigation Company water right.

The BLM Application to Appropriate was originally filed by the Huachuca Audubon Society, Chiricahua Sierra Club, and Defenders of Wildlife on August 12, 1985, and assigned to BLM on May 25, 1986. Although this is a very junior appropriation, there are no senior surface rights above the BLM properties or within the study corridor except for the St. David Irrigation Company (SDIC) located at the terminus of the study corridor. The SDIC rights are essentially sufficient to meet baseflow requirements in the study corridor, while the BLM application would have provision for high flows.

The BLM is confronted with two problems:

A. Establishing the ground-water/surface water connection, and

B. Poor priority once that connection is established.

Resolution of these problems is essential to the long-term maintenance of stream and riparian values along the San Pedro River. Alternatives, which are discussed in greater detail in the Recommendations chapter, include

(1) agreements with major ground-water users in the basin,

(2) designation of the basin as an Active Management Area under the Arizona Ground-Water Management Act, or

(3) assertion of a Federal Reserved Water Right. In addition, BLM may wish to consider acquisition, transfer, or change in use of its acquired wells.

RECOMMENDATIONS (Instream Flows)

Instream flow recommendations are expressed as a percentage of median daily flows for each month in the year. Median flows are believed to be more representative of daily flow conditions than mean flows because of the highly skewed nature of daily flow distributions. The annual San Pedro River flow regime was stratified into four distinct seasons to facilitate the instream flow analyses. The April-June spring season is the primary low-flow period, and the July-September summer season is the primary high (flood) flow period for the river. A secondary low-flow period occurs during the fall (October-November), and a secondary high-flow period occurs during the winter (December-March). Recommended instream flows are provided and justified below. All flow recommendations reflect consideration for historic base-flow declines.

Recommended Instream Flows for the BLM San Pedro River Properties			
Period	Month	Flow Recommendation, cfs	
		Palominas	Charleston/Tombstone
Fall	Oct.	3.7	12.2
	Nov.	3.6	13.6
	Dec.	5.5*	17.1*
Winter	Jan.	7.9*	19.5*
	Feb.	8.6*	20.3*
	Mar.	6.3*	18.9*
Spring	April	2.5*	12.2*
	May	1.2*	7.9*
	June	0.6*	4.2*
Summer	July	7.0*	19.0*
	Aug.	7.0*	19.0*
	Sept.	7.0*	19.0*

* *This value or runoff equating to that amount generated by 60% of the contributing basin being unimpounded or undiverted, whichever is greater, where contributing basin is defined in terms of water yield, not land surface area (see Figure 48.)*

Spring Period

Recommended spring-period (April-June) flows represent 100% of the average median daily flow for the period of record up to 1986 OR 60% of natural storm flow, which ever is greater. Spring-period flows have declined to where present daily flows are less than the 50-year norm. Previously perennial reaches now become dry during this period (e.g., see Figure 28). Thus, the overall length of perennial stream has decreased. This is an aesthetic factor impairing recreational use of the river. It may also adversely influence riparian vegetation seedling establishment by reducing the availability of required continuously moist surface soils. The spring period is a critical period for juvenile fish survival and fish growth, and is an important bird migration period. Recommended flows are required to prevent further loss of open water habitat for fish and wildlife. The general ground-water declines associated with decreased April-June flows probably have not seriously impacted established vegetation. However, local drawdowns due to pumping of the floodplain aquifer may have influenced vegetation survival. Cottonwood is probably the most sensitive species to localized ground-water declines. Further generalized ground-water declines may affect vegetation survival and would work against conditions that favor aggradation and development of floodplains. Recommended spring-period flows will provide for maintenance of a perennial stream throughout the study reach and should correspond to stabilized ground-water levels. During April, May and June, 60 percent of natural storm flow is required for purposes of cottonwood reproduction whenever that value exceeds the recommended flow.

Summer Period

Recommended summer-period (July-September) flows are equal to the mean winter period median monthly flow for the period of record up to 1986 or 60 percent of natural storm flow, whichever is greater. Summer-period peak flows are critical to the maintenance and evolution of geomorphic features—especially floodplains, channels, point bars, and nursery bars. They are also required for the regeneration of riparian vegetation species and may stimulate reproduction of fishes. High (flood) flows are also shown to contribute, though briefly, to recharge of the floodplain aquifer and thus play a role in maintaining water tables, riparian vegetation, and stream flows during some low-flow periods. However, floods in excess of roughly the 10-year return period magnitude may cause excessive riparian zone adjustments and may work against long-term channel aggradation. High flow recommendations equate to a 60 percent reduction in the flood frequency relationship for the river. This corresponds roughly to the reduction associated with shifting the 10-year flood to a 50-year return period.

Base flow recommendations correspond to winter-period base flow conditions and are considerably lower than median daily flow conditions in the summer period. However, it was judged that the higher summer-period median flows—which largely reflect storm runoff—did not significantly enhance water-dependent resource values and that all values were adequately maintained at winter-period median flow conditions.

Fall Period

Recommended fall-period (October-November) flows represent 100 percent of the average median daily flow for the period of record up to 1986. The fall period is a secondary low-flow period, and fall-period base flows have also shown historic declines. Like the spring period, the fall period is a critical period of growth and productivity for fishes. The fall period is also an important bird migration period and potential recreation use period. Reduced fall-period flows influence values in the same way as spring-period flow reductions, but the effects may be somewhat less than for comparable spring-period reductions. However, given the trend of historic declines in fall-period flows and the association between fall-period flows and riparian zone water tables, the study team judged that 100 percent of the median daily flow was required to prevent resource degradation.

Winter Period

Recommended winter-period (December-March) flows represent 100 percent of the average median daily flow for the period of record[1] or 60 percent of natural storm flow, whichever is greater. Riparian zone ground-water gradients suggest that winter-period median flows largely reflect discharge to the stream from the regional aquifer. These flows are critical to maintaining fish, wildlife, and aesthetic values in the stream corridor as well as for maintaining watertable elevations in the riparian zone. Median daily winter flows are roughly twice those of fall period flows and over four times those of the spring period. This is largely a reflection of reduced ground-water pumping and phreatophyte use during the winter period. Median winter-period flow reductions would correlate to measurable reductions in riparian zone ground-water levels and would cause unacceptable reductions in fish nursery habitat. The winter period is also an important secondary high-flow period. Winter high flows rework the channel and create ephemeral backwater areas critical to fish spawning and rearing. Winter is the key spawning season for San Pedro River fishes.

RECOMMENDATIONS (Resource Management and Monitoring)

Additional resource management recommendations which support the purposes of a water right are provided in the Recommendations chapter. Recommendations are developed for land acquisitions, pumping of BLM wells, livestock grazing, channel enhancement structures, erosion control structures, water control structures, vegetation plantings, highway bridges, intergovernmental coordination, and future research. In addition, monitoring recommendations for ground-water levels, channel adjustments, and water quality are provided.

---

[1] *One extreme median flow value for January (1682 cfs at Palominas, and 230 cfs at Charleston) was omitted from the analysis because it was considered to be well outside the normal range of median flow values for the month.*

INTRODUCTION

The Bureau of Land Management's Safford District recently acquired 44,000 acres of riparian land along the San Pedro River in southeastern Arizona on behalf of the United States so that valuable riparian ecosystems, prehistoric and historic ruins and varied wildlife may be protected and managed for the American public.

Legislation has been introduced in Congress to designate the acquired land as the San Pedro Riparian National Conservation Area. As proposed, the BLM is authorized to manage the area in accordance with the principles of the Federal Land Policy and Management Act (FLPMA) in a manner that "conserves, protects, and enhances the riparian, wildlife, archaeological, paleontological, scientific, cultural, educational, and recreational resources of the conservation area." Critical to the management of the San Pedro River properties is the management of the water resource. Specifically, instream flow water rights must be obtained and the ground-water resource must be effectively managed if the riparian and other resource values of the river are to be conserved, protected, and enhanced. Through the State of Arizona, BLM has sought instream flow protection for a specified amount, but has not yet qualified this claim.

Recent developments and expectations of future events in the Upper San Pedro River basin have made water allocation, use and management of the river problematic. These include:

- Rapid economic growth in the Upper San Pedro Basin that would expand the population from 56,000 (1980 census) to 91,822 (Putman et al. 1987) by the year 2000, increasing the rate of ground-water pumping.

- Recurring water quality degradation from anthropogenic sources including mining-related pollutants introduced from Mexico.

- Claims for Indian water rights in the Gila River adjudication that threaten the established rights of surface and ground-water users.

- Potential designation of the basin as an "active management area" that would subject the basin to management under the Arizona Groundwater Management Act.

- Potential for upstream diversions in Mexico and the United States.

- Potential for increased development of basin ground-water resources in Mexico.

The Bureau's ability to maintain the many riparian resource values in the area will depend directly upon the continued availability of river flows, and the effective management of floodplain and ground-water resources.

PROJECT LOCATION

The San Pedro River, a tributary to the Gila River, is located in southeastern Arizona. The project reach begins 6 miles north of the international border with Mexico, flows north-northwest for some 37 miles and terminates near St. David, Arizona (Figure 1).

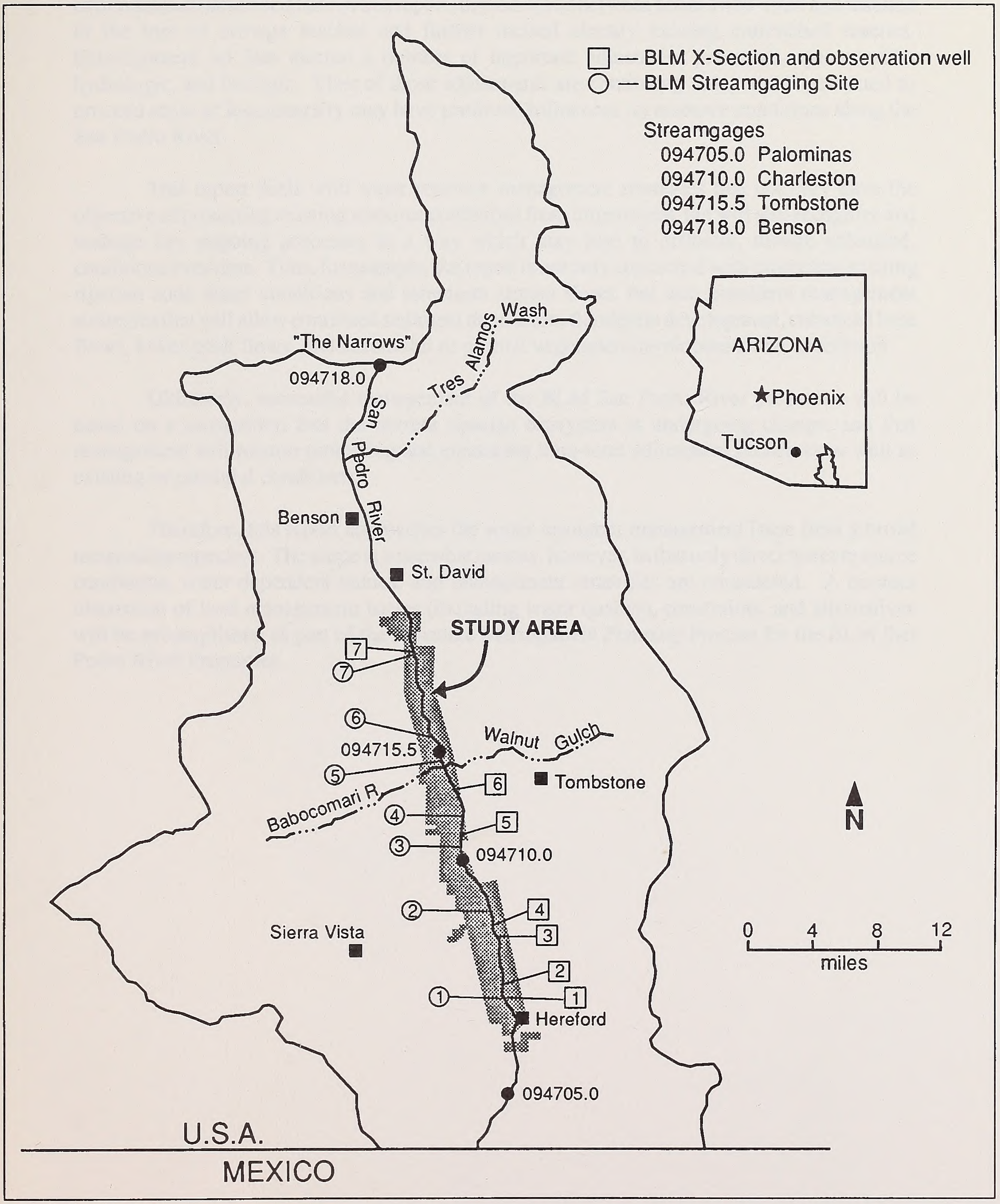


Figure 1. San Pedro River project location map.

SCOPE

The BLM San Pedro River properties represent an important and unique resource. However, by most accounts the properties are degraded both in terms of historic hydrologic condition and habitat diversity. That degradation is associated closely with the episode of river entrenchment (described later in this report) that occurred between about 1880-1926 and resulted in the loss of cienega reaches and further incised already existing entrenched reaches. Entrenchment set into motion a number of important adjustment processes—geomorphic, hydrologic, and biologic. Most of those adjustments are continuing today and if permitted to proceed more or less naturally may have profound influences on resource conditions along the San Pedro River.

This report deals with water resource management strategies that not only have the objective of protecting existing resource conditions from impairment, but will also recognize and manage key ongoing processes in a way which may lead to different, though enhanced, conditions over time. Thus, for example, the report is not only concerned with protecting existing riparian zone water conditions and minimum stream flows, but also considers management strategies that will allow continued sediment deposition, floodplain development, enhanced base flows, lower peak flows, and successful or normal vegetation development and succession.

Ultimately, successful management of the BLM San Pedro River properties will be based on a recognition that the current riparian ecosystem is undergoing change, and that management will require protecting and enhancing long-term adjustment processes as well as existing or potential conditions.

Therefore, this report approaches the water resources management issue from a broad temporal perspective. The scope is somewhat narrow, however, in that only direct water resource conditions, water-dependent values, and management strategies are considered. A broader discussion of land management issues (including water quality), constraints, and alternatives will be accomplished as part of the Resource Management Planning Process for the BLM San Pedro River Properties.

PROJECT OBJECTIVES

The San Pedro River Water Resources Assessment Project was an interdisciplinary team effort intended to develop (for BLM management) legal, administrative, and technical alternatives for managing instream flows and maintaining favorable water conditions for riparian vegetation growth and reproduction.

Six major objectives were identified for the project:

1. Determine the natural flow regime (average annual flow duration, median monthly flows, flood frequencies, and low-flow characteristics and trends) and channel characteristics of the San Pedro River.
2. Determine riparian vegetation water requirements, current ground-water conditions in the riparian zone, and critical or threshold riparian ground-water conditions for riparian vegetation maintenance.
3. Determine surface/ground-water relationships including surface recharge of the floodplain aquifer and the effect, if any, of nearby ground-water pumping on streamflow.
4. Develop recommended minimum flow conditions for maintenance of dependent riparian and instream values.
5. Develop, in coordination with the Interior Department, Department of Justice, and State of Arizona, a strategy for acquiring an instream flow water right sufficient to maintain instream flow-dependent resource values.
6. Develop other recommended water management strategies (in addition to a water right application) including land management alternatives, cooperative management alternatives (with other agencies), monitoring, and further research.

APPROACH AND METHODS

The project approach was keyed to two concurrent activities: 1) a comprehensive resource assessment and, 2) a legal analysis and management assessment. The resource assessment consists of four basic steps:

1. Quantify hydrologic and geomorphic conditions.
2. Describe water-dependent values, processes, and conditions.
3. Relate resource values to water and geomorphic conditions.
4. Evaluate the influence of alternative flow levels on resource values.

The concurrent legal analysis and management assessment involves the identification and evaluation of legal, institutional, and technical constraints and management options, the formulation of alternative water rights strategies, and recommendations for management. By necessity, there must be close coordination between the two concurrent activities.

The project approach is based upon three overriding concepts. First, most rivers and associated resources have unique conditions, physical processes, and values that need to be carefully evaluated and described before deciding on more specific evaluation techniques. Second, the evaluation of water resource conditions should be keyed to an analysis of water-dependent resource values and how those values are influenced by changes in water conditions. Third, the wide array of management opportunities and constraints means that specific aspects of a water management strategy—for example water rights alternatives—must be evaluated within the larger context of alternative technical and administrative management options. All recommendations are based on expert professional judgment. The specific bodies of knowledge, sources of experience, and analytical tools used to support those judgments are determined by the individual experts.

With these concepts in mind, an interdisciplinary team was formed representing key water resource conditions, values, and issues. The objective was to develop expert analyses of various components of the water resources management issue, and to facilitate interaction between specialists in evaluating alternative management objectives and strategies. Disciplines represented on the Project team include surface water hydrology/geomorphology, ground-water hydrology, fisheries, riparian vegetation, recreation, and water rights. The way in which conditions, values, and management recommendations are integrated in an overall process is depicted in Figure 2.

Literature reviews and interviews with various professional contacts were conducted during November and December 1986. In December 1986, team members walked the length of the study area to subjectively evaluate conditions, processes, issues, and interactions. Aerial photography of the entire study reach was acquired and used to help evaluate, stratify, and select field survey locations.

A detailed field survey was conducted in January 1987. Seven riparian area cross sections were surveyed, 11 riparian zone water-table observation wells were installed, riparian vegetation was described and measured along all cross sections, and weekly stream gaging was initiated at seven locations. Field sampling locations are located on Figure 1 and in more detail in Table 1. Throughout the study, information was collected on water rights affected by the San Pedro River.

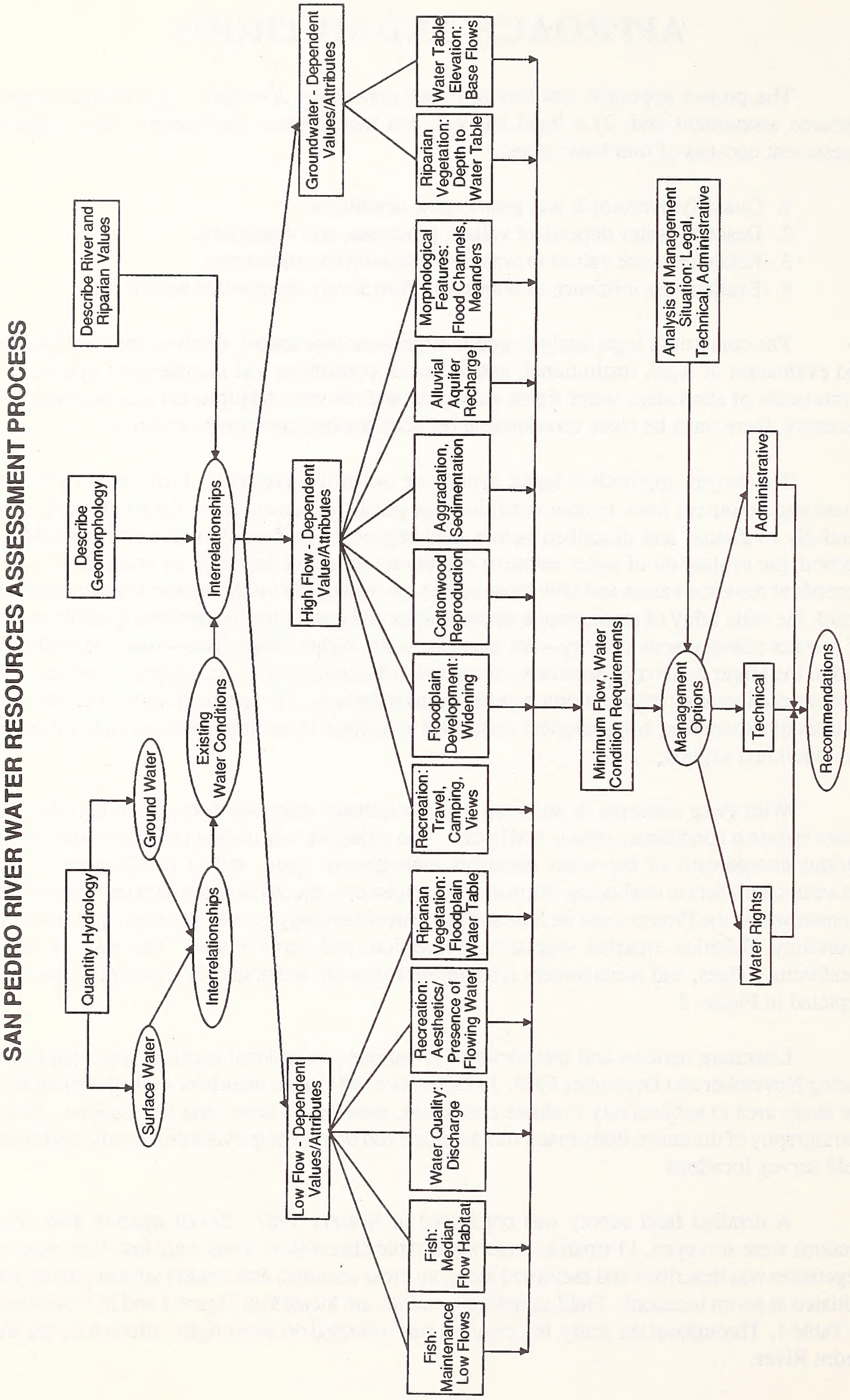


Figure 2. San Pedro River project water resources assessment process.

Table 1. Field Sampling and Survey Locatiions

Well Name	Legal Description	Distance from River	Corresponding Cross-Section
Hereford #1	T. 23 S., R. 22 E. sec. 10NESENE	128'	2. Hereford
Hereford #2	T. 23 S., R. 22. E. sec. 9SWSESE	360'	1. Hereford
Cottonwood #1	T. 22 S., R. 22 E. sec. 17SWSWNE	58'	3. Lewis Spring
Lewis Spring	T. 21 S., R. 21 E. sec. 31SESESE	242'	4. Lewis Spring
Boquillas #3	T. 20 S., R. 22 E. sec. 22SENENW	129'	6. Boquillas Ranch
Boquillas #2	T. 20 S., R. 22 E. sec. -22SENENW	178'	(None)
Boquillas #1	T. 20 S., R. 22 E. sec. 15SENWSE	139'	(None)
Contention	T. 19 S., R. 21 E. sec. 21NENESW	131'	(None)
Summers	T. 19 S., R. 21 E. sec. 8SWNESE	156'	(None)
Diversion Dam	T. 19 S., R. 21 E. sec. 4SESWSW	305'	7. Diversion Dam

The information collected was used to:

1. Describe associations between vegetation class, landform position, and depth-to-water.
2. Describe riparian vegetation water requirements (from literature).
3. Describe relationships between streamflow and riparian zone water table depths.
4. Describe relationships (if any) between streamflow and regional (deep) aquifer water table depths.
5. Identify reaches that gain streamflow from ground water and reaches that lose streamflow to ground water.
6. Quantify flood-frequency and discharge-depth (inundation) relationships.
7. Describe channel morphology and long-term channel evolution.
8. Analyze water-dependent recreation and aesthetic attributes.
9. Analyze fishery values and instream flow requirements.

Alternative legal strategies for establishing and managing instream flows are also evaluated. Issues include:

1. Establishing and protecting minimum flows for maintenance of instream fisheries resources,

recreation values, wildlife water, and riparian zone water table conditions (including the management of existing water rights and the possible acquisition of additional water rights).

2. Quantifying the importance of very high flows to vegetation reproduction and channel morphology.
3. Establishing ground-water/surface water connection and identifying appropriate monitoring and protection mechanisms.

The instream flow quantification is the result of a team evaluation of flow levels and associated water conditions. Minimum acceptable flows were identified by individuals representing the water-dependent resource values based upon a description of how alternative flow levels influence both instream and riparian zone water conditions. Consideration is also given to trends in historic resource and hydrologic conditions. Again, recommended flows represent an expert professional judgement.

DESCRIPTION OF THE STUDY AREA

The San Pedro River originates in desert grasslands of northern Sonora, Mexico, and flows about 140 miles north to enter the Gila River near Winkleman, Arizona. Its watershed of over 4000 mi^2 includes most major vegetational life zones of North America, ranging from coniferous forests on mountains higher than 7400 ft. above sea level to Sonoran desert scrub at 1800 ft. 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 1000 ft. thick (Roeske and Werrel 1973). Its floodplain is usually a half mile or more wide, except where bedrock outcrops approach the stream near Charleston in the study reach (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 in the study reach is about 0.27 percent.

Most of the San Pedro River mainstream today is incised. Downcutting is greater than 9 to 13 ft. 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 at Charleston has averaged 59 cfs over 65 years. 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. 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 daily and seasonal bases.

Incision has resulted in declines in local water tables and drying of former 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 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).

Present riparian vegetation consists of cottonwood (*Populus fremontii*), Goodding Willow (*Salix gooddingii*), Seep Willow (*Baccharis glutinosa*), and mesquite, as well as several grasses (esp. sacaton, forbs, and shrubs) (Figure 3). Salt cedar (*Tamarix chinensis*) has invaded the system in many reaches and is especially predominant at the northern end of the study area.

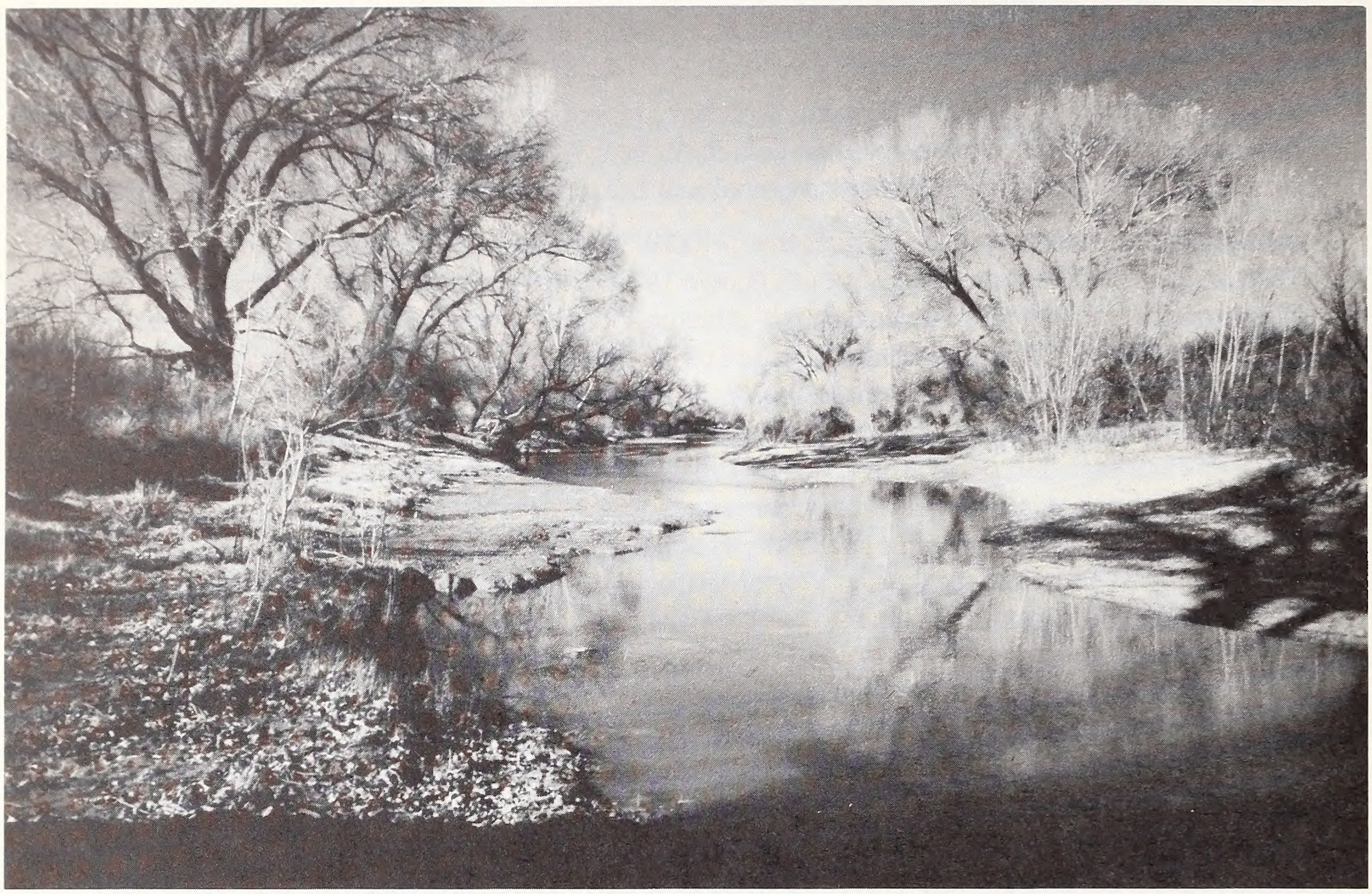


Figure 3. Photographs of San Pedro River in the study reach.

HISTORIC HABITATS

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 thathe 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 prior to technological development. Cienegas are discussed in greater detail in the chapter on Fluvial Geomorphology.

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 some of 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 cottonwood, 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 21-mile 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 6 to 9 ft. 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 13 ft. 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 surveyors' 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.

Riparian vegetation on the river in the past century is summarized by Lacey et al. (1975) as follows:

> "In the middle 1800s, parts of San Pedro River were marked by channelization and other parts flowed slowly through grassy marshes flush with its banks, often flooding extensively behind beaver dams."

Wildlife habitat was described by Lacey et al. (1975). Grizzly bears were still abundant in the riparian woodland along San Pedro River, as late as 1859, and during Tombstone's glory days (1880s), the large razorback sucker (*Xyrauchen texanus* [Abbott]) was caught in the river and sold commercially in Tombstone (Minckley 1965).

Lacey et al. (1975) relate the changes that have occurred during the last 100 years as follows:

- a steady decline in the abundance of grass (sacaton).

- a marked increase in shrubs on the desert plains and foothills.

- channel-cutting, with subsequent head-cutting through many acres of grassland.

Ames (1977) presents photographs of the San Pedro River at Monument 98 at the International Border taken in the years 1900 and 1969. No riparian vegetation was present at the turn of the century at Monument 98; 69 years later a dense growth of mesquite and cottonwood trees existed.

Ames (1977) relates that in the early 1900s, Pima and Santa Cruz counties had up to 173,000 head of cattle that devastated the rangeland. Rainy season flooding caused gullying and heavy soil loss.

San Pedro River before entrenchment was quite different than the river we see today. The lower part of San Pedro River as seen by Pattie in 1825 was described as a small stream with groves of timber, and 16 miles upstream from its mouth it had cottonwoods and willow on the banks. The river was full of beaver which Pattie and his party trapped in the intervals between fighting Indians, Bryan (1928).

PRESENT WATER-DEPENDENT RESOURCE VALUES

RIPARIAN VEGETATION

The present cottonwood/goodding willow/seep willow riparian communities along the San Pedro River are considered one of the finest remaining desert riparian ecosystems. This chapter describes current vegetation in relation to landform and discusses water requirements for riparian vegetation growth and reproduction. In addition, the role of riparian vegetation in floodplain development and terrace building is described.

Water Requirements for Riparian Vegetation

Scarce water in the Southwest stimulated intensive studies of riparian vegetation water requirements and the effect of riparian vegetation removal on stream water that could be used for agricultural crop production.

Annual evapotranspiration (ET) including precipitation averaged 43 inches on Gila River before clearing and removal of phreatophytes, which resulted in a reduction of ET by 19 inches (Culler et al. 1982).

Evapotranspiration for the San Pedro River from the International Border to the narrows is presented in Table 2 (Putman et al. 1987). Salt cedar requires the greatest amount of water as compared to seep willow, cottonwood, and mesquite.

Riparian vegetation may obtain moisture from the unsaturated zone above the water table or from the saturated zone below the water table, depending upon the species. Salt cedar and willow use very little moisture from the saturated zone, but mesquite uses considerable moisture from the saturated zone. These trees are all classified as phreatophytes; however, their moisture utilization characteristics are different (McQueen and Miller 1972).

Present Riparian Vegetation

Abiotic variables are generally most important in determining riparian vegetation composition (Brown et al. 1979). Important abiotic factors are regional climate, stream hydrology, bed surface characteristics, and frequency and intensity of flooding (Taylor 1982).

A significant parameter that influences riparian vegetation is permeability of the substrate to water. Gravel/silts and sands are more permeable than fine silts and clays. Permeable substrata where water can reach farther from the stream channel will support the most abundant vegetation (Taylor 1982).

Major tree-shrub species found along San Pedro River are cottonwood (*Populus fremontii*), goodding willow (*Salix gooddingii*), and seepwillow (*Baccharis glutinosa*). These species provide much of the habitat for the large variety of birds that use the area.

The consumptive use of water in these plant species is high, as illustrated in Table 2.

Seep willow, desert broom, burrobrush, and desert willow occur in the wide sandy channels that are disturbed by summer floods; seep willow, however, requires a sustained flow for germination and seedling establishment (Lacey et al. 1975). Because of its shallow roots, seep willow is confined to shallow ground-water sites. Since seep willow is adversely affected by the loss of shallow ground water, mesquite eventually dominates the area (Lacey et al. 1982). Seep willow is the pioneer species that establishes a foothold for other riparian species to begin the stream terrace building process.

The mesquite bosque communities primarily occur on floodplains elevated above the current channel level (Lacey et al. 1975). Mesquite are capable of rooting to depths of 175 feet, but usually occur within 25 feet or less of the surface (Lacey et al. 1975). All riparian associations where mesquite is dominant are called mesquite bosque communities (Lacey et al. 1975).

Table 2. Estimated annual consumptive use of water by phreatophyte species along the San Pedro River (in inches per acre for 100% densities).

River Reach	F	Tamarisk (K=1.357)	Seep Willow (K=.886)	Cottonwood (K=1.131)	Mesquite (K=.622)
International Border to USGS Streamgage Near Tombstone*	64.8	87.9	57.4	73.3	40.3
USGS Streamgage Near Tombstone to "The Narrows"**	63.8	86.6	56.5	72.2	39.7

* *"F" factor calculated at Tombstone* (From Putman et al. 1987)
** *"F" factor calculated at Apache Powder Company*
K = *Emperical use coefficient for growing season*
F = *sum of monthly use factors for the period*

The tamarisk community (salt cedar) is generally found in the lower portion of the San Pedro Project area north of Fairbanks. Tamarisk was not noted in the upstream areas dominated by cottonwood-willow. The sacaton grass community is found primarily on floodplains characterized by shallow ground-water table.

Stream Transects

Stream transects were surveyed to provide an understanding of the relationship of shallow ground water, plant root depth, distance of riparian vegetation from stream channel edge, and stream bottom relationship to water depth in the observation wells.

Examples of two stream transects are presented in Figures 4 and 5. The relationship of riparian vegetation stream terrace surface to ground-water depth and vegetation distance from the stream is illustrated for Hereford Bridge, a straight stream reach, and Boquillas Ranch, a curved stream reach. The curved stream reaches are generally twice the width of straight reaches.

Figure 4. Depiction of riparian vegetation position and relationship to ground water on a typical straight Channel reach.

Figure 5. Depiction of riparian vegetation position and relationship to ground water on a typical channel bend.

Table 3. Cottonwood, range of dbh, root depth to water, and distance from the stream edge (San Pedro River from 7 stream transects.

Cottonwood	DBH (inches) (in feet)	Root Depth to water (in feet)	Distance from stream edge (in feet)
	1 - 3	1 - 7.5	10 - 110
	4 - 15	2.5 - 8	10 - 120
	16 - 24	6 - 13	130 - 170
	25 - 88	5 - 27	130 - 550

Cottonwood colonization occurs after Baccarus pioneering on the stream bar. Aggradation of alluvium subsequent to bar building during flooding requires that root depth accommodate depth of aggradation for roots to obtain moist soil near the ground water or for roots to tap the ground water (See Figure 6).

Cottonwood trees occur on all stream terraces. The oldest largest in diameter trees occur the greatest distance from the stream and on the highest stream terrace (Table 2). The new cottonwood stands are established on stream bars and stream banks.

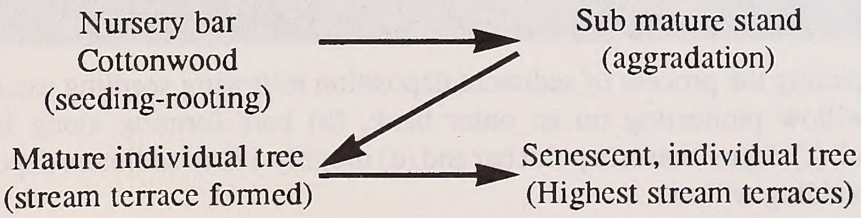
Riparian Plant Revegetation

Brady et al. (1985) describe the development of riparian gallery forest as beginning with moist nursery bars located in overflow channels or abandoned meanders that provide moist areas for seepwillow (Baccharis plutinosa) to pioneer. As the stand of seepwillow develops, sediment aggradation occurs providing a seed bed for cottonwood (Populus fremontii) seeds, or the expansion of Goodding willow (Salix gooddingii) roots.

Rainfall and stream flow do not annually coincide with seed drop from cottonwood trees. Paxson (1981) lists the requirements for the development of southwestern riparian forests as follows:

1. creation of a favorable seedbed;
2. tree stands progress from nursery bars to senescent individuals as they continually modify their own habitat;
3. flooding—light to moderate—favors establishment and development through deposition of nutrient-rich sediments and increased soil moisture; and
4. successful seeding cannot be expected on an annual basis since it depends upon a "proper sequence of flooding," i.e., no flooding large enough to be catastrophic until stands are well developed.

Once cottonwood have successfully seeded following seepwillow pioneering efforts, evolution from seedling to senescence progresses as follows:



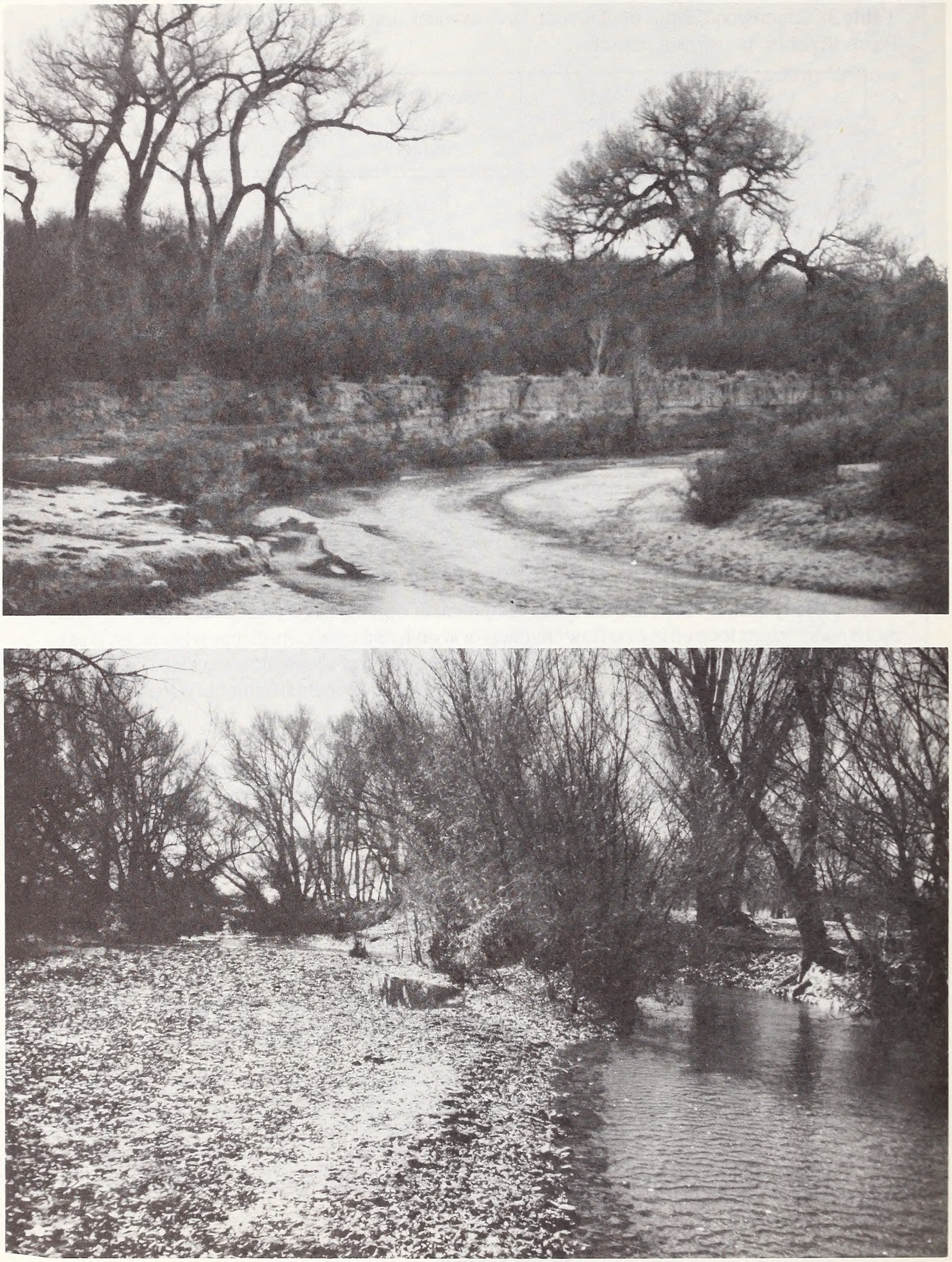
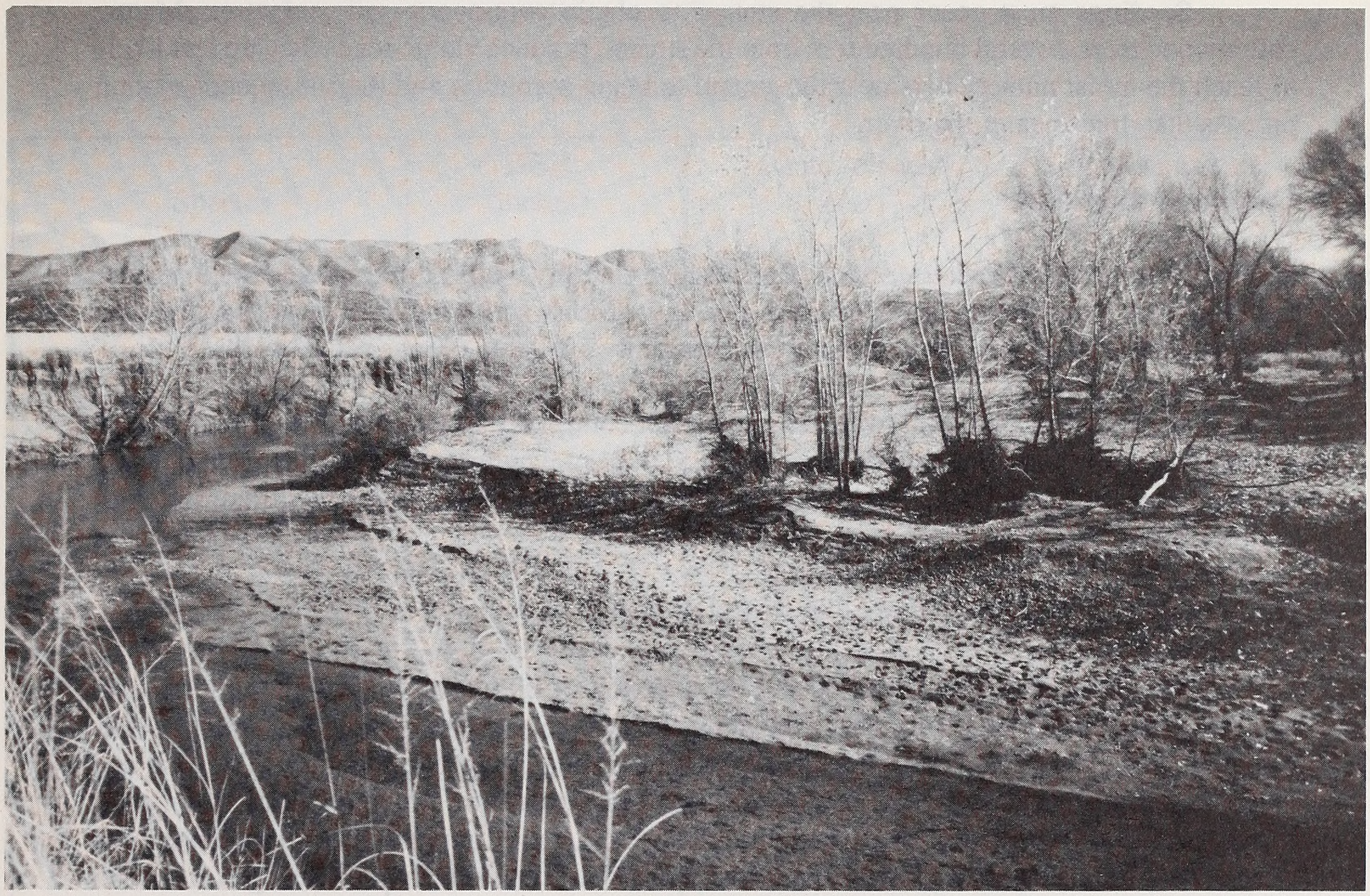


Figure 6. Photos depicting the process of sediment deposition following seedling establishment: (a) seep willow pioneering on an outer bank, (b) bars forming along line of young cottonwood, (c) deposition on a point bar and (d) roughly 6 ft. of sediment deposition around mature Goodding willow.



Seedings must occur near the stream to obtain continuous soil moisture. Mature cottonwood trees, several hundred feet from the stream, produce viable seeds that are less likely to reach the moist nursery bars near the stream to begin sprouting and the subsequent rooting process than trees nearer the river.

Cottonwood Seeding

Cottonwood (*Populus fremontii*) seeds lose viability within 1 to 5 weeks after dispersal. Seedling root growth rate average 6 mm per day. Moist soil conditions must prevail until seedlings grow to depths where moisture is constantly available (Fenner et al. 1984).

Modification of river flow patterns, by water control at dams, has had a significant effect on vegetation along Salt River (Fenner et. al 1985). The prevention of spring runoff will prevent adequate water flow during and after seed drop to assure germination and seedling rooting of cottonwood.

Cottonwood Root Depth -Water Depth Relationship

Several studies have verified the dependency of cottonwood trees on continuously shallow ground water and soil surface moisture for survival. Fenner (1979) and Johnsen et al. (1976) found that cottonwood trees are dependent on shallow ground water. U.S. Fish and Wildlife Service (1980) reported heavy mortality (46 percent) of cottonwood trees along the lower Verde River that coincided with a drought in 1977, and extremely low water releases into the river from Bartlett Dam. The death of trees could have resulted from lowering of the water table during low river flows in combination with ground-water withdrawals. Tree mortalities were 60 to 84 percent in areas influenced well fields where ground-water level is at times lowered by pumping.

Other riparian tree species, such as Goodding willow, mesquite, salt cedar, are much more tolerant to drought than cottonwood trees (Whitlow et al. [1979] and Horton [1974]).

Cottonwood Root Depth

Soil moisture availability to plant roots depends on soil texture and structure. If the water table should recede rapidly, root growth and penetration would not follow the drop in water level. Silt and clay soils like those found in the San Pedro stream terraces have good water-holding capacity as compared with the poor water-holding capacity of coarse textured soil such as sand and gravel. Therefore, cottonwoods located in finer-textured soils may survive temporary water table declines better than trees in soils with poor water holding capacities. Cottonwood root depth is estimated on the seven stream cross-sections Tables 4a to 4g.

Stream Transects

Seven stream transects, four curved reaches, and three straight reaches were surveyed, the vegetation described, and a well head placed on the transect to relate ground-water depth to tree-shrub root depth (Tables 4a-4g).

Table 4. Ground-water depth and tree and shrub root depth.

Table 4a - Hereford (Straight Stream Reach) (January 1987)

Species	DBH (inches)	Depth to water (feet)	Distance from stream edge (feet)
Cottonwood	1 - 3	3	10
	1 - 3	4	20
	2	4	40
	18 - 48	5	130
Goodding Willow	1 - 3	3	20
Baccarus	5.5	65	

Table 4b - Hereford (Curved Stream Reach) (January 1987)

Species	DBH (inches)	Depth to water (feet)	Distance from stream edge (feet)
Cottonwood	6 - 12	6	10
	6 - 10	7.5	75
	50	7.5	395
	64	7.5	550
Willow	2	7.5	70
Mesquite		6	550

Table 4c - Lewis Springs Br. (Curved Stream Reach) (January 1987)

Species	DBH (inches)	Depth to water (feet)	Distance from stream edge (feet)
Cottonwood	20 - 24	7.5	170
	2 - 12	2.5	30
	2	8	10
	8 - 10	7	120
	40	15	600
Goodding Willow	15 - 18	7.5	160
	12	8	70

Table 4d - Lewis Springs Br. (Straight Stream Reach) (January 1987)

Species	DBH (inches)	Depth to water (feet)	Distance from stream edge (feet)
Cottonwood	18 - 24	7.5	150
	3/4 - 2-1/2	3	80
	18 - 24	10	80
Goodding Willow		12.5	145

Table 4e - Charleston (Straight Stream Reach) (January 1987)

Species	DBH (inches)	Depth to water (feet)	Distance from stream edge (feet)
Cottonwood	48	27	160
		7.5	35
		7.5	35
Goodding Willow		17	130
Desert Willow		10	70
Mesquite		10	0
Baccarus		2.5	10

Table 4f - Boquillas Ranch (Curved Stream Reach) (January 1987)

Species	DBH (inches)	Depth to water (feet)	Distance from stream edge (feet)
Cottonwood	3 - 6	7.5	110
	10	8	65
	88	14	410
Goodding Willow	10	8	65
	18	9.5	360
Baccarus		7.5	110
		4	30
		4	20
		10	200
Mesquite		10	200

Table 4g - St. David (Curved Stream Reach) (January 1987)

Species	DBH (inches)	Depth to water (feet)	Distance from stream edge (feet)
Cottonwood	8 - 18	5	50
	1 - 2	2	40
	4	3	80
Goodding Willow	8 - 10	5	50
	15	9	390
Baccarus		6	270
		10	450
Mesquite		9	480
Tamarisk		8	570

Recommendations

The conditions required to maintain riparian vegetation in its present status are:

1. Perennial stream flow will ensure the availability of shallow ground water for the roots of riparian vegetation.

2. Cottonwood reseeding requires a moist seed bed and shallow ground water for rooted seedlings. This moisture is supplied by the infrequent spring runoff on the San Pedro River. Dam construction, stream diversion, or excessive ground-water pumping could prevent the spring"run-off" (when it rarely occurs) moisture needed for seed sprouting and seedling rooting.

3. Removal of tree shrub seedlings by livestock grazing should be prevented to allow for natural tree/shrub revegetation.

4. Artificial planting of cottonwood or other riparian vegetation is not recommended for the San Pedro River at this time. Tree forestation along the river eventually results in bar building and stream course migration. Trees should not be planted until you can predict where it is you wish for the river channel to move. Natural successional changes appear to be the most prudent management.

FISHES AND AQUATIC HABITATS

Acquisition of much of the upper San Pedro River in the United States by the Bureau of Land Management presents a possibility for protection and management of a Southwestern stream and its plant and animal resources. Part of those resources are fishes, of which many species are endangered in the region. If existing populations can be maintained and former inhabitants eventually reintroduced, it will be a major contribution to native fish conservation.

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 times (Table 1), of which 8 persist as remnant populations in the drainage as a whole. Two fishes, the longfin dace and the desert sucker, persist in the San Pedro River mainstem.

Objectives

This chapter details the fish fauna of the San Pedro River basin, traces and documents changes, assesses problems associated with maintenance of native fishes in the area, including those pertaining to adequacy of present and future stream flows. Specific topics include:

1. History of the San Pedro River native fish populations, and the causes for their decline;
2. Present species and relative abundance of fishes that inhabit San Pedro River in the study area;
3. Water flow regimen and water quality that affect the life history of fish species such as flooding, low flow, and intermittent flow;
4. 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 native fish species (Appendix III).

Table 5. Common and scientific names of native and introduced fishes from the San Pedro River basin, Arizona, United States, and Sonora, Mexico.

NATIVE TAXA	
Family CYPRINIDAE (minnows)	
Roundtail chub	*Gila robusta* (Baird and Girard)
Gila chub	*G. intermidia* (Girard)
Spikedace	*Meda fulgida* (Girard)
Colorado squawfish	*Ptychocheilus lucius* (Girard)
Longfin dace	*Agosia chrysoqaster* (Girard)
Speckled dace	*Rhinichthys osculus* (Girard)
Loach minnow	*Tiaroqa cobitis* (Girard)
Family CATOSTOMIDAE (suckers)	
Flannelmouth sucker	*Catostomus latipinnis* (Baird and Girard)
Sonoran sucker	*C. insignis* (Baird and Girard)
Desert sucker	*Pantosteus clarki* (Baird and Girard)
Razorback sucker	*Xyrauchen texanus* (Abbott)

NATIVE TAXA continued	
Family CYPRINODONTIDAE (killifishes 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* (Mitchell)
Family CLUPEIDAE (shads, herrings)	
Threadfin shad	*Dorosoma petenense* (Gunther)
Family CYPRINIDAE (minnows)	
Common carp	*Cyprinus carpio* (Linnaeus)
Goldfish	*Carassius auratus* (Linnaeus)
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)

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 6). 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 in Table 6.

Native fishes in some tributaries, especially those like Aravaipa Creek and Redfield Canyon that must have been of an erosive nature for millennia, 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 Minckley 1986). Seven of the original San Pedro fauna of 13 fish species remain there. It is therefore possible that apparent persistence 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).

Table 6. Records verified by specimens (X) and probable occurrences due to existence of later records (O) of native and introduced fishes in the San Pedro River mainstream from the late 1800s through 1986.

YEARS OF OCCURRENCE OR COLLECTION

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.

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	O	?	-	-	-	-	-	-	-	-	-	-	-
Razorback sucker	X	X	?	-	-	-	-	-	-	-	-	-	-	-
Flannelmouth sucker	O	X	O(?)	-	-	-	-	-	-	-	-	-	-	-
Roundtail chub	O	X	O(?)	-	-	-	-	-	-	-	-	-	-	-
Gila Chub	O	O	O(?)	-	-	-	-	-	-	-	-	-	-	-
Speckled dace	O	O	O	O(?)	-	-	-	-	-	-	-	-	-	-
Loach minnow	O	X	O	O	O	O	X(?)	-	-	-	-	-	-	-
Desert pupfish	O	X	O	O	O	O	X(?)	-	-	-	-	-	-	-
Spikedace	O	X	O	O	X	O	X	O	X(?)	-	-	-	-	-
Sonoran topminnow	O	O	O	O	O	X(?)	O	O	O	O	O	X(?)	-	-
Sonoran sucker	O	X	O	X	X	X	X	X	X	X	O	O	X(?)	-
Longfin dace	O	X	O	X	X	X	X	X	X	X	X	X	X	X
Desert sucker	O	X	O	X	X	X	X	X	X	X	X	X	X	X
NON-NATIVE TAXA														
Common carp	-	-	X	O	O	O	O	O	X	O	O	O	X	O
Rainbow trout	-	-	?	O	O	O	O	O	X	O	O	X	O	O
Black bullhead	-	-	-	-	X	O	O	O	O	O	O	O	O	O
Green sunfish	-	-	-	-	X	O	O	O	X	X	O	O	X	O
Mosquitofish	-	-	-	-	?	X	O	O	X	X	X	O	X	X
Goldfish	-	-	-	-	?	-	-	-	X	O	O	O	O	O
Fathead minnow	-	-	-	-	?	-	-	-	X	X	O	O	X	X
Yellow bullhead	-	-	-	-	?	-	-	-	X	O	X	O	X	O
Channel catfish	-	-	-	-	?	-	-	-	X	O	X	O	O	O
Bluegill	-	-	-	-	?	-	-	-	X	O	X	X	O	O
Largemouth bass	-	-	-	-	?	-	-	-	-	X	O	O	O	O
Brook trout	-	-	-	-	-	-	-	-	-	X	O	O	O	O
Threadfin shad	-	-	-	-	-	-	-	-	-	?	X	O	O	O
Red shiner	-	-	-	-	-	-	-	-	-	-	?	-	-	X

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

Existence 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 6).

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 heterogeneous than now to support such a diversity of species (all categories). The former existence of cienega habitats, as discussed elsewhere in this report, probably had an important effect on habitat diversity and size, and on hydrologic regime.

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 do 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 0.3 in. 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 6 years of age at less than 8 in. 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 14 to 15 in. 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 reestablishment.

Adult Colorado squawfish have been reported in the upper San Pedro River including 3.0 feet long at Fairbanks in 1846 (Cooke 1938), similar-sized fish 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). The single vertebra of a razorback sucker identified by Miller (1955) from Quiburi was from a fish perhaps 3.0 feet long, which is near maximum for the species (McCarthy 1986; McCarthy and Minckley 1987). Chamberlain's report (1904) 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 suckers 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 20 in. TL. Individuals 4 ft. 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 90 mi. 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 floods. 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 disprove the hypothesis that both these species were migrants as opposed to representatives of reproducing populations.

Flannelmouth sucker is known from the San Pedro River only from 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). Flannel-mouth also attain large sizes as adults, to more than 23 in. 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 benthic invertebrates. Reproduction was in spring and early summer in mouths of tributaries to the Colorado River in Grand Canyon National Park (Carothers and Minckley 1981). Mainstream reproduction is typically over gravel bottoms 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 0.3 in. 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 15 in. 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 no recent records for the species from such habitat were found.

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, cienegas, 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 reestablishment 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. peconsensis*) 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 100° F 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 1 in. 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 of 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, Meffe et al. 1983).

Sonoran topminnow is a livebearer. Males have an intermittent 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 (Schoenherr 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 temperatures exceed 100° F (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 three or four summers.

Speckled dace were 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 13 in. TL even in small creeks and approaching 24 in. 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 1981).

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 relatively large size in rivers, to 13 in. TL, but often remains less than 10 in. 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).

Hydrologic Factors Affecting Life Histories of Native Fishes

The present flow regime 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; ie., 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., die-offs), 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 result. 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 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 regime 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).

No evidence from historic or other records was found 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 interactions, 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 ubiquitous forms with strong colonizing capabilities, flexible reproductive habits, and broad tolerance to habitat extremes and available foods.

Water Quality and 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 mg/l 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 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 (Lewis 1977).

Toxicity and other features of pollution in the upper San Pedro River have resembled these other systems, but have 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/1 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 ground water. 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.).

Existence 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, heterogeneous channel. Toxic or sedimenting wastes would be retained and their impacts exacerbated by longer exposure times and greater local concentrations in both the longer and shorter term. If foreign materials in toxic quantities enter ground waters, then pass to the stream or into wells, another problem will be created. Greater storage of ground water 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.

Conclusions and Management Considerations

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) are extirpated.

From a fisheries standpoint, the main stem of the San Pedro River in the study reach is essentially a habitat-limited system. Management of minimum instream flows can maintain the existing fishery, and should be an immediate priority. However, habitat enhancement and diversity is required to significantly improve the mainstem fishery.

Enhancement of fish habitats in the natural mainstream of the San Pedro River will only occur naturally when geomorphic processes allow parts of the channel to proceed toward a pre-disturbance state. However, this may require many decades. A major priority should be to maintain at least the present minimum and median discharges in permanent reaches (see Surface Water Hydrology chapter) and to attempt to increase the parameters by active watershed and ground-water management. Doubling of median discharge and increasing minimum flow (equivalent to "no flow" each year at some gaging stations) would maintain the present fish fauna and further be adequate to accommodate reintroduction of most of the indigenous fauna. Major goals should be to ensure high quality fish habitat by increasing minimum flow and decreasing flood peaks through watershed management. See Appendix II for an analysis of the relationship between flow rate, wetted perimeter, and cross-section area. In general, wetted perimeters increase rapidly with increases in discharge up to roughly the median water flow rate. Wetted perimeters increase less rapidly with discharge as flows increase above median winter conditions. Relationships between discharge and cross-sectional area of flow are linear and constant up to the bankfull discharge rate.

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 monitored. Kinds to be reestablished depend on development of habitat and on biological factors such as the presence of introduced fishes. See Appendix III for additional information on reintroduction of threatened and endangered fish species.

WILDLIFE[2]

The riparian ecosystem along the San Pedro River Corridor, one of the few remaining, free-flowing river systems in the Southwest, provides critical food, water, shade, and cover for a large number of wildlife species. This desert riparian system hosts approximately 47 species of amphibians and reptiles, of which 8 are obligate (depending entirely upon the immediate riparian zone) and the remaining 39 being facultative (often found along riparian habitats but also occurring elsewhere and not totally relying upon the riparian habitat). Amphibians rely completely on (surface) water for survival, while reptiles are not as closely tied to surface water sources although they feed heavily on the insect biomass which riparian systems shelter and nurture. Of special consideration are the Sonoran mud turtle and the frogs and toads which depend totally on the open water and riparian habitat for survival.

While most of the mammals that are present in the San Pedro River corridor have widespread ranges throughout the United States or are common at higher and moister mountain elevations, the highest densities are found along the riparian ecosystems. Approximately 52 species of mammals have been documented using the Chihuahuan desert riparian ecosystem, the majority of which are present along the San Pedro River. Species such as raccoon, bobcat, beaver, porcupine, white-tailed deer, mule deer, and javelina are obligate users of the riparian zone and are dependent on that zone and the resulting vegetation for food, water, and cover. In addition, many of the remaining 45 mammals are facultative, using the riparian vegetation for foraging and for cover regularly. Of special importance is the retention of pristine habitat for species which have been all but extirpated from their historical range such as the jaguar, red wolf, jaguarundi, and ocelot.

Species such as skunks, coyote, bobcat, grey fox, and ring-tailed cat use the riparian ecosystem for hunting where their prey species are found in the highest densities.

Well over 275 species of birds have been documented within the San Pedro Valley, of which 45 are considered riparian obligates. Species which exclusively use the riparian zone and totally depend on open water and the adjacent riparian vegetation for roosting, nesting, and feeding include herons, egrets, waterfowl (including black-bellied whistling duck), rails, gallinules, coots, green kingfisher, Mississippi kite, gray hawk, black hawk, yellow-billed cuckoo, tropical kingbird, brown-crested flycatcher, yellow warbler, common yellowthroat, summer tanager, and song sparrow. Many of the species are considered sensitive and several other found along the San Pedro River are at the periphery of their range in the United States. Species of special concern include the gray hawk, black hawk, yellow-billed cuckoo, tropical kingbird, and the summer tanager, all of which are currently rare or very rare in the western United States. Retention of open water and the riparian ecosystem is critical for the survival of many of these species.

Without the existing aquatic and riparian systems, the myriad of wildlife species which are present along the San Pedro River would greatly decrease and many would be totally lost.

RECREATION

The proposed San Pedro legislation states that a management plan should be developed to "conserve, protect, and enhance the riparian area and the aquatic, wildlife, archaeological, paleontological, scientific, cultural, educational, and recreational resources of the conservation

---

[2] *This chapter represents a brief summary of water-dependent wildlife values. Detailed wildlife assessments are being conducted independently of this study.*

area." Recreation and related aesthetics are thus stated objectives for which the area is to be managed. It should be pointed out here that a traditional form of obtaining user preferences and perceptions—the formal user survey—is not possible here. Recreational use of the San Pedro has been limited, and BLM has no data on previous or current use and therefore no records of visitors that would provide a list to sample from. As a result, our work here is somewhat speculative in terms of the types of recreation opportunities to be provided and the attributes that potential users are likely to consider important.

The Recreation Resource

The resource values that form the basis for the proposed designation as a Riparian National Conservation Area are discussed in detail in the Interim Management Guidelines. They include water resources, vegetation, wildlife, cultural resources, paleontological resources, recreation, visual resources, and to a lesser extent grazing, mineral, and socio-economic resources. The proposed legislation calls for a management plan "designed to assure protection of the riparian area and the aquatic, wildlife, archaeological, paleontological, scientific, cultural, educational, and recreation resources and values of the conservation area."

According to the Interim Management Plan, there are no data describing current recreational use, but such use is believed to be minimal because the area has been and is currently closed to public access. Possible recreational uses include wildlife observation, hiking, backpacking, picnicking, wading, camping, hunting, horse riding, and photography (the proposed legislation excludes the use of off-road vehicles). Interpretation and recreational or educational use of archaeological, paleontological, and cultural resources is also an important possibility. Recreational quality is thus closely tied to the integrity of the area's other resources.

Management objectives specified in the Interim Plan include the following:

- Control access to prevent conflicts and protect resources.
- Protect existing wildlife resources.
- Protect cultural and paleontological resources and surrounding environments from vandalism, collecting, and off-road vehicle use.
- Preserve a flowing stream for the maintenance of the riparian ecosystem.
- Retain existing scenic values.
- Control recreational use and determine the range of recreational potential.
- Develop public concern and facilitate public involvement in the San Pedro River or River properties.

These objectives underscore the importance of the riparian ecosystem. Riparian habitats support a diversity of plant and animal communities, and these attract human use. The San Pedro is an area which clearly has been altered by human use, so it does not offer opportunities for a wilderness or perhaps even a primitive type of recreation experience. But the recreational and aesthetic attributes of the area are clearly tied to maintenance of the flowing stream, diversity of riparian vegetation and habitat, diversity of wildlife, and preserving existing cultural resources.

It is also clear that the exact definitions of the recreation opportunities to be provided are still evolving through work with current and potential recreation users. This requires that our work here is somewhat speculative, trying to anticipate the kinds of opportunities that will be provided and identifying their important attributes.

Important Attributes of the San Pedro

A list of recreation attributes for the San Pedro was developed using information from a variety of sources. These include previous instream flow studies on the Colorado River in

Grand Canyon and Beaver Creek in Alaska, a number of other studies, Interim Management Guidelines, land managers, public meetings, the Recreation Advisory Committee, and field work. The list is presented in Table 7 and discussed below.

General Attributes

Interacting with the natural environment is an important attribute of many outdoor recreation activities. The San Pedro lands contain roads, railroad grades, buildings, powerlines, a diversion dam, sand and gravel operations, and farm fields, so the area does not offer opportunities for a wilderness or primitive type of recreation. But the area has been set aside as a conservation area precisely because it is a relatively undisturbed, unmodified ecosystem.

Given the overriding management goal of protecting this ecosystem, it seems clear that the types of recreation opportunities to be provided will require a relatively natural setting which is not significantly more modified than at present. It is thus important to avoid actions which further compromise the naturalness of the river corridor. The obvious factors here are developments such as roads or buildings which might decrease primitiveness in and of themselves, or change the character of the area through dramatic increases in use.

Changes in flows are less obvious management factors which could have equally dramatic effects. At the low flow end of the spectrum, minimum flows which approximate the current minimums in terms of volume and water quality are probably necessary for the river to appear in its natural state. Such flows are probably also necessary to maintain natural vegetation. However, from an aesthetic point of view, there appear to be three generalized low flow "levels" which may relate to visitor preferences. The first level is actually the no-flow situation which would equate to a dry stream bed. The second flow level occurs between about 0.1-1 cfs and represents a "wet streambed" situation with pools and some visible indication of flowing water. The third flow level occurs between roughly 1 cfs and the flow level which completely inundates the sand-bedded low flow channel (see Appendix II). This level represents the clearly flowing water situation, and provides opportunities for hearing the sound of flowing water. It is our judgement that visitors would prefer some flowing water (level 2) to no flowing water (level 1), but that the higher flows associated with level 3 would improve the aesthetic appearance of the river and would—to a point—be preferred by most visitors.

Table 7. Recreation Attributes of the San Pedro River.

General Attributes
relatively natural (unmodified) setting
presence of water
water quality (unpolluted water)
presence of shade
openness
scenery, views
traveling along the river
relatively unobstructed travel
ecosystem which supports a diversity of plant and animal species
observing flora and fauna
experience a unique ecosystem
fishing (potential)
camping

Table 7 continued.

- Camping attributes
    - clean, unlittered sites
    - natural appearance
    - scenic view
    - isolation from other groups (for remote sites)
    - shade
    - nearness to river
    - flat, open area for sleeping

- Aesthetic attributes
    - scenery
    - views/vistas
    - presence of water
    - sight and sound of flowing water
    - presence of flora and fauna

- Attributes of Archaeological Sites
    - ability to get to sites
    - ability to see remnants/artifacts
    - information about sites
    - knowing that sites will not be destroyed

However, at flows greater than about 2/3 of the flow level which fills the low-flow wash, travel becomes impaired, and the aesthetic diversity associated with flowing water in a sand wash is lost. Thus, low flows between about 5-20 cfs may represent a "preferred" flow level for most aesthetic-related attributes.

At the high flow end of the spectrum, the high water events which occur with heavy rains are also important to the natural appearance of the river corridor. These high flows are responsible for the open sand or gravel bars which form the bank full channel, which is large relative to the wetted surface at normal or low flows. Eliminating high flows would probably alter the character of the river. Observations of successive flood plains along the river show that areas which have not been scoured by recent high flows may fill in with vegetation, changing the character of the channel and the river bank. Such a change could affect a number of other important characteristics, which are discussed below.

The presence of water often acts as a "magnet" which attracts people for recreation activities. This is particularly true in the desert southwest, where water is scarce and its presence creates a unique ecosystem. Water quality is important as well. Although recreational users are not generally able to make fine discriminations with regard to water quality, water which was obviously polluted would be a significant negative factor. In terms of flows, then, one would need a minimum flow great enough to provide flowing surface water which appears unpolluted.

The presence of shade is another attractor for both humans and wildlife in the desert. Along the San Pedro, shade comes from vegetation, particularly the large cottonwood trees which are found in the riparian zone. Maintaining shade thus means preserving the high and low flow regimes necessary to maintain the riparian vegetation.

"Openness" may seem like an unusual requirement in a desert area generally characterized by sparse vegetation. However, it becomes an issue for the San Pedro because the presence of water has the potential to support dense riparian vegetation. Much of the riparian zone consists of thick stands of willows, small cottonwoods, or tamarisk, often difficult to walk or see through. Open areas occur where high flows clear vegetation from the stream channel or where large cottonwoods provide an overstory which shades out the understory. In terms of flows, then, it is important to preserve the high and low flow regimes necessary to maintain flood channels free of vegetation and sustain the large cottonwoods.

Several other important attributes are related to openness. Scenery and views are important to recreation users. In dense riparian vegetation, it is often difficult or impossible to see out. The openness provided by flood channels and large cottonwoods provides varied scenery often difficult or impossible to see out. The openness provided by flood channels and large cottonwoods provides varied scenery and views over greater distances.

The ability to travel along the river, parallel to its course, is another important recreation attribute. This can be done in several ways. The first is by traveling on existing roads or railroad grades. This option offers relatively unobstructed travel, but these routes are generally far enough from the river itself that one loses sight of the water and even the riparian vegetation. This makes the experience little different from being on a road in other parts of the desert, thus losing the unique character of the San Pedro.

Another option is to travel closer to the river, off of roads but still up on the "bench" into which the river channel has been cut. This gets one closer to the river, but it is still out of the riparian vegetation, and is often in dense mesquite which makes travel difficult and unpleasant.

A third option is to travel along the stream bank, in the riparian zone. This allows one to better experience the unique riparian vegetation as well as to see the river itself. Such travel is relatively easy and pleasant in flood channels which high water keeps free of vegetation, and in areas with large cottonwoods with relatively little understory. It is more difficult and less pleasant in areas of dense willows, tamarisk, or small cottonwoods.

The fourth option is to travel in the river channel, on the sand and gravel bars which are regularly cleared by high flows. This means crossing the river frequently as the wetted channel meanders back and forth and closes off the bars against the bank. This is in many ways the most pleasant way to travel because it is relatively unobstructed, allows the closest interaction with the river itself, and provides open views and scenery along the river channel.

The latter two options are the most desirable from a recreational point of view. They require high flow and minimum flow regimes which keep the main and flood channels free of vegetation and which preserve large cottonwoods as part of the riparian vegetation.

The unique riparian ecosystem of the San Pedro is one of the primary reasons for establishing the area as a Riparian National Conservation Area. Maintaining the uniqueness and diversity of this system is particularly important to the recreation experiences which involve observing or studying flora and fauna. In terms of flows, this requires flow regimes which will maintain the natural vegetation and allow long-term successional changes to occur.

Fishing is not an attribute at this time due to lack of fish. It is mentioned here only as a potential issue because fish studies suggest that the San Pedro supported more numerous populations of larger fish in the past. Flow regimes which allow long-term successional changes to occur might lead to re-establishing a recreational fishery, which would then become an important attribute.

Camping Attributes

Camping is another potentially important attribute of recreation use of the San Pedro.

The area has potential for both developed and primitive camping. In either case, clean, unlittered sites would be important to users. To the extent that camping occurs on open gravel or sand bars along the river, high flows which cleanse these areas would be important for maintaining this attribute. Natural appearance would require the flow regimes needed to maintain natural vegetation. Scenic views from camps in the riparian zone require the openness resulting from high water scouring of vegetation and/or large cottonwood trees.

For remote sites, isolation from other groups is important. Even in developed sites, some degree of screening may be desirable. Both require flows which maintain vegetation, as does the presence of large shade trees. Nearness to the river is also likely to be important to campers, and they would be likely to prefer flows which at the minimum provide moving water in the stream.

Aesthetic Attributes

The effects of flows on aesthetic attributes have been mentioned tangentially in the preceding discussion. Scenery and views would change if low flows below the current minimums altered the character of streamside vegetation or if high flow events were not present to keep sand and gravel bars clear and provide an open river corridor. The presence of water is an obvious attraction of the area, particularly moving water. Current minimum flows leave the San Pedro low enough to walk across without getting one's knees wet. Low flows below that minimum could leave a virtually dry streambed with stagnant pools, a situation with considerably less aesthetic appeal than a flowing stream. The presence of flora and fauna in a relatively undisturbed ecosystem is obviously a major aesthetic attribute of the area.

Attributes of Archaeological Sites

Archaeological sites are an important part of the San Pedro resource. Many of these sites, however, are located up out of the riparian zone, making their characteristics less closely related to flows. Use of archaeological sites for recreation-related purposes requires ability to get to sites and, once there, reasonable ability to see remnants of structures and other artifacts. Information about sites is probably also important to archaeology buffs, as is knowing that sites will not be destroyed. None of these attributes appear to be flow-related, although one might argue that having the ecosystem in a condition similar to that faced by early inhabitants might improve understanding of cultural resources.

Summary and Conclusions

Recreation and aesthetic attributes of the San Pedro River are largely dependent upon maintenance of the natural character and biological habitat associated with riparian vegetation and surface streamflows. Low flows are important from an aesthetic standpoint, in addition to their role in supporting riparian vegetation, fish, and wildlife. High flows help maintain the natural character of the channel and the openness of gravel bars, which in turn facilitate such activities as hiking, wildlife viewing, picnicking and camping.

Figure 7. San Pedro River, Arizona.

FLUVIAL GEOMORPHOLOGY

This chapter deals with fluvial processes which influence landforms within the study area. Relationships between riparian zone morphology, and hydrologic and vegetation conditions are also described. The emphasis is on current conditions and processes as well as on evolutionary status and trend. Management implications are summarized.

Background

The alluvial deposits in the upper San Pedro River valley are largely lacustrine valley fills (Melton 1965). The fills are the result of damming by volcanic intrusions and uplifting along a regional arc extending from south and east of Tucson to northwest of Phoenix. In many places alluvial fans, pediment caps, and bajada deposits overlay lacustrine fills. In more recent geologic times, regional base levels have lowered resulting in the overall long-term downcutting of valley fills in the San Pedro River Valley as well as other major drainages in the region (Melton 1965).

The inner valley of the modern San Pedro River is part of an alluvial river system; it is a river which is formed in fluvial sediments transported, deposited, and reworked by the river, itself. The river and its riparian zone are thus dynamic systems undergoing constant adjustment in response to changes in runoff, sedimentation rates, and channel and floodplain conditions.

Most accounts suggest that prior to about 1880 the San Pedro River was a discontinuously entrenched system characterized by areas of entrenchment interspersed by meandering "wash" zones and cienega areas (Cooke and Reeves 1976). Entrenched reaches are reported to have occurred at Charleston a couple of miles upstream of Fairbanks, and near St. David. Cienegas occurred near Fairbanks, upstream from Charleston, and in the Palominas-Hereford area (Cooke and Reeves 1976). It is interesting to note that former cienegas were located along stream reaches which gain flow from ground water (see the gain-loss analysis in the Surface Water Hydrology chapter). Former cienega areas seem to correspond to reaches of relatively mild slope which may result from downstream structural controls (Cooke and Reeves 1976) (Figure 13). Photographic accounts of the river in the late 1800s show that the now-abundant cottonwoods were no more than an infrequent component of stream zone vegetation (Hastings and Turner 1966).

Cienega deposits which occurred along the San Pedro River appear at first to be somewhat an anomaly in the long-term pattern of valley erosion. Cienega deposits in the San Pedro River Valley have been laid down in the three or more episodes of alluviation since about 500 B.C. (Melton 1965). Most likely, cienegas formed under climatic conditions similar to today's. And, as mentioned above, their occurrence may be keyed to regional ground water. Cienegas are fine-grained deposits, which support dense stands of vegetation under very moist soil conditions. Most authors believe cienega deposition and erosion—while complex—is controlled in large part by changes in vegetation type and density (Melton 1965).

Cienega deposits have been the object of the most recent episode of incision which occurred between about 1880-1925 along the San Pedro River. Cienegas explain in part the discontinuous nature of the recent entrenchment phenomenon along the river and explains how aggradational processes and landforms are very much a part of the San Pedro system, despite the longer term trend toward base-level induced valley erosion.

Melton (1965) attributes recent Cienega entrenchment almost exclusively to the reduction of grass cover—both on the cienegas and the adjacent uplands. Deposits of sand and gravel from adjacent uplands then increased transverse gradients in the cienegas, concentrating flows and initiating erosive conditions. Other authors believe that long-term climate patterns or the exceedance of critical slope thresholds may also have been factors influencing recent episodes of entrenchment (Cooke and Reeves 1976; Schumm and Hadley 1957). The latest episode of entrenchment occurred during a period when several very large floods coincided with a period of severe vegetation depletion in the cienegas. The hydraulic variables involved in cienega deposition and entrenchment are discussed in greater detail below.

Processes and Mechanisms

Channel and riparian area adjustments along the San Pedro River may be classified as either normal dynamics or rapid response (Van Haveren and Jackson 1986). Normal dynamics refers to adjustments that occur as part of normal channel/riparian function under dynamic equilibrium conditions. Adjustments associated with conditions of dynamic equilibrium include incremental bank cutting, meandering, bar formation, and cycles of streambed scour and fill. In addition, flood flows and floodplain vegetation interact to cause sediment deposition. As described elsewhere in this report, San Pedro River riparian ecosystems depend on normal channel and floodplain dynamics for vegetation reproduction and succession.

Rapid response refers to adjustments that occur rapidly in response to sudden changes in controlling factors, or to the exceedance of critical geomorphic thresholds. For example, long-term changes in discharge, sediment delivery, or channel/floodplain conditions caused by changes in climate or land-use, may initiate periods of excessive channel instability and adjustment (Heede 1980; Harvey et. al. 1985; Cooke and Reeves 1976). Also, more gradual changes resulting from channel evolution may cause exceedance of a stability threshold for slope or base-level elevation that, in turn, initiates a period of rapid adjustment—for example, downcutting (Schumm 1977; Bull 1979). Attributes of both rapid channel response and normal channel dynamics are key to understanding the relationship between the San Pedro River and its associated riparian response.

Following the rapid sequence of entrenchment, which occurred between 1880 and 1926, the San Pedro River has—and is continuing—to undergo an evolution to a new dynamic equilibrium condition which reflects current hydrologic and land-use conditions. That evolution consists primarily of widening, bar development, and the creation of floodplains. To date, river evolution following entrenchment corresponds to the descriptive model of entrenchment developed by Elliott (1979) and further discussed in Harvey, et al. (1985). That model, depicted in Figure 8, has initial entrenchment followed by periods of active widening, lateral channel adjustments, and floodplain development. Widening is the primary prerequisite for reestablishment of stable floodplain vegetation communities which, in turn, contribute to sediment deposition and the development of properly functioning floodplains. This model of channel evolution is generally supported by Hereford (1984) in a study of twentieth century alluvial stratigraphy on the Little Colorado River, Arizona.

The mechanisms of channel/floodplain evolution following entrenchment involve incremental processes associated with "normal" dynamics and occur mostly during periods of high flow. In the case of the San Pedro River, these processes consist primarily of river meandering, bank cutting, point bar deposition, and floodplain development.

Classical meandering involves both the lateral and downstream migration of channel bends (Figure 9). Helical flow patterns contribute to the scouring of cut banks on the outside of meanders, and the deposition of sediment on the large point bars which form on the inside of meanders. Point bars further function as floodplains, and when vegetation becomes established, they may be particularly effective in dissipating stream energy and inducing sedimentation during flood flows. When a point bar is forming, or when it is being encroached by an upstream

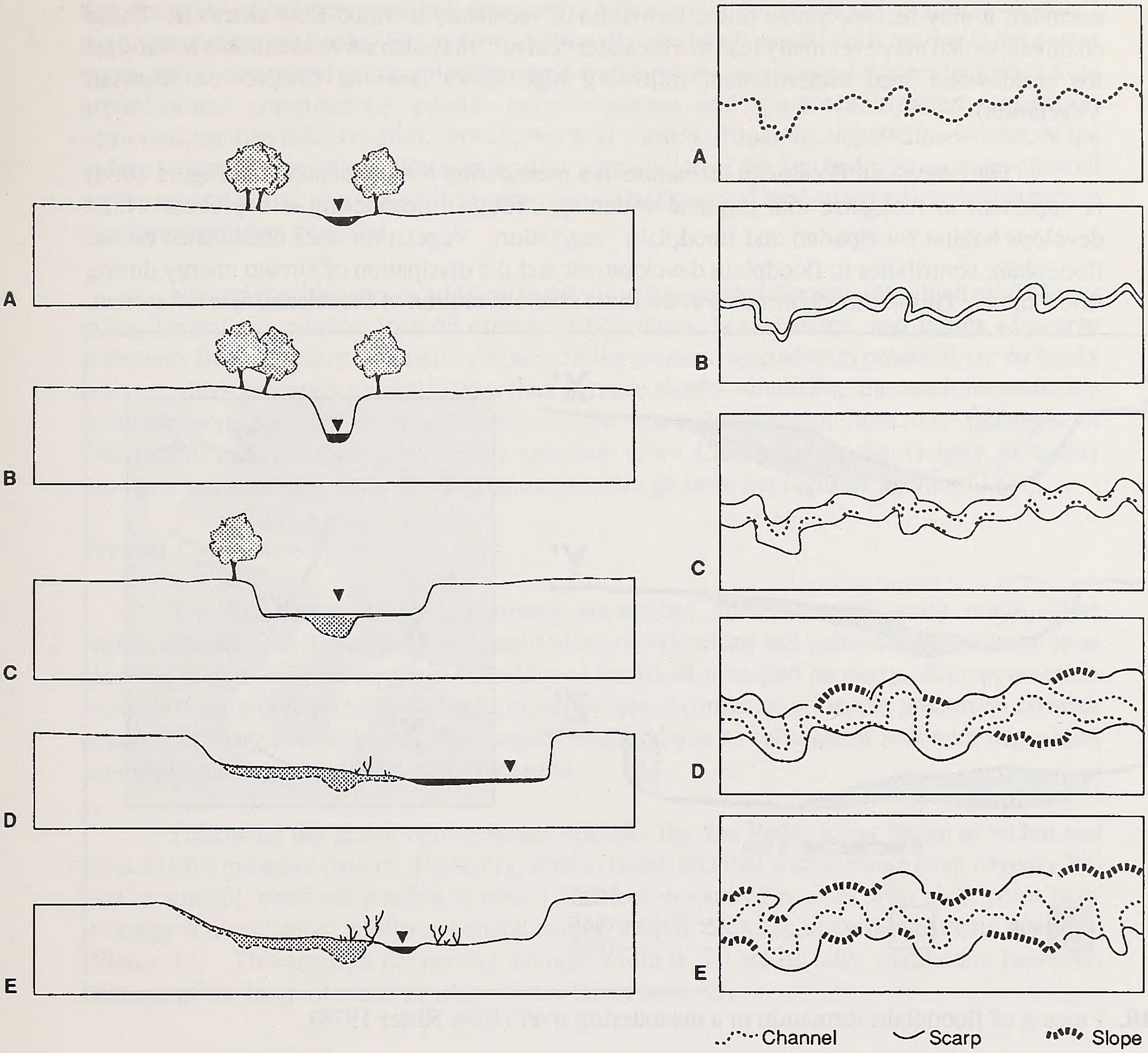


Figure 8. Model of arroyo evolution following entrenchment: (a) cross-section view, (b) plain view (after Elliott 1979).

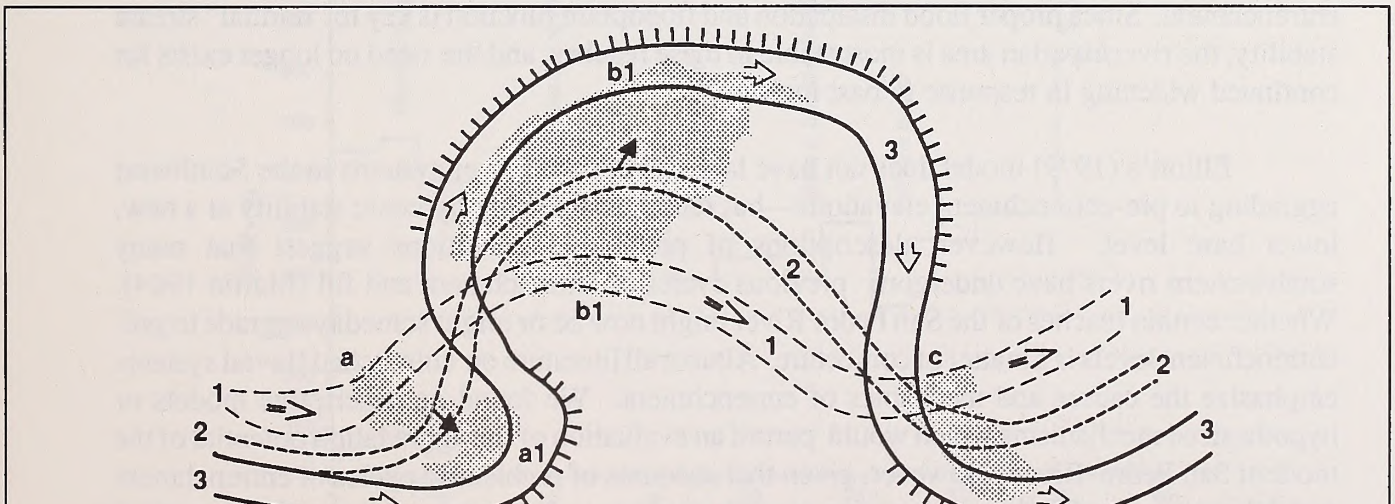


Figure 9. Lateral and downstream migration of meander bends (from Schumm 1977).

meander, it may be susceptible to the formation of secondary or flood-flow channels. These channels, which may eventually lead to a meander "cut off" may also serve as suitably moist sites for cottonwood seed establishment following high flows (see the Chapter on Riparian Vegetation).

The process of floodplain formation in a meandering river is depicted in Figure 10. It is important to recognize that physical widening through meandering is a process which develops habitat for riparian and floodplain vegetation. Vegetation once established on the floodplain, contributes to floodplain development and the dissipation of stream energy during flood flows. This in turn contributes to the more stable evolution of the stream/riparian system.

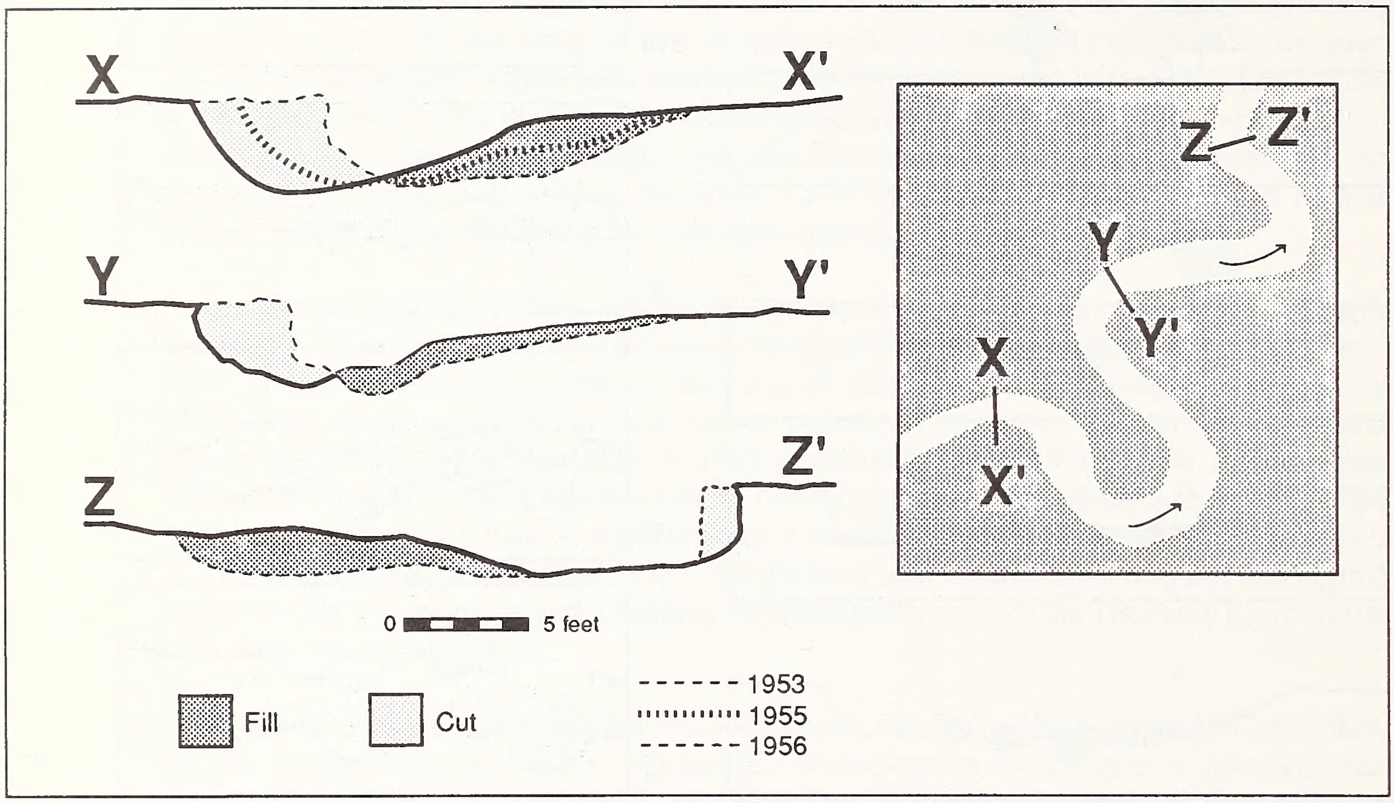


Figure 10. Process of floodplain formation in a meandering river (from Ritter 1978).

In certain reaches, the San Pedro River is actively bank cutting and widening. In other reaches, the river seems to have established adequate width and has developing floodplains on both sides—yet well confined within the outer cut banks created following the last episode of entrenchment. Since proper flood dissipation and floodplain function is key to "normal" stream stability, the river/riparian area is most stable in these reaches, and the need no longer exists for continued widening in response to past incision.

Elliott's (1979) model does not have large, entrenched river systems in the Southwest aggrading to pre-entrenchment elevations—but rather establishing dynamic stability at a new, lower base level. However, descriptions of prehistoric conditions suggest that many southwestern rivers have undergone previous cycles of entrenchment and fill (Martin 1964). Whether certain reaches of the San Pedro River might now be or might someday aggrade to pre-entrenchment levels is a matter of conjecture. Almost all literature on entrenched fluvial systems emphasize the causes and mechanics of entrenchment. We found no descriptive models or hypothesized mechanisms which would permit an evaluation of the aggradation potential of the modern San Pedro River. However, given that accounts of prehistoric cycles of entrenchment and fill exist in the Southwest, it seems possible that a set of circumstances could exist which would permit a slow evolution to pre-entrenchment conditions in some reaches.

It is interesting to observe the great depth of vegetation-induced deposition along the

San Pedro River, which commonly approaches 8 feet, and in some places has almost obscured the original outer cut banks (Figure 6). Additionally, the San Pedro River is unique in the extent to which it is connected to the regional ground-water system (see Ground Water chapter). Large ground-water contributions permit more vigorous and abundant riparian vegetation communities than exist on drier, more ephemeral washes. Riparian vegetation, in turn, helps induce sediment deposition. Working against aggradation of the San Pedro River main channel are the several bridge crossings which serve to confine flows and land-use practices which reduce riparian vegetation densities.

Natural mechanisms in addition to developed vegetated floodplains which might favor main-channel aggradation include organic debris dams, beaver dams, and inputs of coarse sediments from tributary channels. Areas with the greatest aggradation potential are probably reaches which presently exhibit milder than average slopes—including the reach immediately upstream and downstream from Hereford, the reach downstream from the "narrows" at Charleston, and—possibly—the reach upstream from Charleston in the vicinity of Lewis Springs. Interestingly, these are also areas of recharge from the regional aquifer.

Present Conditions

The San Pedro River is presently entrenched throughout the study reach. The entrenchment depth is roughly 8 feet near Palominas/Hereford and increases downstream to as much as 25 feet near the northern boundary of the BLM-managed property. Entrenchment is most dramatic where primary cut banks exist because of continued widening processes. In other reaches, primary cut banks may be largely obscured due to subsequent sediment deposition processes and established riparian vegetation.

Following the recent entrenchment episode, the San Pedro River began to widen and reestablish a meander pattern. Presently, active (flood) channel widths range from roughly 200 feet in straight, confined reaches to over 1,500 feet in curved reaches with large point bars. Average active channel widths in general exhibit a slight decrease in the downstream direction (Figure 11). This trend in decreasing average width is not statistically significant, however, because of the large increase in width below River Mile 35.

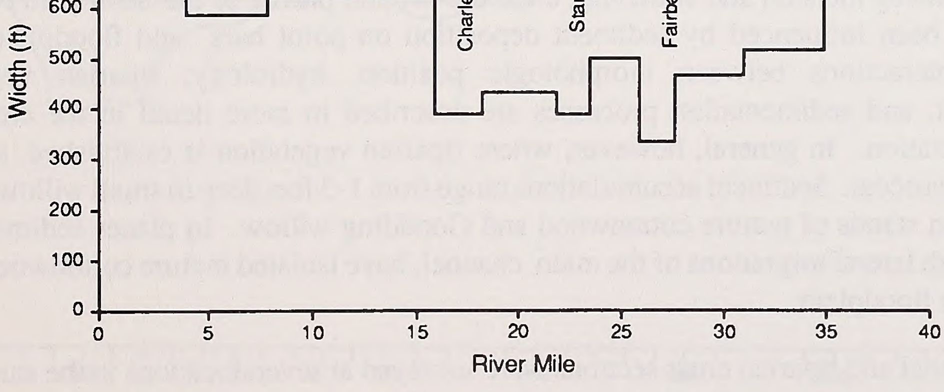


Figure 11. San Pedro River active channel widths.

Sinuosities presently range from almost 1.8 ft./ft. near Hereford to between 1.0-1.1 ft./ ft. between River Miles 8-16, near Fairbanks, and down-stream from River Mile 35 (Figure 12). While sinuosities do not correlate to average active channel width, they, too, tend to decrease in the downstream direction. Also, the largest individual width readings are on large meanders, and the smallest individual width readings are on confined straight reaches.

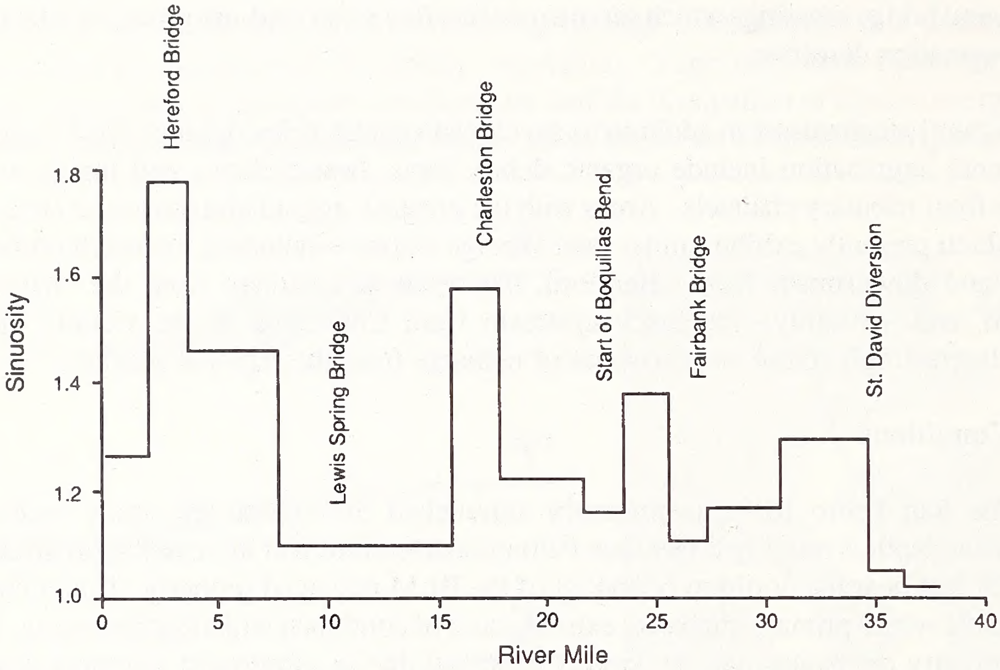


Figure 12. San Pedro River sinuosities.

The tendency for the San Pedro River to become more deeply entrenched, narrower, and somewhat less sinuous as it traverses northward through the study reach may be, in part, due to the decidedly convex nature of the longitudinal stream profile (Figure 13). Slopes range from roughly 0.19 percent in the upper (southern) reaches of the river to roughly 0.38 percent at the northern end of the study area. While the overall profile is generally convex, there are several short reaches of alternating steep and mild slopes. Comparatively steep slopes of 0.69 percent and 0.46 percent occur at the Charleston "narrows" and roughly 1/2 to 1-1/2 miles upstream from Fairbanks, respectively. A comparatively mild slope of 0.14 percent occurs between the northern end of the Charleston "narrows" to roughly the bend at the Boquillas Ranch. The convex longitudinal profile in the study reach probably results in part from structural controls near Charleston, and downstream from Fairbanks. Profile characteristics may also be influenced by the cienega processes described above, and possibly by tendencies of some Southwestern streams to degrade from the upstream to the downstream direction (Harvey, et al., 1987).

Following incision and widening, the cross-section profile of the San Pedro River has increasingly been influenced by sediment deposition on point bars and floodplains. The important interactions between morphologic position, hydrology, riparian vegetation establishment, and sedimentation processes are described in more detail in the chapter on riparian vegetation. In general, however, where riparian vegetation is established, sediment accumulations occur. Sediment accumulations range from 1-3 feet deep in small willows to over 8 feet thick in stands of mature cottonwood and Goodding willow. In places sedimentation, combined with lateral migrations of the main channel, have isolated mature cottonwood stands off the active floodplain.

Channel and riparian cross sections were surveyed at seven locations in the study reach (Figure 1). Cross section profiles are shown in Figures 14a to g. Vegetation associations with cross-section position are discussed in the riparian vegetation chapter. Ground-water depths within each cross section are described in the Ground Water chapter. Flood levels at each cross section are discussed in the surface water hydrology chapter.

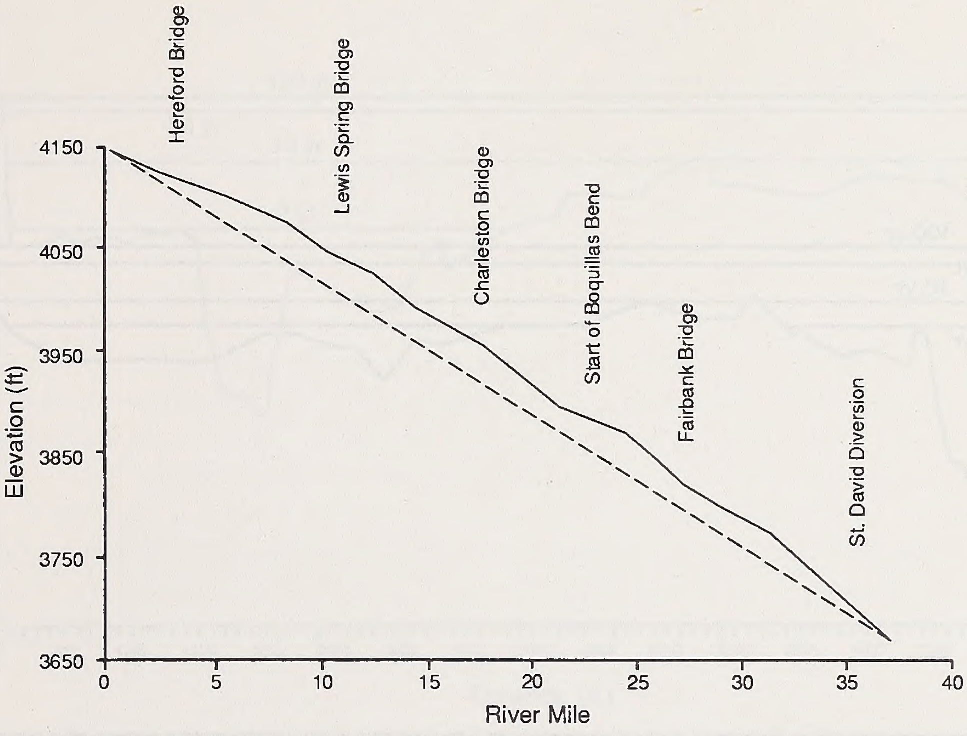


Figure 13. San Pedro River longitudinal profile.

Figure 14. (a-g) San Pedro River channel cross sections indicating the inundation extent of flood flows with 2-year, 10-year, 50-year, and 100-year return periods.

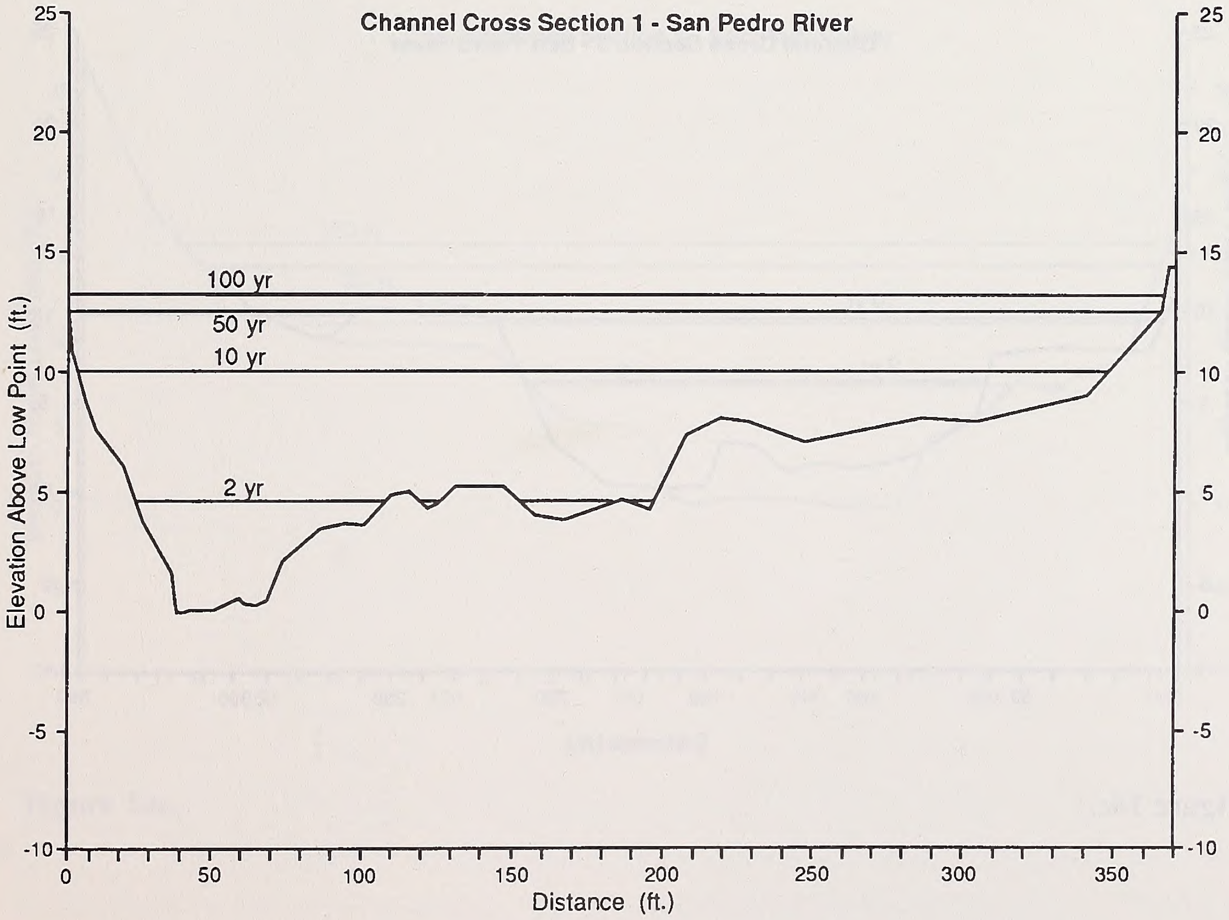


Figure 14a.

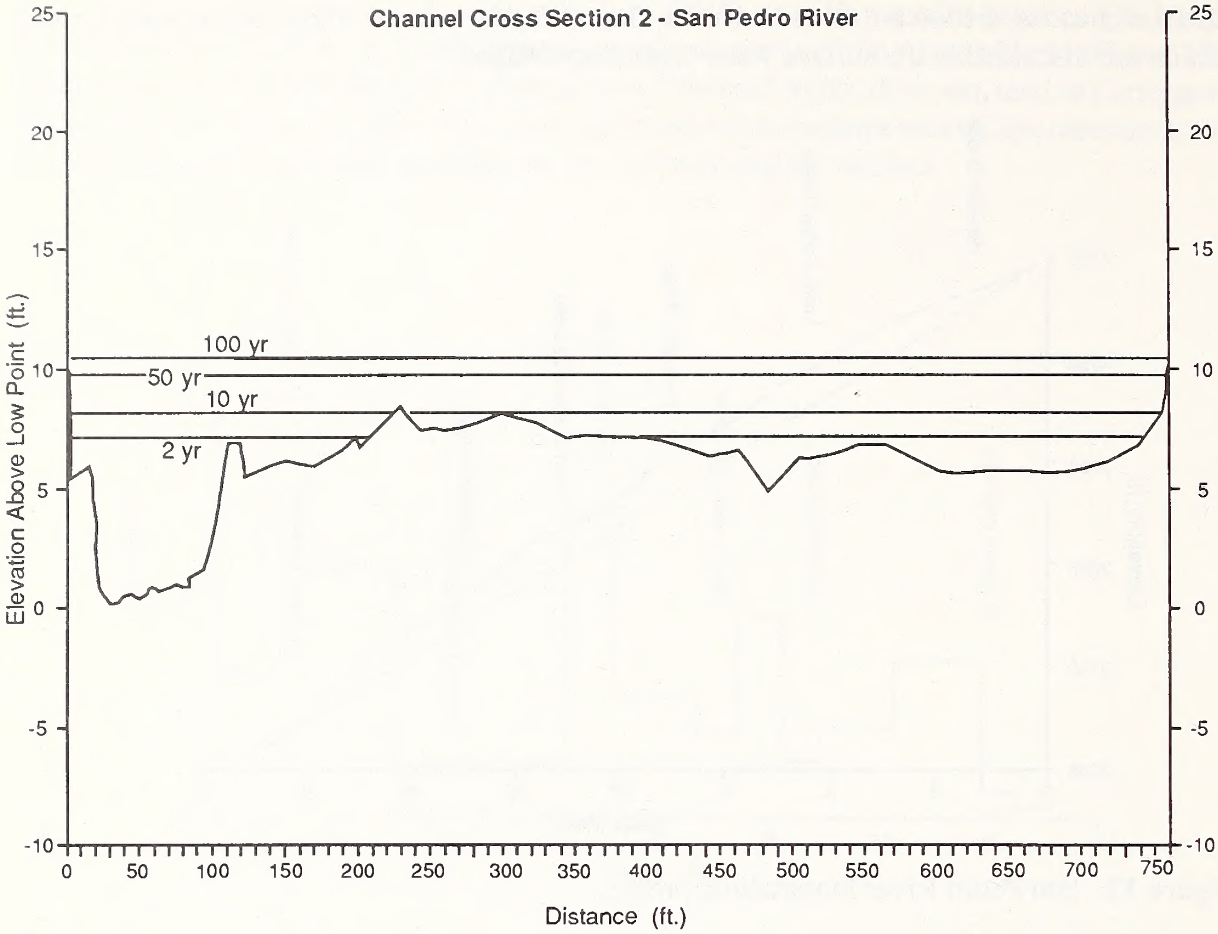


Figure 14b.

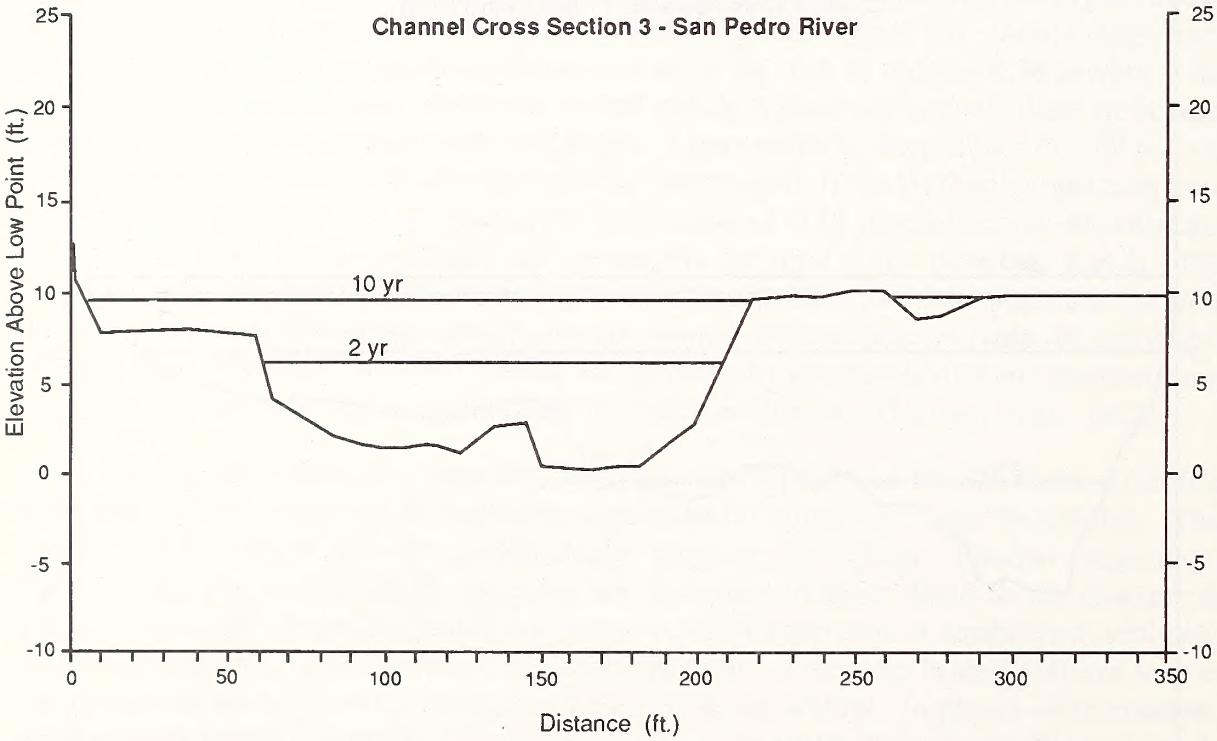


Figure 14c.

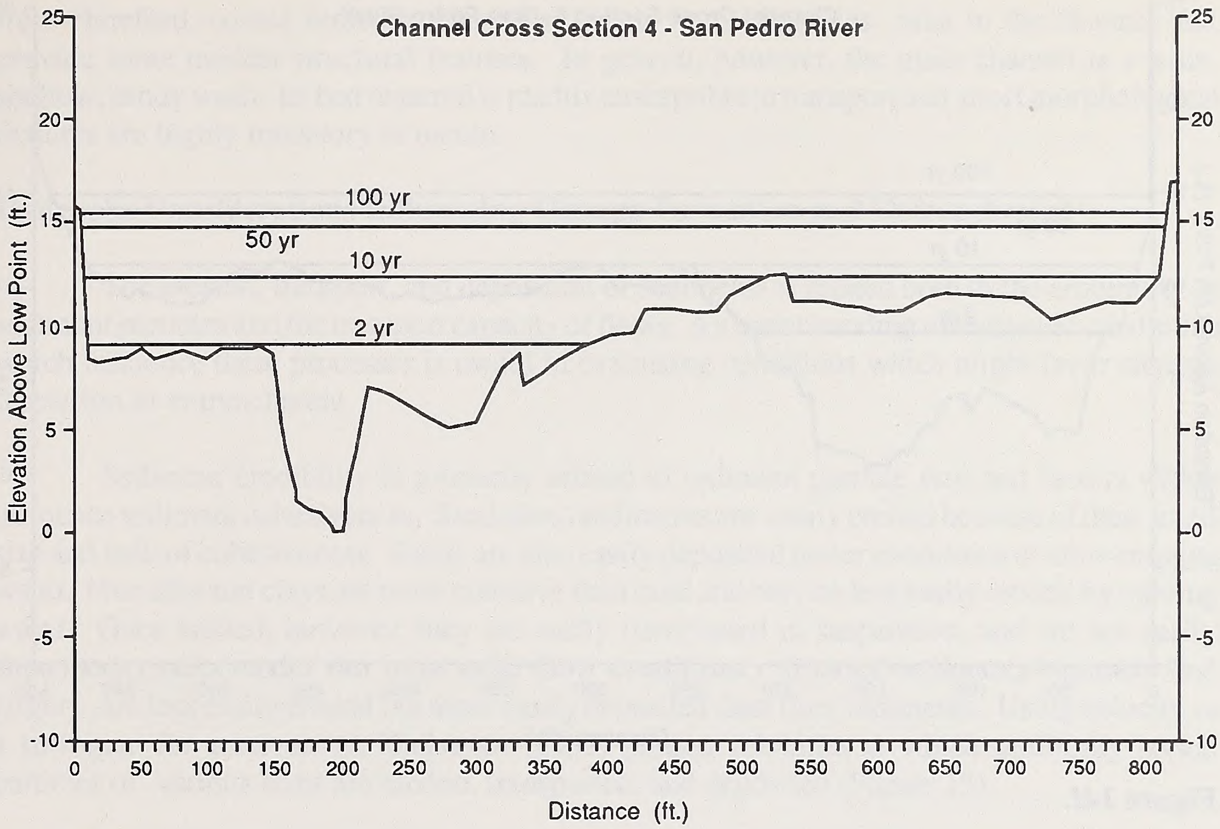


Figure 14d.

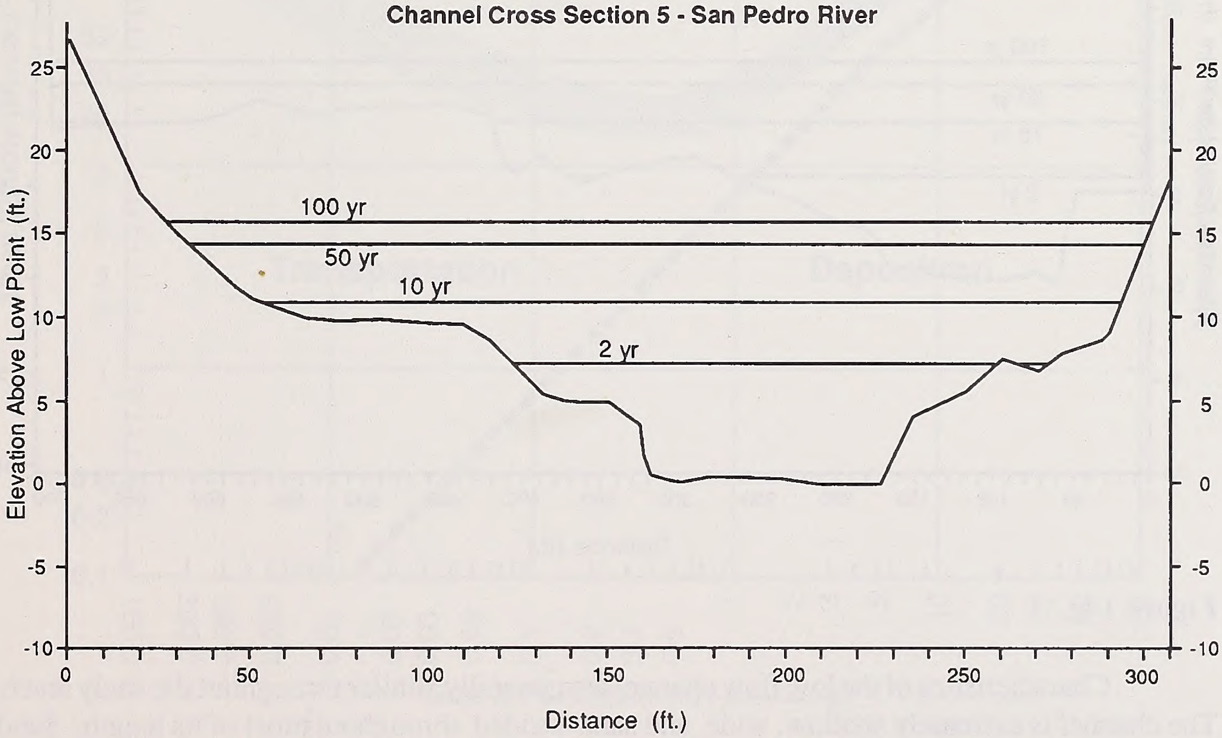


Figure 14e.

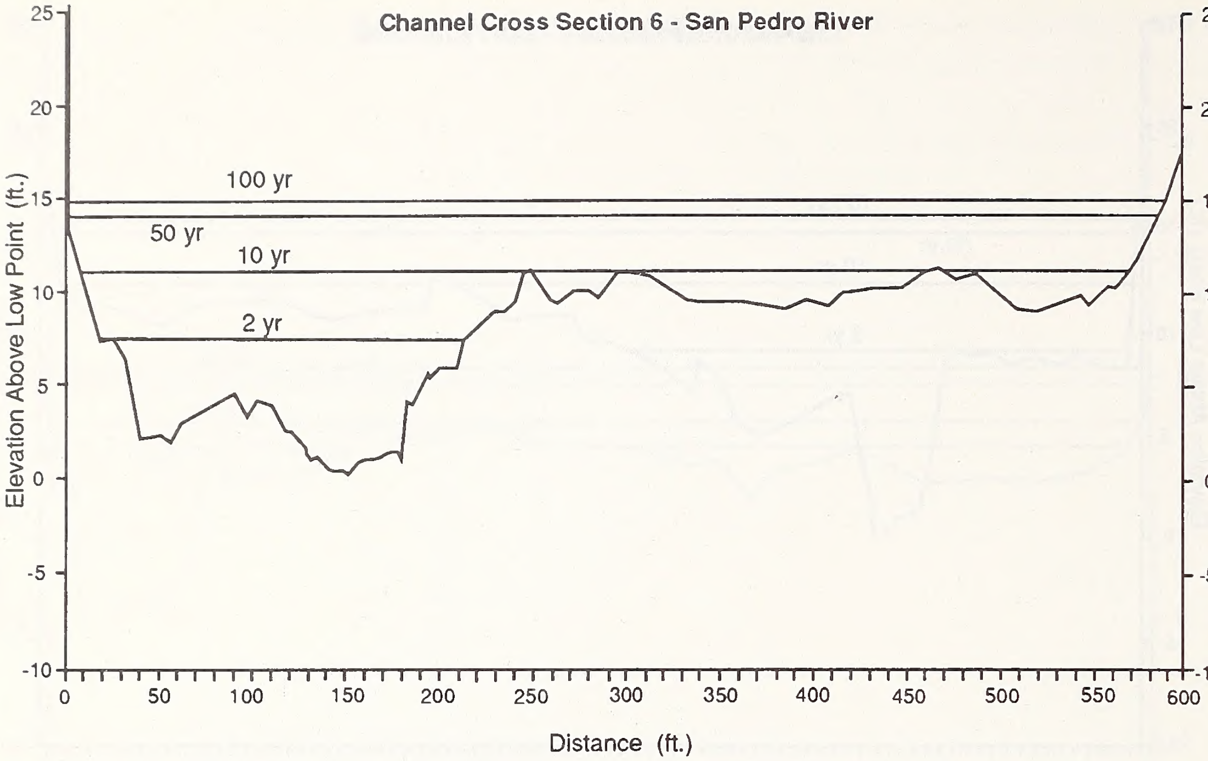


Figure 14f.

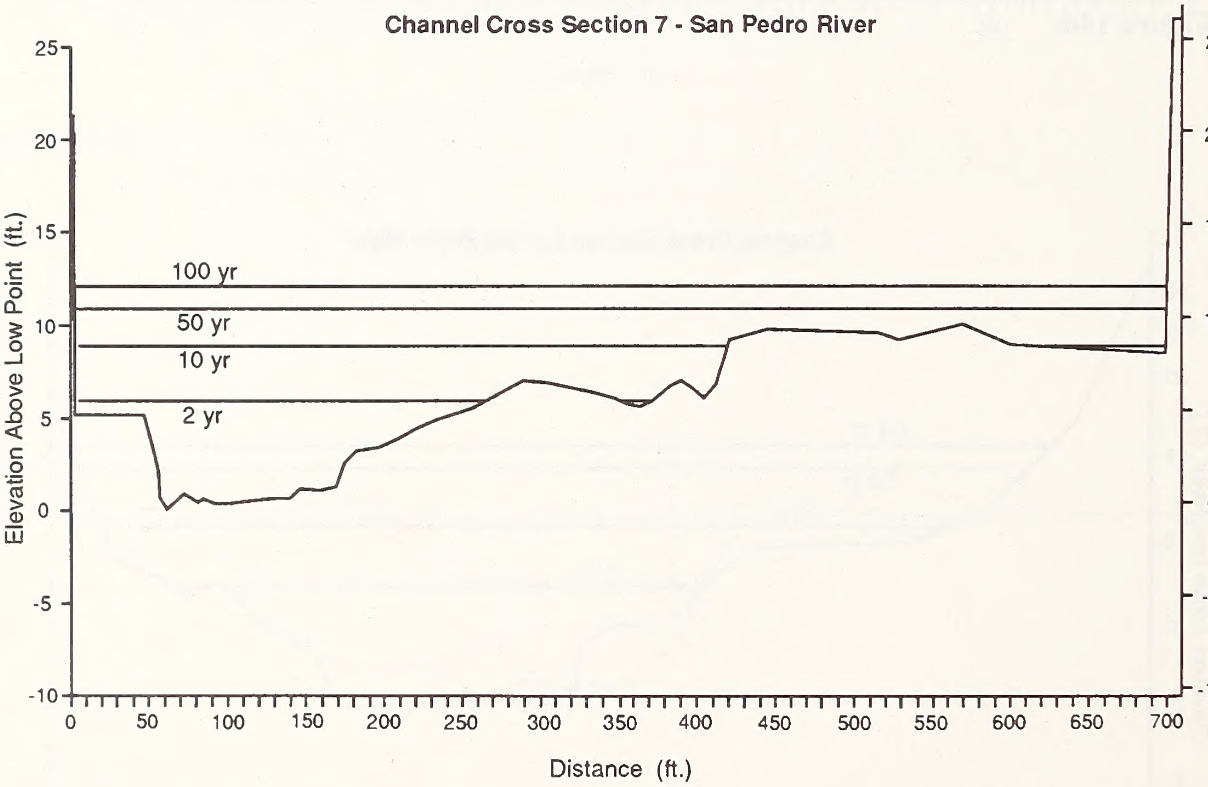


Figure 14g.

Characteristics of the low flow channel are generally similar throughout the study reach. The channel is extremely shallow, wide, and sand-bedded throughout most of its length. Sand continues to be transported as bedload even during low-flow periods. As a result, the channel is devoid of any significant pools, and banks are often either poorly developed or partially inundated by sand. There are several reaches—specifically at Charleston and near the Tombstone gage where bedrock influences channel characteristics and some structural features—including small pools and developed banks—exist. Also, several miles downstream from Hereford, coarse sediment materials, inputs from tributaries, exist in the channel and provide some modest structural features. In general, however, the main channel is a wide, shallow, sandy wash. Its bed material is readily susceptible to transport and most morphological features are highly transitory in nature.

Hydraulic Considerations Influencing Cienega Formation and Entrenchment

The erosion, transport, and deposition of sediments is related both to the erodibility of sediment particles and the transport capacity of flows. An understanding of hydraulic conditions which influence these processes is useful in evaluating conditions which might favor cienega formation or entrenchment.

Sediment erodibility is primarily related to sediment particle size and factors which influence sediment cohesiveness. Sand-sized sediments are easily eroded because of their small size and lack of cohesiveness. Sands are also easily deposited under conditions of slow-moving water. Fine silts and clays are more cohesive than sand and may be less easily eroded by moving water. Once eroded, however, they are easily transported in suspension, and are not easily deposited, except under the most mild flow conditions. Coarser sediments—gravels and larger—are less easily eroded but more easily deposited than finer sediments. Using velocity as a surrogate for erosiveness, Hjulstrom (1939) plotted velocities at which uniformly sorted particles of various sizes are eroded, transported, and deposited (Figure 15).

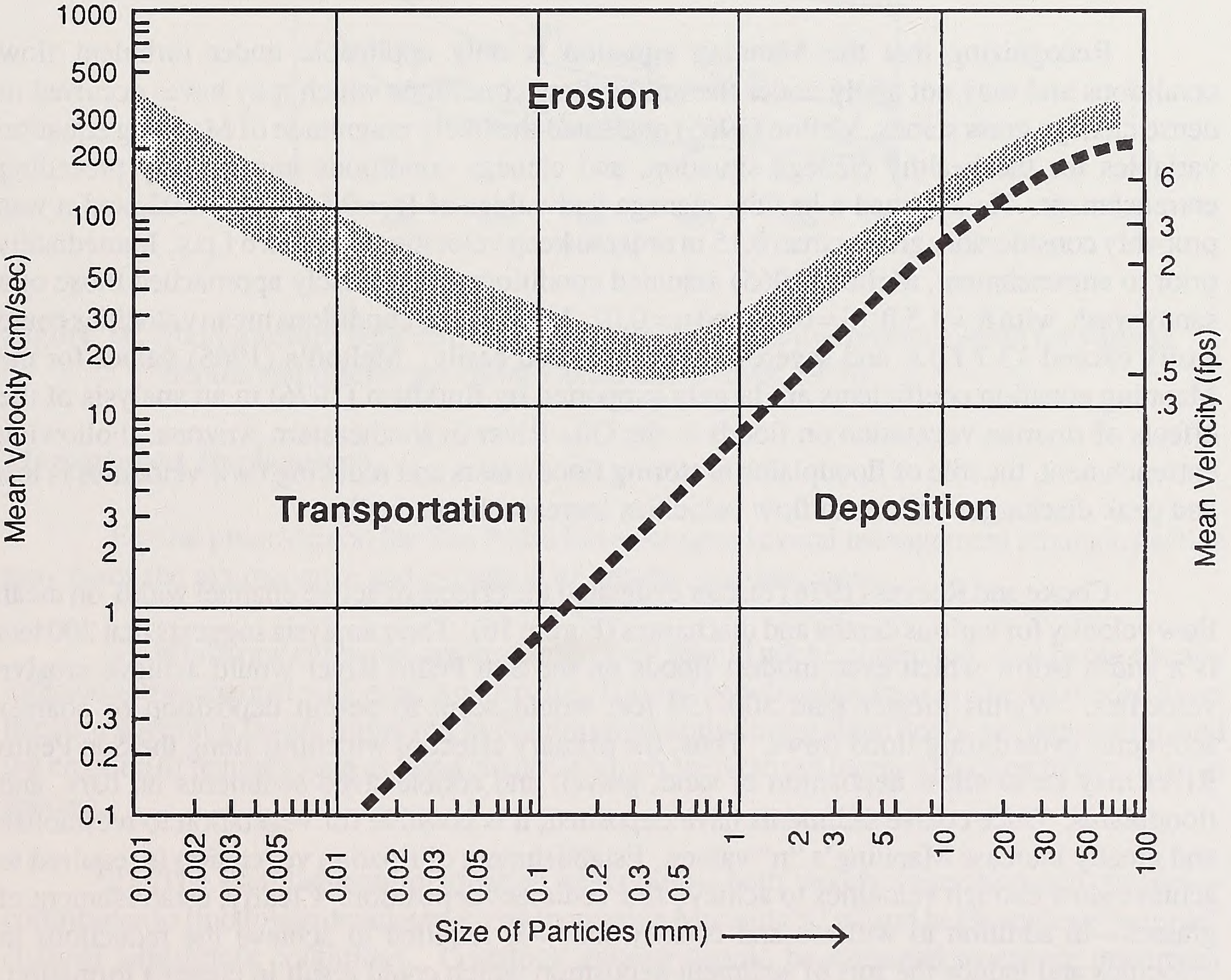


Figure 15. Erosion, transport, and deposition of uniformly sorted sediment particles (after Hjulstrom 1939).

Flow erosiveness, being indexed by mean velocity, is affected by discharge rate and hydraulic geometry. For any rate of discharge, velocity is controlled by the cross-section geometry of the flow (width, depth, wetted perimeter), the channel gradient, and any resistance to flow caused by channel roughness (including friction caused by bed sediments or vegetation, or drag resulting from large channel form features, rocks, trees, roots, etc.). All of the factors influencing flow velocity are related in the Manning equation:

$$V = \frac{1.49}{n} S^{1/2} R^{2/3} \qquad (1)$$

where V = mean velocity in feet per second
S = gradient of water surface
R = hydraulic radius in feet, where hydraulic radius is defined as the cross-section area of flow divided by the wetted channel perimeter. In shallow, wide channels R is roughly equal to flow depth.

n = Manning roughness coefficient

Melton (1965) identified 6 f.p.s. as a critical velocity above which cienega deposits would erode. However, given the fine sediment composition of cienegas, velocities considerably less than 6 f.p.s. may have been sufficient for erosion if vegetation cover was severely reduced (see Figure 15).

Recognizing that the Manning equation is only applicable under turbulent flow conditions and may not apply under the milder flow conditions which may have occurred in dense cienega grass stands, Melton (1965) evaluated the likely magnitude of Manning equation variables for the healthy cienega situation, and cienega conditions immediately preceding entrenchment. He assumed a healthy cienega had values of $R = 0.5$ ft., $S = 0.02$, and n was probably considerably greater than 0.15 in order to keep velocities less than 6 f.p.s. Immediately prior to entrenchment, Melton (1965) assumed conditions more closely approached those of a sandy wash, with $R = 1.5$ ft., $S = 0.02$, and $n = 0.02$. Under those conditions mean velocities could easily exceed 13.7 f.p.s. and severe erosion followed easily. Melton's (1965) values for the Manning equation coefficients are largely supported by Burkham (1976) in an analysis of the effects of riparian vegetation on floods in the Gila River in southeastern Arizona. Following entrenchment, the role of floodplains in storing floodwaters and reducing flow velocities is lost and peak discharges and mean flow velocities increase dramatically.

Cooke and Reeves (1976) further evaluated the effects of active channel width on mean flow velocity for various depths and discharges (Figure 16). Their analysis suggests that 200 feet is a width below which even modest floods on the San Pedro River would achieve erosive velocities. Widths greater than 500-750 feet would seem to permit deposition of coarser sediments even during flood flows. Thus, the primary effect of widening along the San Pedro River may be to allow deposition of sand, gravel, and cobble-sized sediments on bars and floodplains. Once coarse sediments have deposited, it is possible for vegetation to reestablish and greatly increase Manning's "n" values. Establishment of riparian vegetation is required to achieve slow enough velocities to achieve fine sediment deposition. Clearly, establishment of grasses—in addition to willows and cottonwoods—is required to achieve the reductions in velocities and induce the sort of sediment deposition which could result in cienega formation.

Present relationships between discharge depth and velocity on the San Pedro River are provided in Appendix II. In general, wider, more vegetated conditions result in more favorable hydraulic conditions for sediment deposition.

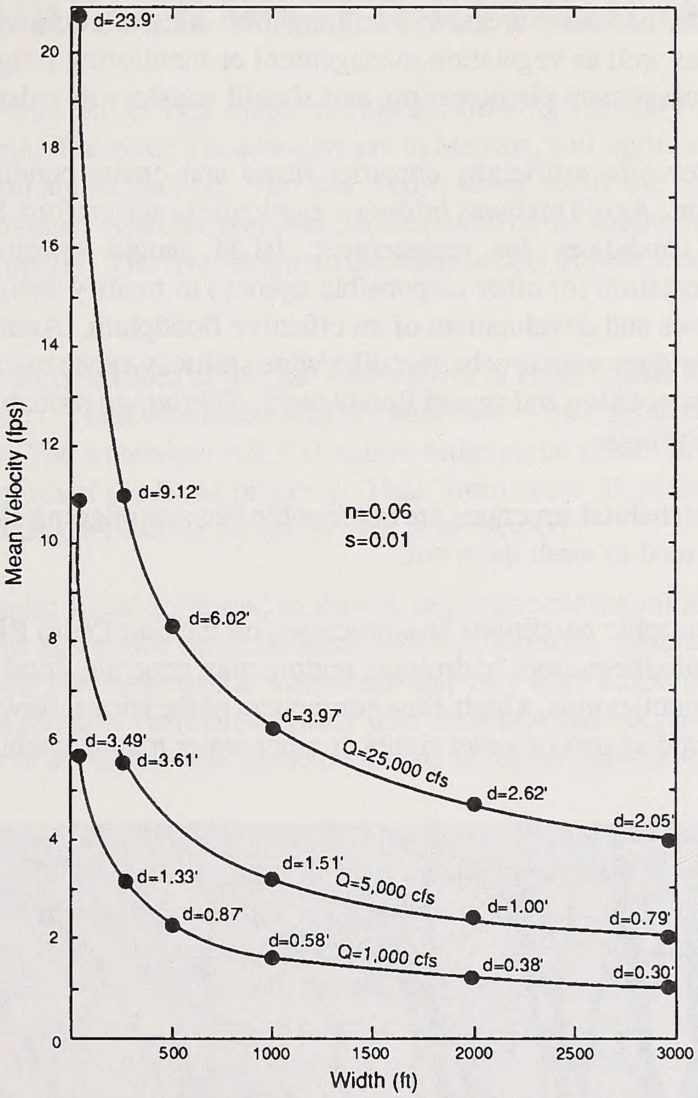


Figure 16. Relationships between mean flow velocity and active channel width for various depths and discharges (from Cooke and Reeves 1976).

Management Implications

Fluvial processes on the San Pedro River suggest several management strategies which may favor the maintenance and evolution of healthy riparian areas:

1) While raw cut banks are unsightly, they should not be controlled. Cut banks usually indicate active channel widening is occurring. This is a beneficial process on the San Pedro River because widening favors improved hydraulic conditions during floodflows, sedimentation, and the creation of features such as flood channels which are required for reproduction of key riparian species.

2) The establishment of riparian vegetation—both woody vegetation and grasses—contributes to floodplain development by increasing Manning's "n" and helps achieve "normal" channel adjustment conditions. Livestock grazing should be managed to ensure maximum development of riparian area vegetation.

3) Where sediment depths are great, and when lateral channel adjustments have occurred, it will not be uncommon to find groves of cottonwoods isolated from the active floodplain. These trees will develop normally as long as they have access to the riparian area

ground-water resources, but these areas will no longer be sites of cottonwood reproduction. Visitor staging areas, as well as vegetation management or monitoring programs may well be influenced by this successionary phenomenon, and should consider its existence.

4) Bridges serve to artificially constrict flows and create conditions which favor downcutting and erosion. As old highway bridges—particularly at Hereford, Lewis Springs, and Charleston—become candidates for replacement, BLM should encourage the Arizona Department of Transportation (or other responsible agency) to modify designs to permit wide dispersion of flood flows and development of an effective floodplain. Another idea would be to consider replacing bridges with low barrier dike/wide spillway-type structures which would function to induce sedimentation and spread floodwaters. This would probably be most feasible at Hereford or Lewis Springs.

5) Instream fish habitat structures are not feasible because ongoing channel adjustments and high flows would tend to wash them out.

6) Most geomorphic conditions and processes on the San Pedro River are dependent upon flood flows. While the present hydrologic regime may generate flood flows in excess of historic (pre-entrenchment) norms, a high-flow component of the annual flow regime is required and should be considered as part of water rights or other water management strategies (Figure 17).

Figure 17. Photograph of primary cut bank now partially obscured by riparian vegetation and subsequent sediment deposition.

SURFACE WATER HYDROLOGY

The San Pedro River is a major northward-flowing tributary to the Gila River in southeastern Arizona. The river's headwaters are in Mexico, and approximately 30 miles of its total 155-mile length are in Mexico. The San Pedro River enters the United States roughly 3 miles south of Palominas, Arizona, and over 5 miles south of the southern boundary of the BLM San Pedro River property. The river length in the study area is 37 miles, and the average gradient is 0.27 percent.

The total watershed area of the San Pedro River is 4,483 square miles, 696 square miles of which is in Mexico. Total watershed area at Palominas—just south of the BLM property—is 741 square miles. The watershed is 2,500 square miles at the USGS streamgage near Benson, which is 20 miles north of the BLM property. Thus, from about 35 percent to 87 percent of the San Pedro River drainage basin at the study area is in Mexico.

The San Pedro River is formed in alluvial deposits near the middle of a large structural trough. Valley floor elevations range between 4,000-5,000 feet. Mountains, which border the valley floor, form the perimeter of the watershed and vary from 6,000 ft. to about 9,500 feet in elevation. Basin vegetation correlates closely with elevation and ranges from desert grasslands on the valley floor to subalpine and montane forests at higher elevations.

The climate of the watershed is arid to semi-arid. Summers are warm, and winters experience warm days and cool nights. Average annual precipitation ranges from 11 inches at Benson to 15 inches at Fort Huachuca, and is probably much higher in the mountains. Annual precipitation is distributed bimodally, with about 50-60% of the annual total occurring as convectional storms in July, August, and September, and roughly 20 percent occurring as broad frontal storms in December, January, and February. Spring and fall are normally very dry. Snow may occur during winter at lower elevations, and is common at higher elevations. Less than 1 inch of the basin precipitation is recorded as annual streamflow. Climate data for the upper San Pedro River basin was summarized by Putman et al. (1987) and is presented in Table 8.

Table 8. Summary of annual precipitation and temperature data at weather observation stations in the upper San Pedro basin from Putman et al. (1987) (Data in Climatological Data Annual Summaries, Arizona, NOAA; and Sellers and Hill 1974)

Station	Elevation (Feet Above Mean Sea Level)	Annual Precipitation (In.)			Temperature (°F)		
		Min.	Average	Max.	Min.	Average	Max.
Benson	3590	4.17	11.53	19.87	6	62.8	113
Fairbanks	3850	4.82	11.66	19.63			
Fort Huachuca	4664	7.21	15.24	25.57	9	62.2	104
Tombstone	4610	7.6	13.93	23.82	6	63.7	108

Surface flows in the San Pedro River occur as both rainfall runoff and ground-water discharge. The highest annual flows occur in the July-September period in response to short-duration, high-intensity thunderstorms. These flows are "flashy" and are characterized by extremely rapid rises, high peak flow rates, and rapid declines back to baseflow conditions. A secondary period of rainfall runoff occurs in the winter. Winter runoff events are less flashy than summer events and generally produce much lower peak flow rates (Table 10). Annual low-flow periods commonly occur in May and November. Baseflows represent discharge from the floodplain aquifer, which in turn is recharged both by the regional aquifer system and by rainfall-induced high flows (see the chapter on Ground Water, also Putman et al. [1987] and Roeske and Werrell [1973]). The river is perennial from just north of Hereford to just south of Fairbanks due to the discharge of ground water to the stream (Putman et al. 1987). However, as discussed below, baseflows in perennial reaches are variable depending upon location downstream.

Discharge rates are not only influenced by the amount and timing of runoff and ground-water discharges but also by channel and floodplain characteristics, and losses due to evaporation, phreatophyte transpirations, ground-water recharge, and man-made diversions and withdrawals. At present, the only surface diversion is located just upstream from the northern boundary of the BLM property. The diversion by the St. David Irrigation District has averaged 500 acre feet per month, and accounts for a major portion of surface low flows during the spring-summer irrigation season. Also, as discussed elsewhere in this report, ground-water pumping which influences water table levels in the floodplain aquifer probably influences rates of stream loss to ground water.

The U.S. Geological Survey operates three stream gages in or adjacent to the study reach at Palominas, Charleston, and near Tombstone. Streamgage information and Period-of-Record for each gage is described in Table 9.

Table 9. U.S. Geological Survey stream gages on or near the BLM San Pedro River properties.

Gage	Location	Period of Record	Drainage Area
094705.00 (at Palominas)	T23S R22E Sec. 33 1950-1986	1930-1940; (649 in Mexico)	741
094710.00 (at Charleston)	T21S R21E Sec. 11 1913-1986	1905; (696 in Mexico)	1219
094715.50 (near Tombstone)	T19S R21E Sec. 28 (696 in Mexico)	1968-1986	1740

In addition to the abundant U.S. Geological Survey gage record, BLM initiated a gaging program (Figure 18) as part of this project at seven river locations. All gaging sites are located on Figure 1.

Surface flow data for the San Pedro River in the study area are summarized and analyzed below. Analysis is provided for annual flows (yields, means, medians, trends), monthly flows (means, medians, ranges), daily flows (annual daily flow-duration), flood flows, and low flows (means, trends). In addition, indirect rating curves are developed for seven surveyed cross sections to analyze hydraulic characteristics of different flow rates (e.g., depths, wetted perimeters).

Terms

In relating surface water flow statistics to a discussion of instream flow requirements, it is extremely important that terms used in the surface water flow analysis are understood. When

Figure 18. BLM streamgaging and surveying activities.

analyzing surface water statistics, it is important to distinguish between mean flows, median flows, and the range of flows. Similarly, when analyzing trends over time, it is important to distinguish between correlation coefficients and the significance of a linear trend.

A frequency distribution (monthly or annual) of daily flows for the San Pedro River is highly skewed to the right. This means that most daily flows are quite low, but infrequent flows may be extremely high (Figure 19). The mean is a measure of central tendency and is an arithmetic average of all flows in the period. In a skewed distribution, the mean is heavily influenced by a few large flow values. The median value of a set of measurements is the middle value when measurements are arranged in order of magnitude. Thus the median daily flow for a period of time would be a flow rate which is exceeded 50% of the days in that period. In contrast, flows exceeding the mean in a highly skewed distribution might actually be very uncommon. The range in a set of measurements is simply the difference between the highest and lowest measurements. Mean flow rates are useful descriptors of runoff volumes and may be useful in analyzing attributes such as water use, ground-water recharge, and trends in runoff volume (seasonal or annual). Median flow rates are useful descriptors of "normal" flow conditions in the river—that is, conditions most likely to be encountered by a visitor to the river or by flow-dependent wildlife and fishes. The upper end of the range of flows—or peak flows—are useful in flood analyses and are important flow attributes in the analysis of geomorphic processes and conditions, and in the design of hydraulic structures. During low-flow period, means, medians, and lower range values may be similar.

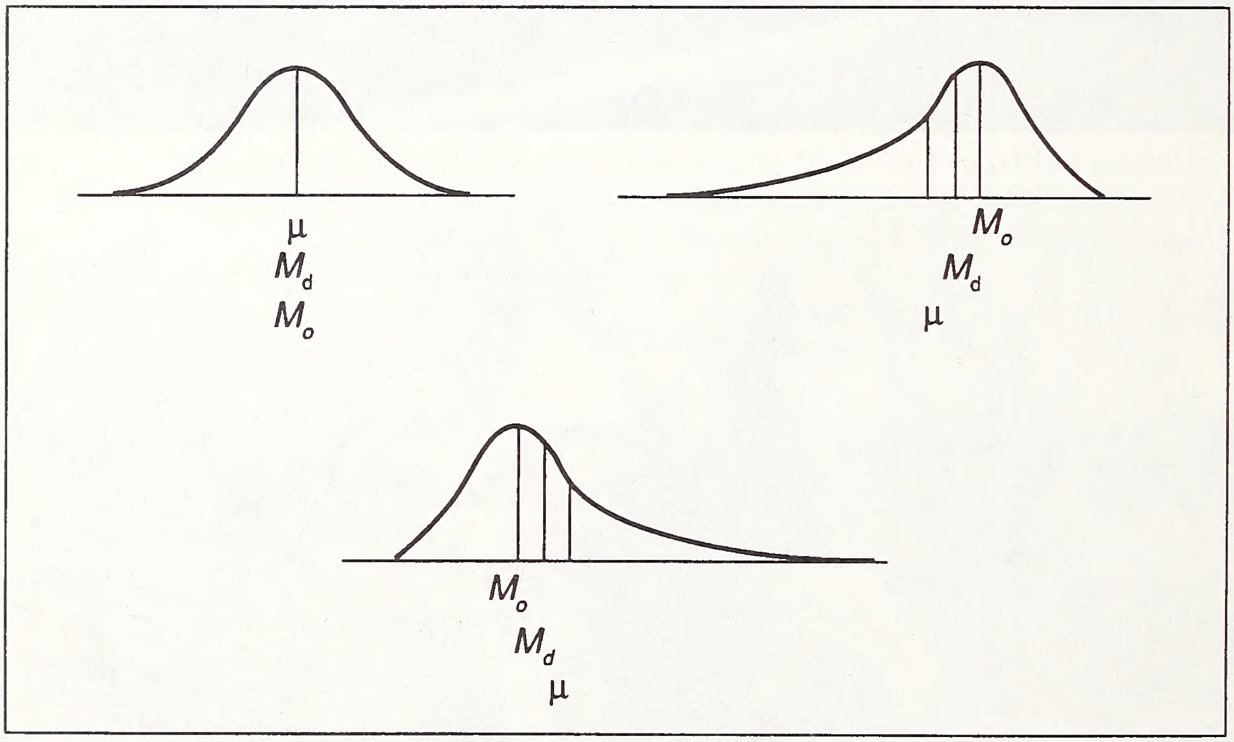


Figure 19. Relationships among the mean, median, and mode in skewed distributions: (a) a bell-shaped distribution, (b) a distribution skewed to the left, (c) a distribution skewed to the right.

Linear regressions were used to index any trends in surface water flow statistics over time. Because time (year) would not be expected to be a good predictor of flows (precipitation, for example, might be a better predictor of flow), it can be expected that the correlation coefficient (r) and r^2 will be low. A low r^2 means that variations in the dependent variable are poorly predicted by variations in the independent variable. The significance of the regression is a measure of the significance of the slope term, m, in the linear equation $y=mx+b$, where y is the dependent variable, x is the independent variable, and b is the value of the y intercept. The significance of m is tested using an "F" statistic (Neter and Wasserman, 1974).

Annual Flows

Mean annual discharge in the San Pedro River at Charleston averages about 60 cfs (s=37.6cfs) over the 72-year period of record. Since 1932, the mean annual discharge at Palominas averaged 33 cfs (s=25.3 cfs). The mean annual discharge at Tombstone (1967-1984) averaged 54 cfs (S=37.3). Annual flows at Charleston are about 62 percent higher than at Palominas for corresponding periods of record. This is due in part to the larger contributing watershed and the correspondingly larger peak flows at Charleston, and in part to the substantial ground-water contribution to the stream between Palominas and Charleston.

Thorough analysis of annual discharge is provided in Putman et al. (1987). A summary of annual discharge, total runoff volume (acre-feet), and annual winter-period and summer period peak flows is provided in Table 10 for the river at Charleston. Statistical summaries of mean annual discharge and total runoff volume are provided in Table 11. Median annual flows are discussed in the flow-duration analysis section below.

Linear regressions of mean annual flow over time were developed to determine if there has been any overall trend in average annual runoff volume at Charleston. For the 1931-1985 period of record, there has been no significant trend—either up or down—in annual runoff (Figure 20). However, there is a highly significant (p=0.99) negative trend in annual runoff when the period of record is extended back to 1902 (Figure 21). This is because of a number of very large flood events between 1910-1926.

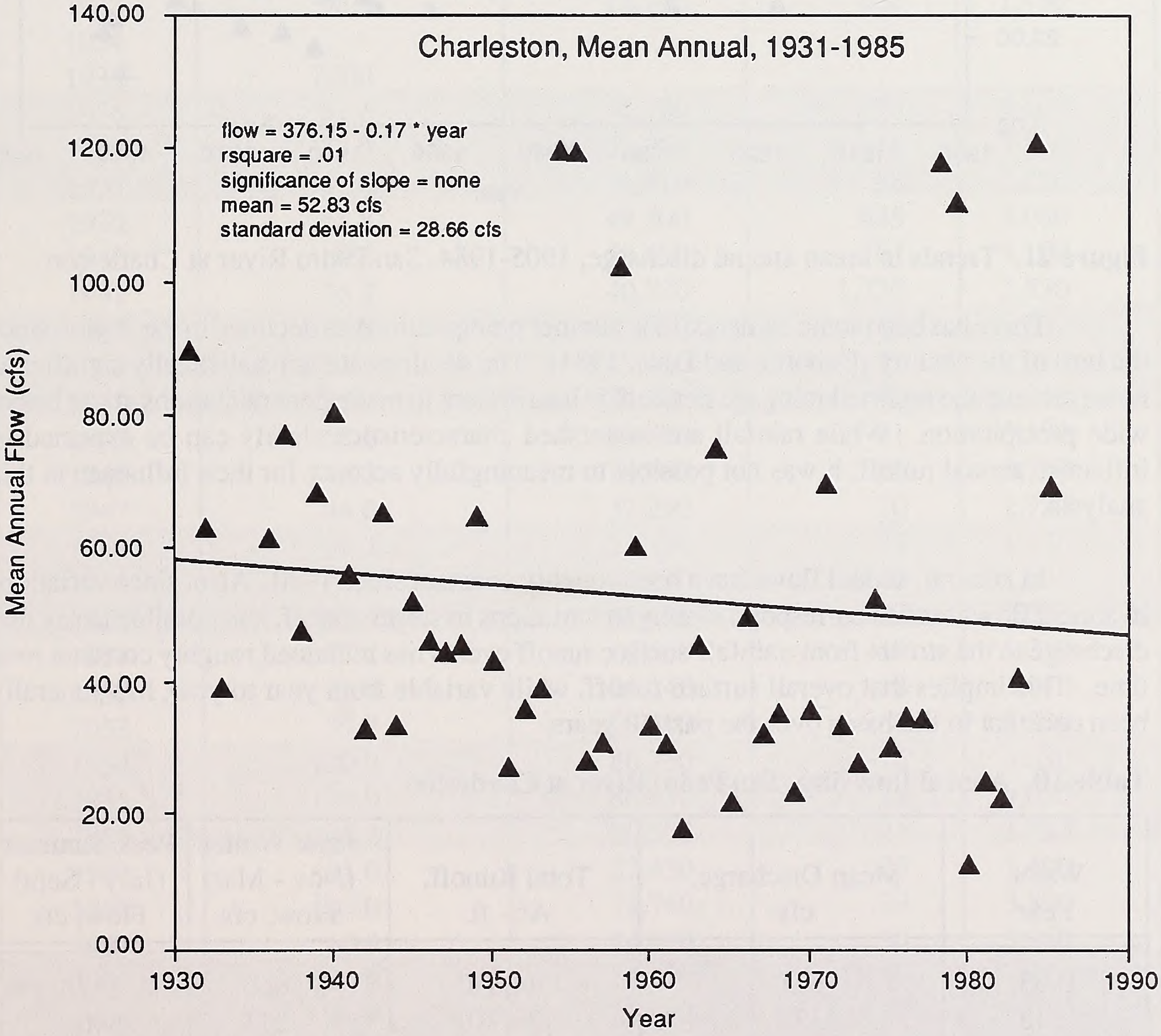


Figure 20. Trends in mean annual discharge, 1931-1985, San Pedro River at Charleston.

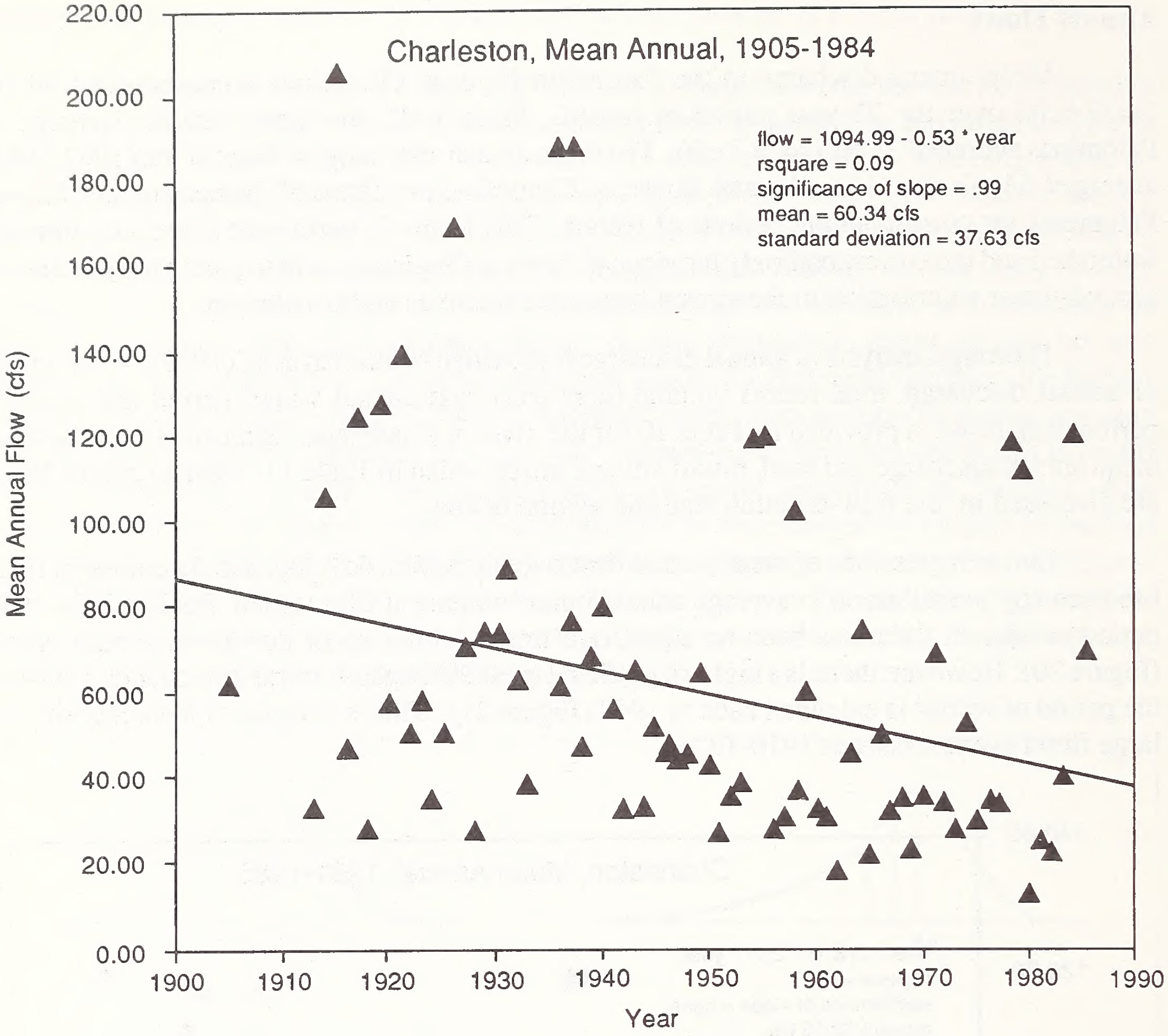


Figure 21. Trends in mean annual discharge, 1905-1984, San Pedro River at Charleston.

There has been some evidence that summer precipitation has declined in the region since the turn of the century (Osborne and Lane, 1984). The declines are not statistically significant, however, and the reported raingage network is insufficient to make generalizations about basin-wide precipitation. While rainfall and watershed characteristics clearly can be expected to influence annual runoff, it was not possible to meaningfully account for their influence in this analysis.

In general, annual flows have been roughly constant since 1930. Also, since variations in annual flows tend to correspond closely to variations in storm runoff, it is possible to say that discharge to the stream from rainfall-surface runoff events has remained roughly constant over time. This implies that overall surface runoff, while variable from year to year, has generally been constant in the basin over the past 50 years.

Table 10. Annual flow data, San Pedro River at Charleston.

Water Year	Mean Discharge, cfs	Total Runoff, Ac - ft.	Peak Winter (Nov - Mar) Flow, cfs	Peak Summer (July - Sept) Flow, cfs
1905	62.0	44,880	669	287
1913	32.8	23,710	211	846
1914	106.0	76,540	1,120	3,000

Water Year	Mean Discharge, cfs	Total Runoff, Ac - ft.	Peak Winter (Nov - Mar) Flow, cfs	Peak Summer (July - Sept) Flow, cfs
1915	206.0	149,300	3,000	1,090
1916	47.2	34,280	400	1,760
1917	125.0	90,180	105	5,180
1918	28.0	20,290	20	920
1919	128.0	93,010	56	6,050
1920	57.2	41,760	590	860
1921	140.0	101,500	9	6,700
1922	50.4	36,500	23	1,900
1923	58.3	42,230	33	3,080
1924	34.8	25,260	562	524
1925	50.8	36,790	14	2,400
1926	170.0	122,700	38	98,000
1927	1.4	51,660	60	2,050
1928	27.7	20,070	27	350
1929	74.7	54,070	64	3,650
1930	73.9	53,500	65	3,590
1931	89.7	64,960	476	4,090
1932	63.3	45,940	717	1,720
1933	38.9	28,140	102	1,430
1934				
1935	2000			
1936	61.6	44,700	630	3,400
1937	77.3	55,980	38	3,880
1938	47.8	34,610	58	2,290
1939	68.8	49,800	625	3,080
1940	80.6	58,490	163	9,100
1941	56.3	40,730	1,720	2,530
1942	32.8	23,720	164	852
1943	65.8	47,620	21	2,910
1944	33.5	24,300	43	1,240
1945	52.2	37,820	31	3,190
1946	46.3	33,490	25	3,760
1947	44.6	32,290	20	2,920
1948	45.7	33,170	24	1,530
1949	65.2	47,180	263	1,880
1950	43.4	31,430	72	1,950
1951	27.2	19,660	19	1,010
1952	26.0	26,140	16	1,840
1953	39.2	28,400	60	3,330
1954	120.0	86,730	16	5,690
1955	120.0	86,910	23	4,050
1956	28.2	20,500	25	1,330
1957	31.0	22,430	73	1,400
1958	103.0	74,740	29	3,890
1959	60.9	44,070	30	3,960
1960	33.5	24,300	1,250	470
1961	30.9	22,390	21	1,010
1962	18.3	13,280	156	457

Table 10 continued.

Peak Winter Water Year	Mean Discharge, cfs	Total Runoff, Ac - ft.	Peak Summer (Nov - Mar) Flow, cfs	(July - Sept) Flow, cfs
1963	46.4	33,630	14	2,130
1964	75.6	54,910	45	5,510
1965	22.3	16,130	23	929
1966	50.5	36,590	508	1,230
1967	32.8	23,720	16	1,620
1968	35.6	25,850	2,400	404
1969	24.0	17,360	15	861
1970	36.3	26,280	20	1,780
1971	70.4	50,980	19	2,200
1972	34.1	24,780	26	2,060
1973	28.4	20,550	484	574
1974	53.2	38,530	26	3,410
1975	30.7	22,230	18	1,550
1976	35.2	25,530	67	1,400
1977	35.0	25,330	25	841
1978	119.0	86,090	263	23,700
1979	113.0	81,630	7,750	482
1980	13.2	9,590	23	287
1981	25.6	18,530	11	656
1982	23.1	16,740	12	1,830
1983	41.3	29,870	865	665
1984	122.0	88,870	524	2,930
1985	70.5	51,050	6,090	1,,950

Table 11. Annual flow summaries, San Pedro River at Charleston.

		n	mean	SD
Mean Annual Discharge, cfs,	1905 - 1930:	19	81.29	50.83
	1931 - 1985:	53	52.83	28.66
	1905 - 1985:	72	60.34	37.63
Mean Total Runoff, Ac - ft.	1905 - 1985:	72	43,707.22	27,242.57
	1931 - 1985:	53	38,277.17	20,765.38
Median Mean Annual Discharge, cfs,	1905 - 1985:	49.10		
	1931 - 1985:	44.60		
Mean Winter Peak Flow,	1905 - 1930:	19	373.42	706.23
Mean Summer Peak Flow,	1905 - 1930:	19	3,844.05	6,334.84
Mean Winter Peak Flow,	1905 - 1985:	72	461.79	1,227.70
Mean Summer Peak Flow,	1905 - 1985:	73	3,781.85	10,384.58
Mean Winter Peak Flow,	1931 - 1985:	53	493.47	1,371.65
Mean Summer Peak Flow,	1931 - 1985:	54	3,759.96	11,526.84

Monthly Flows

Monthly flows in the San Pedro River in the study area are distributed bimodally over a water year. The highest monthly flows occur in the July-September summer period. A secondary period of high flows occur during the December to March winter period. The lowest flow months are the April to June spring period. A somewhat higher low-flow period occurs in the October-November fall period. In addition, daily flow distributions—particularly during the higher-flow months—are highly skewed. Mean monthly flows during these periods are strongly influenced by a small number of extremely high-flow days.

Mean monthly flows at the three streamgages are summarized in Table 12. Mean monthly flows provide a good index of average monthly runoff volumes. As indicated by the range and standard deviation statistics, mean monthly flows are highly variable from year to year.

Median monthly flows for all three streamgages are given in Table 13. Average median monthly flow is a good indication of daily flows likely to be encountered in any given month. Because of the skewed nature of daily flow distributions, median monthly flows are considerably lower than the corresponding mean monthly flow. Median monthly flows are also highly variable from year to year, as indexed by the range and standard deviation statistics, but are somewhat less variable than mean monthly flow.

Table 12. San Pedro River average mean monthly discharge in cfs (1931-1983).

MONTH	DISCHARGE								
	Palominas			Charleston			Tombstone (1967-84)		
	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
Oct.	25.5	121.0	0-770	36.4	150	3.4-1087	99.0	262.0	0-998
Nov.	5.1	7.7	0-43	14.9	9	5.6-62	14.6	14.0	2.8-61
Dec.	22.2	70.0	.1-414	31.2	62	8.6-429	50.0	99.0	6.4-375
Jan.	22.9	73.0	.04-452	33.5	72	9.7-507	52.5	109.0	9.7-450
Feb.	11.5	16.0	.07-73	25.3	22	9-112	41.2	54.0	9.1-214
Mar.	8.4	14.0	.22-76	21.4	19	9-110	36.4	44.0	9.1-179
Apr.	2.9	3.0	0-15	12.4	5	6-31	13.3	7.0	4.2-29
May	1.3	2.0	0-7	8.3	3	3.9-15	7.3	3.8	1.6-17
June	4.1	6.0	0-23	10.5	14	1.3-89	3.9	6.0	0-22
July	89.8	71.0	3-280	122.4	93	6-359	113.0	105.0	1.8-369
Aug.	151.0	162.0	3-591	230.0	226	10-968	158.0	192.0	14.7-820
Sept.	35.7	51.0	.3-275	64.0	69	4.1-350	56.4	56.8	.09-177

Table 13. San Pedro River average median monthly discharge in cfs (1931-1983).

MONTH	DISCHARGE								
	Palominas			Charleston			Tombstone (1967-84)		
	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
Oct.	3.7	5.9	0-30	12.2	11.9	3-80	13.0	19.0	0-55
Nov.	3.6	3.8	0-14	13.6	5.5	5.8-25	12.2	7.6	2.3-29
Dec.	5.5	5.5	0-16	17.1	6.4	8.5-37	20.2	19.2	7.3-88
Jan.	10.9	26.7	0-1682	23.5	31.1	9.5-230	35.8	52.5	10-229
Feb.	8.6	—	.19-70	20.3	12.3	9.5-80	32.1	28.7	9.1-108
Mar.	6.3	9.7	.01-51	18.9	12.4	9.5-76	29.1	23.1	9.1-179
Apr.	2.5	3.0	0-12	12.2	5.0	6.1-24	15.7	11.1	4.2-29
May	1.2	1.6	0-8	7.9	2.4	3.6-15	1.4	4.4	1.6-17
June	0.6	0.8	0-3.2	4.2	2.1	1.5-12	30.0	2.9	0-22
July	15.7	23.0	0-102	29.1	29.8	0.8-137	67.2	39.2	1.8-369
Aug.	51.9	77.0	5-443	91.6	105.7	4.2-586	18.4	109.6	3.4-464
Sept.	10.7	18.0	0-91	24.2	24.6	3.8-140	18.4	15.2	.56 at-46

Annual Daily Flow Duration

Annual mean daily flow-duration curves were developed for the San Pedro River at the Palominas, Charleston, and Tombstone streamgages (Figures 22a to c). The curves show discharge plotted against the average percent of the time (in terms of days in a year) that that discharge was equaled or exceeded. Thus, the curves indicate the average duration of both high and low flows and the 50 percent discharge is equivalent to the median daily discharge over a 1-year period.

Median daily flows averaged 2 cfs at Palominas, 14 cfs at Charleston, and 12 cfs at Tombstone. At Palominas, discharge is less than 1 cfs about 37 percent of the time, and greater than 100 cfs less than 5 percent of the time. At Charleston, discharge is less than 10 cfs about 30 percent of the time, and greater than 100 cfs less than 10 percent of the time. At Tombstone, discharge is less than 1 cfs over 10 percent of the time, and greater than 100 cfs about 7 percent of the time. The flow duration curves again illustrate the highly skewed nature of daily flows and the predominance, over the year, of relatively low daily flows.

High Flows

Annual peak flows for both the July-September and the December-March high-flow periods are summarized in Table 10. Average summer period peak flow was 3,782 cfs at Charleston. Summer period annual peak flows ranged from 287 cfs to 86,090 cfs at Charleston. Winter period annual peak flows ranged from 11 cfs to 7,750 cfs at Charleston. In all but 2 years, the annual summer period peak flow was larger than the annual winter period peak flow.

Figure 22. Annual mean daily flow-duration curves for the San Pedro River at (a) Palominas, (b) Charleston, and (c) Tombstone.

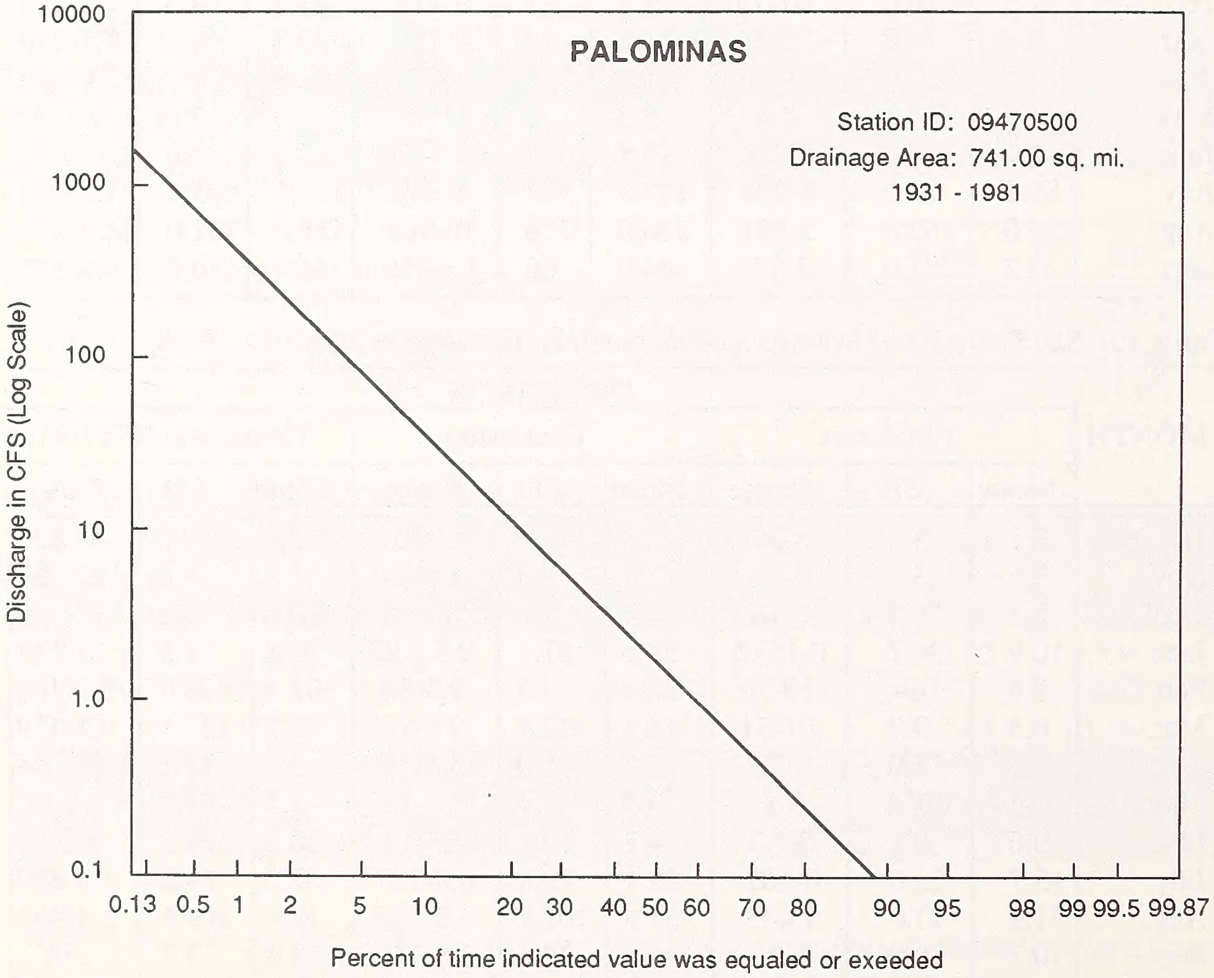


Figure 22a.

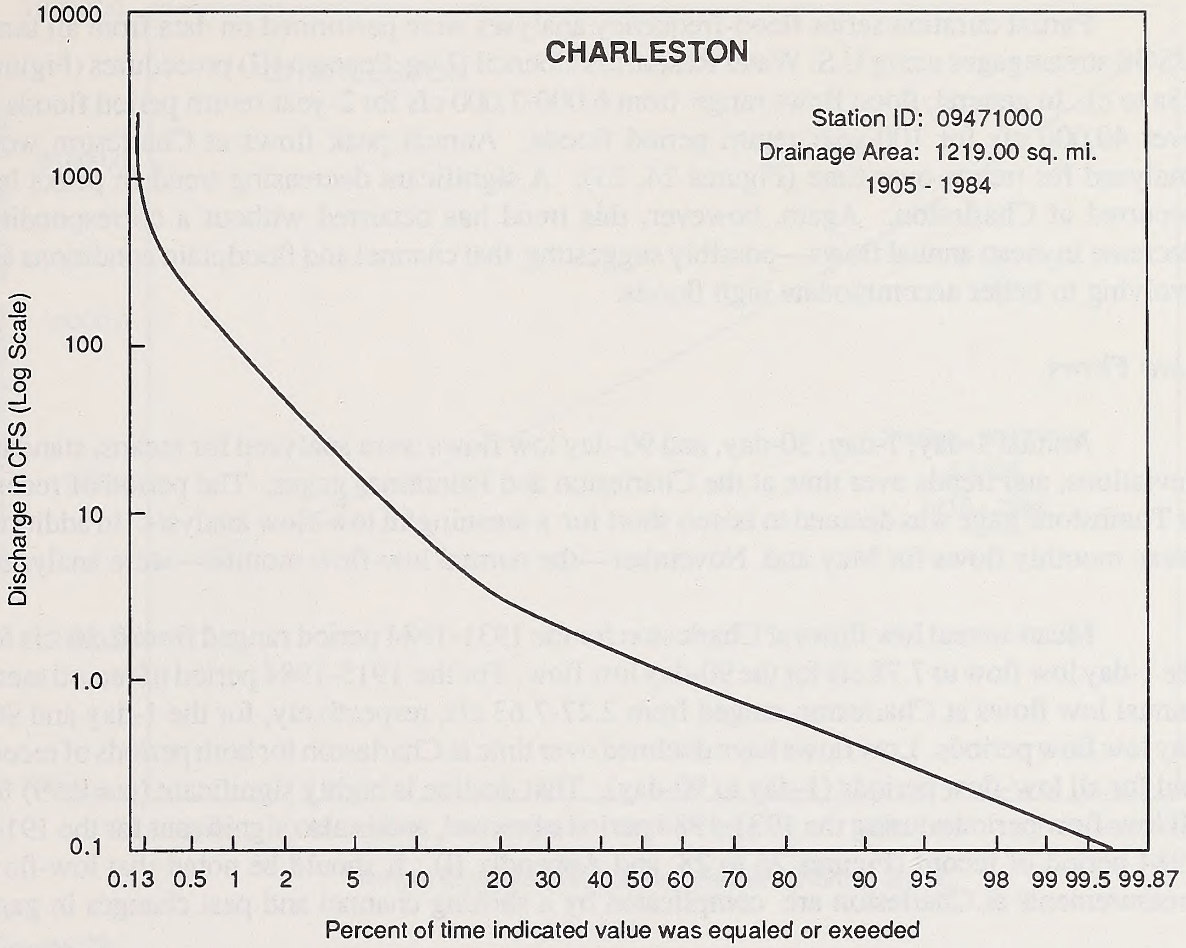


Figure 22b.

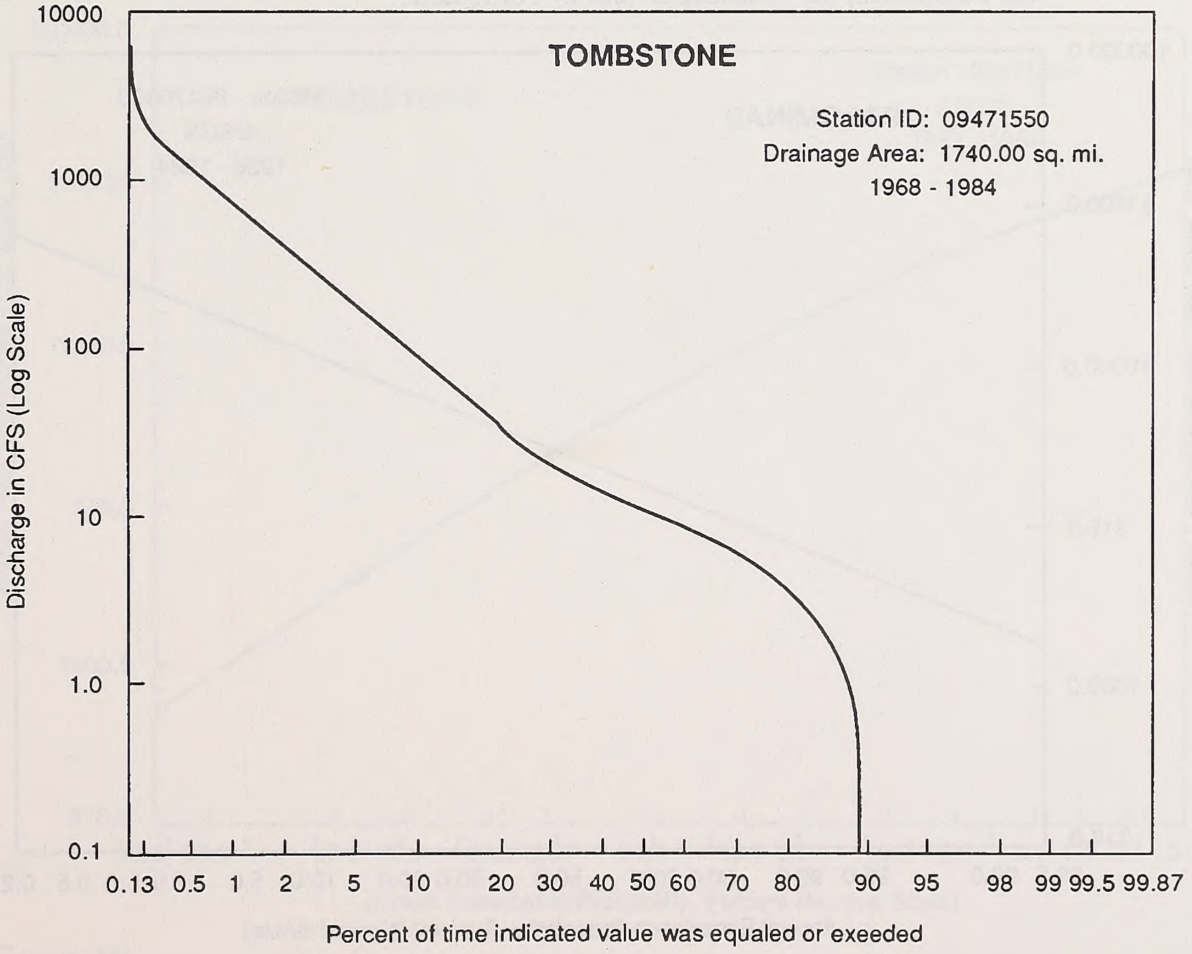


Figure 22c.

Partial duration series flood-frequency analyses were performed on data from all three USGS streamgages using U.S. Water Resources Council (Log Pearson III) procedures (Figures 23a to c). In general, flood flows range from 6,000-7,000 cfs for 2-year return period floods to over 40,000 cfs for 100-year return period floods. Annual peak flows at Charleston were analyzed for trends over time (Figures 24, 25). A significant decreasing trend in peaks has occurred at Charleston. Again, however, this trend has occurred without a corresponding decrease in mean annual flows—possibly suggesting that channel and floodplain conditions are evolving to better accommodate high floods.

Low Flows

Annual 1-day, 7-day, 30-day, and 90-day low flows were analyzed for means, standard deviations, and trends over time at the Charleston and Palominas gages. The period of record at Tombstone gage was deemed to be too short for a meaningful low-flow analysis. In addition, mean monthly flows for May and November—the normal low-flow months—were analyzed.

Mean annual low flows at Charleston for the 1931-1984 period ranged from 2.36 cfs for the 1-day low flow to 7.78 cfs for the 90-day low flow. For the 1915-1984 period of record mean annual low flows at Charleston ranged from 2.27-7.63 cfs, respectively, for the 1-day and 90-day low flow periods. Low flows have declined over time at Charleston for both periods of record and for all low-flow periods (1-day to 90-day). That decline is highly significant (p = 0.99) for all low-flow periods during the 1931-1984 period of record, and is also significant for the 1914-1984 period of record (Figures 26 to 28, and Appendix II). It should be noted that low-flow measurements at Charleston are complicated by a shifting channel and past changes in gage

Figure 23. Log Pearson III flood-frequency relationship for the San Pedro River at (a) Palominas, (b) Charleston, and c) Tombstone.

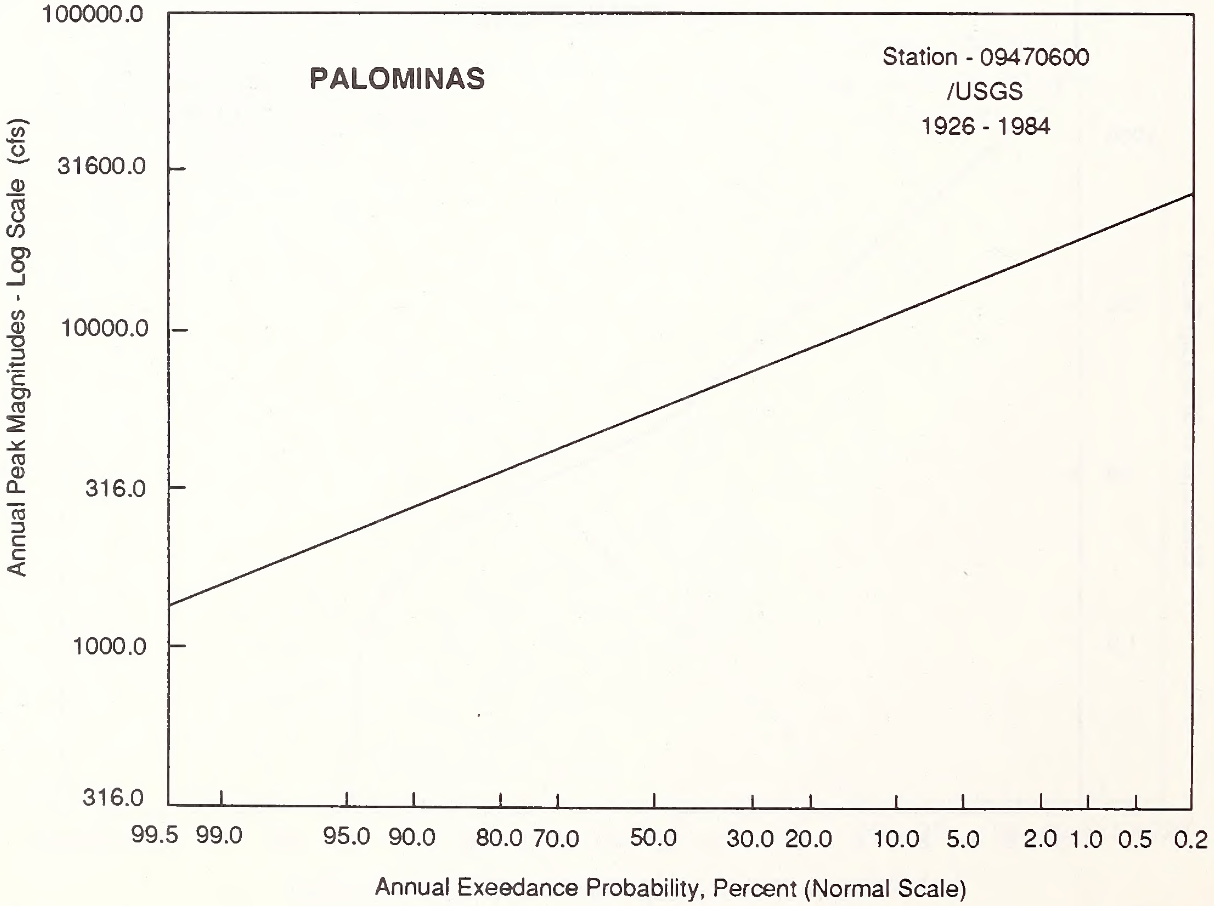


Figure 23a.

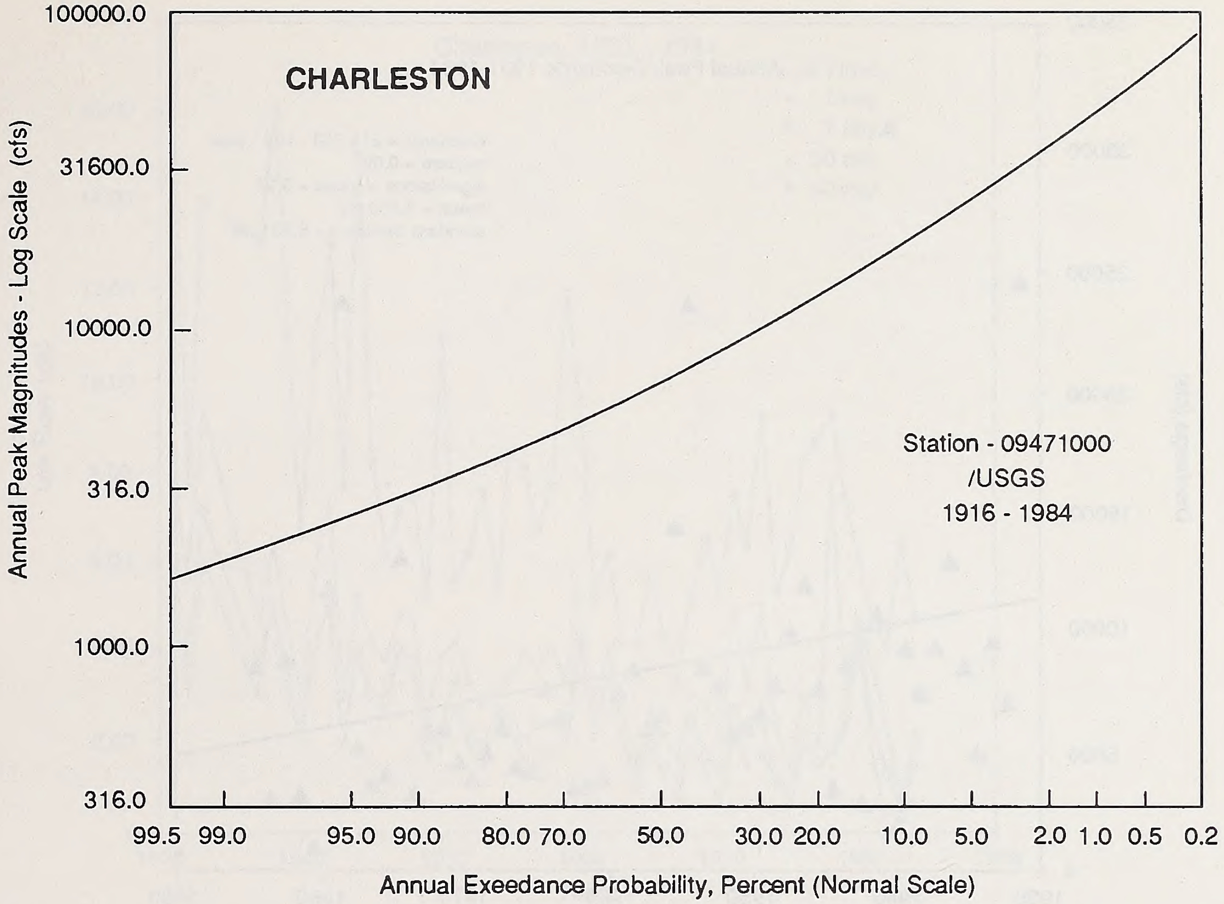


Figure 2b.

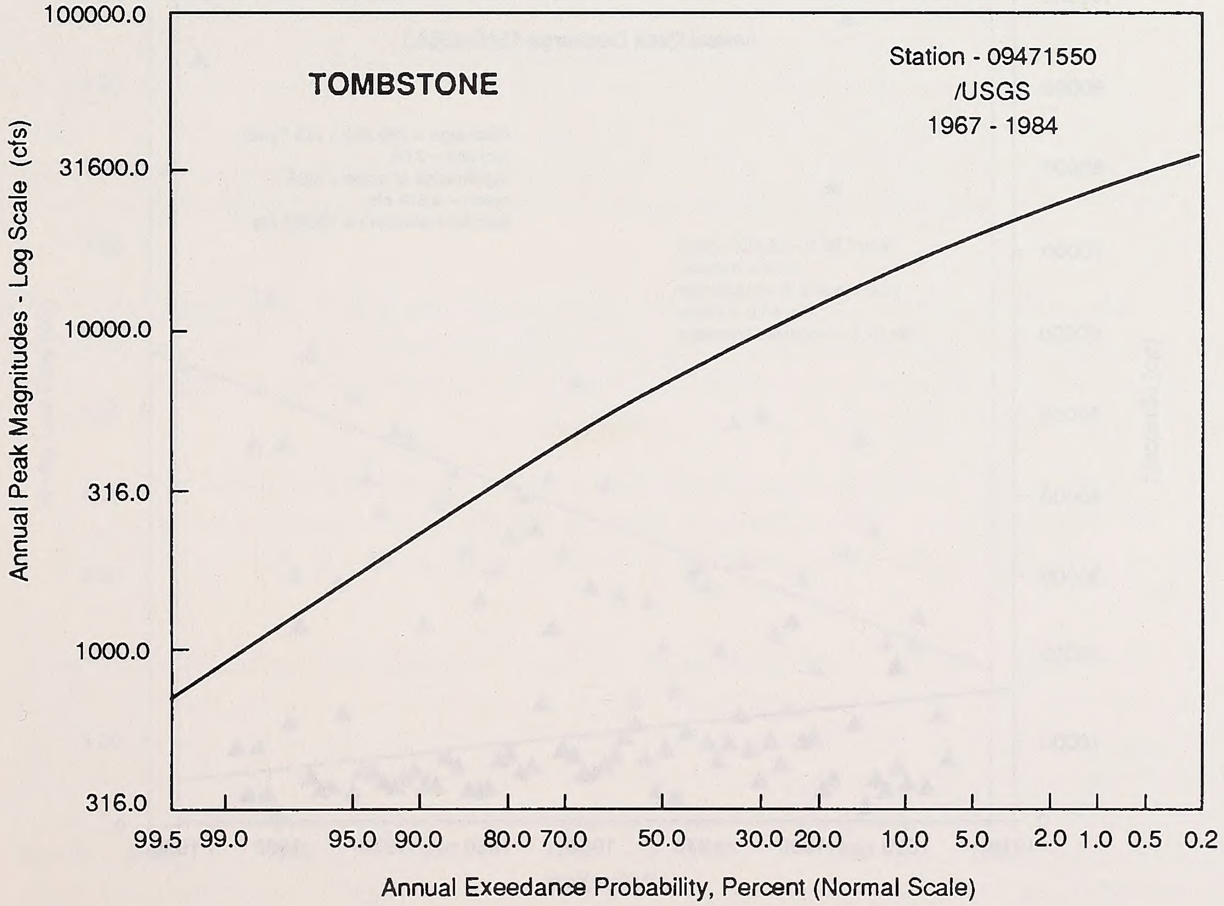


Figure 23c.

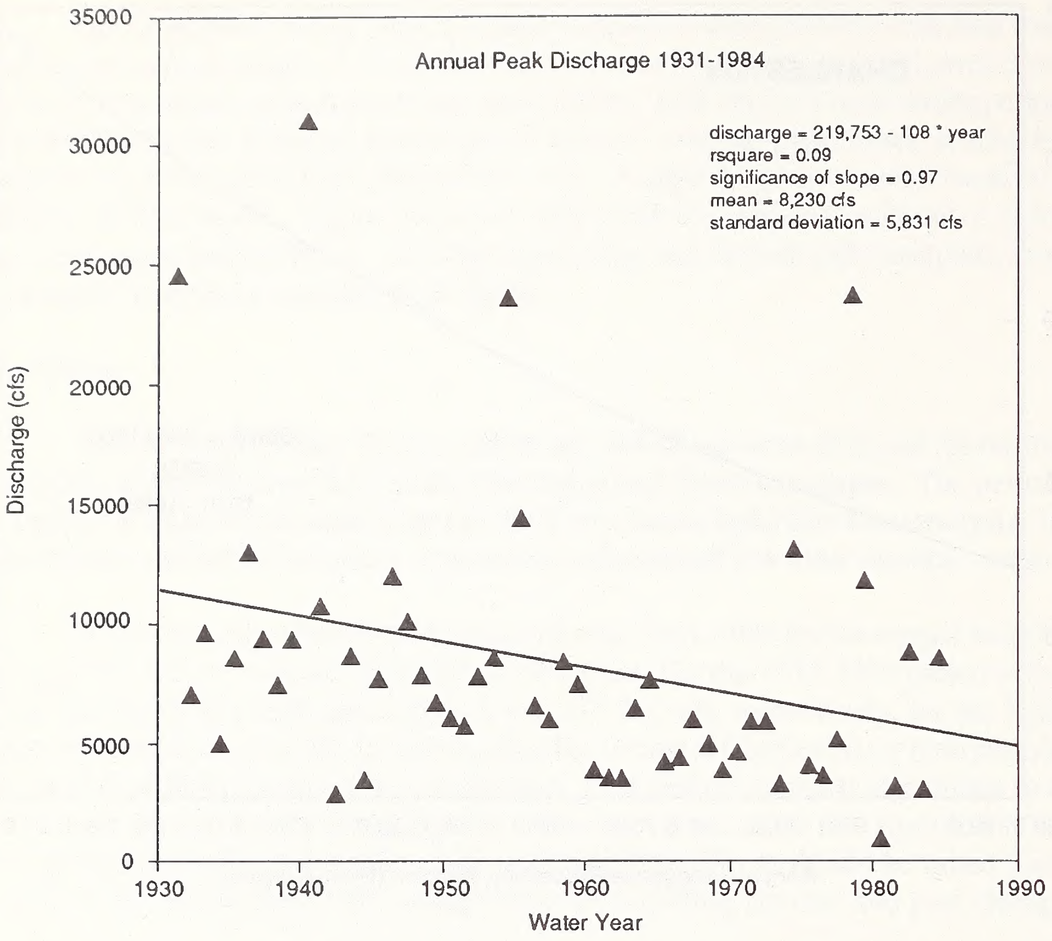


Figure 24. Trends in annual peak flow, 1931-1985, San Pedro River at Charleston.

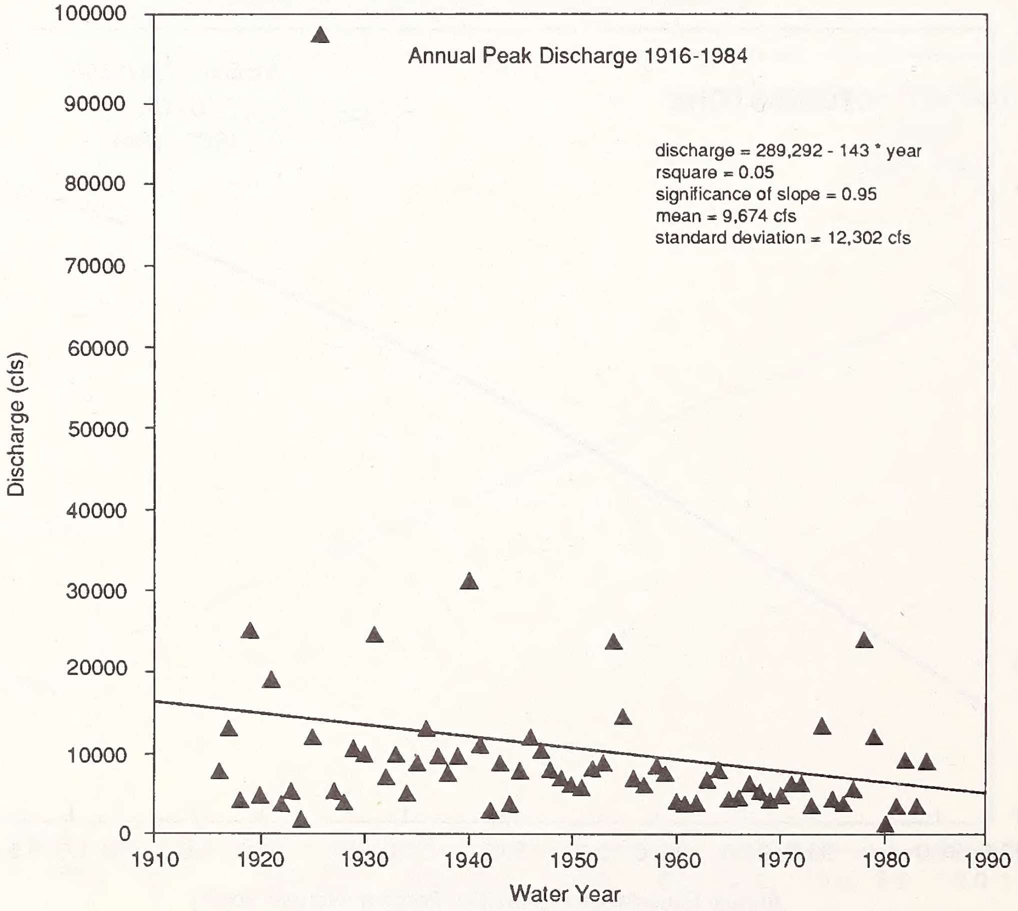


Figure 25. Trends in annual peak flow, 1916-1984, San Pedro River at Charleston.

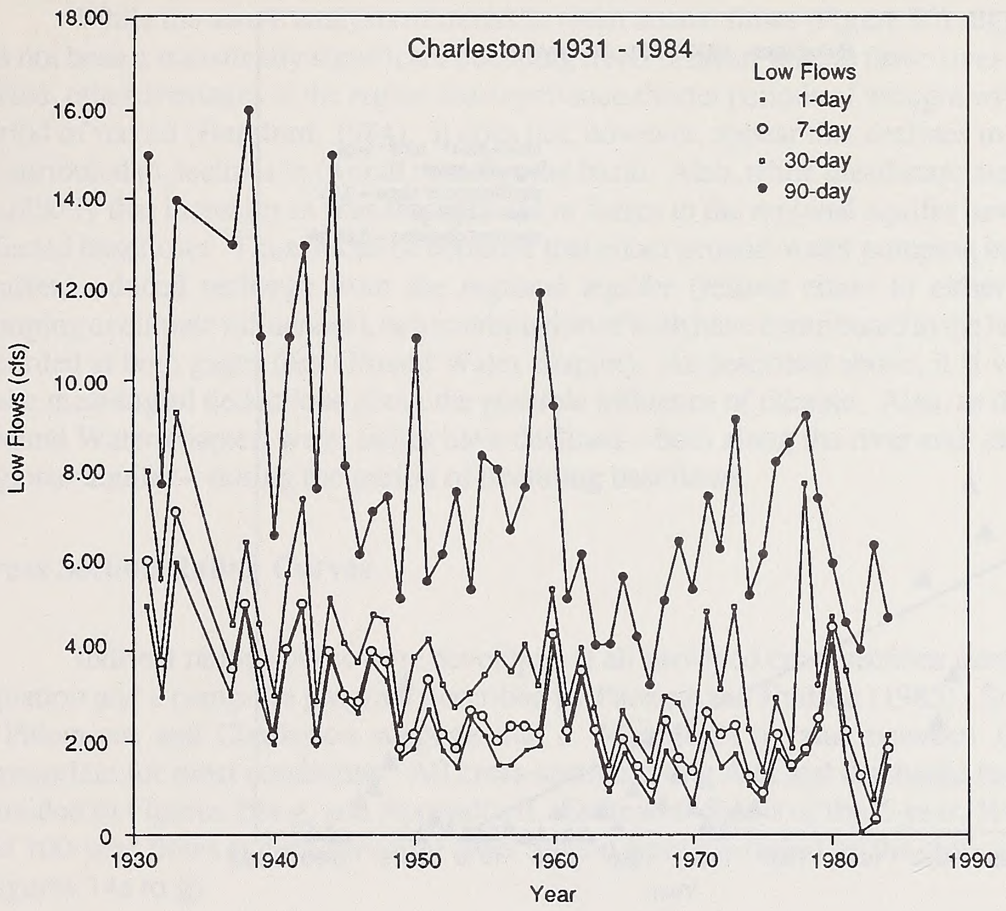


Figure 26. 1-day, 7-day, 30-day, and 90-day low flows for the San Pedro River at Charleston, 1931-1984.

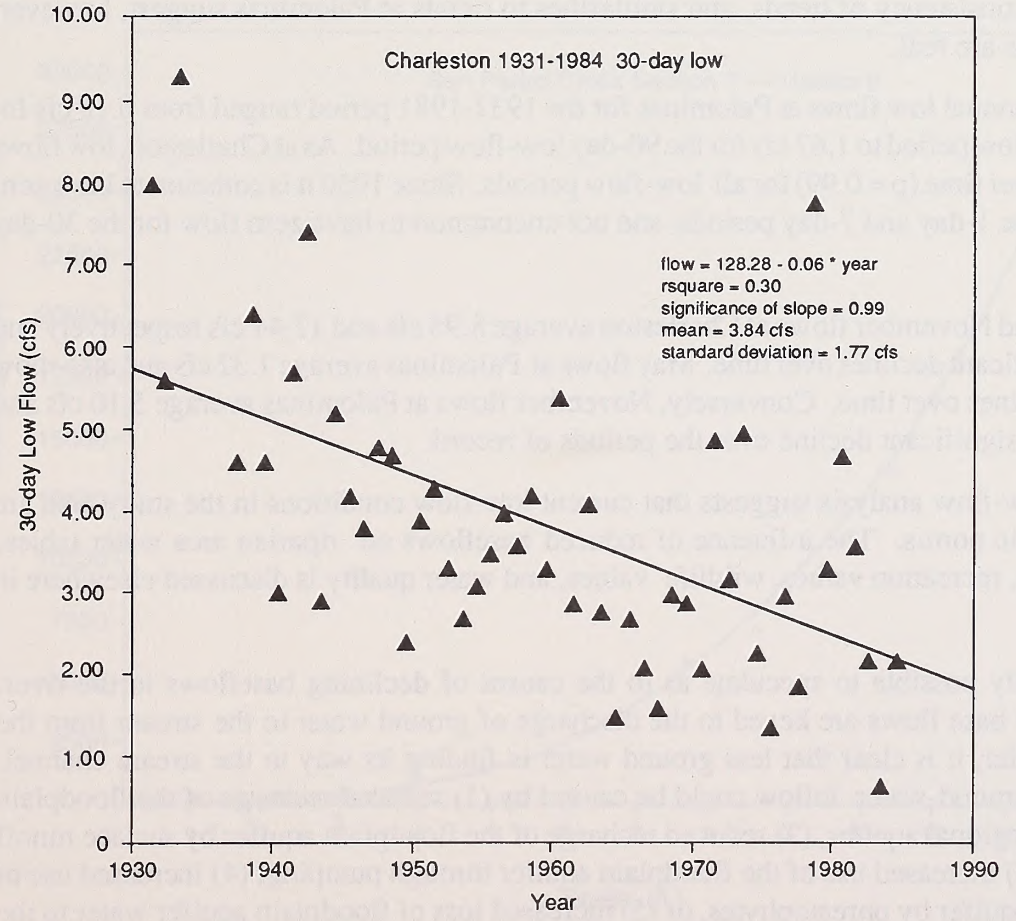


Figure 27. Trend in 30-day low flow for the San Pedro River at Charleston, 1931-1984.

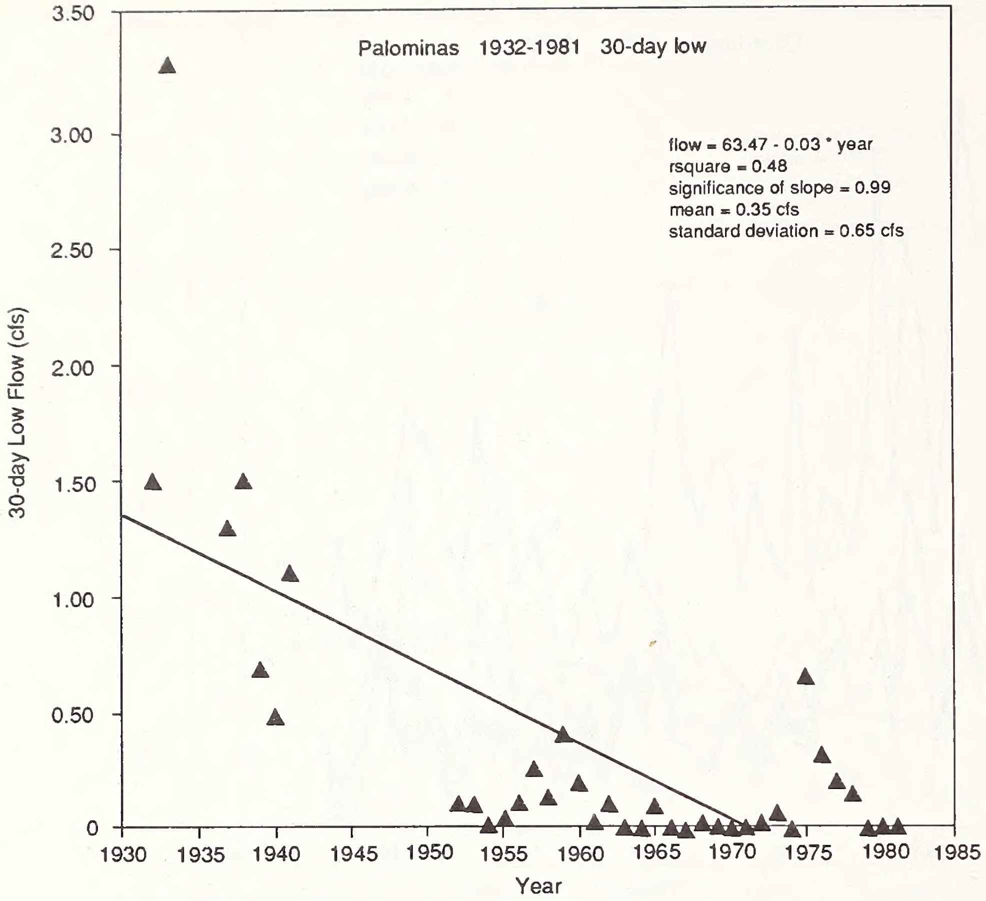


Figure 28. Trend in 30-day low flow for the San Pedro River at Palominas, 1932-1981.

location. The consistency of trends, and similarities to trends at Palominas suggest, however, that these trends are real.

Mean annual low flows at Palominas for the 1932-1981 period ranged from 0.18 cfs for the 1-day low-flow period to 1.67 cfs for the 90-day low-flow period. As at Charleston, low flows are declining over time (p = 0.99) for all low-flow periods. Since 1950 it is common to have zero flow for both the 1-day and 7-day periods, and not uncommon to have zero flow for the 30-day period.

May and November flows at Charleston average 8.96 cfs and 17.44 cfs respectively and also show significant declines over time. May flows at Palominas average 1.32 cfs and also show significant declines over time. Conversely, November flows at Palominas average 5.10 cfs and do not show a significant decline over the periods of record.

The low-flow analysis suggests that current low-flow conditions in the study area are less than historic norms. The influence of reduced baseflows on riparian area water tables, fisheries values, recreation values, wildlife values, and water quality is discussed elsewhere in this report.

It is only possible to speculate as to the causes of declining baseflows in the river. However, since base flows are keyed to the discharge of ground water to the stream from the floodplain aquifer, it is clear that less ground water is finding its way to the stream channel. Reductions in ground-water inflow could be caused by (1) reduced recharge of the floodplain aquifer by the regional aquifer, (2) reduced recharge of the floodplain aquifer by surface runoff (high flows), (3) increased use of the floodplain aquifer through pumping, (4) increased use of the floodplain aquifer by phreatophytes, or (5) increased loss of floodplain aquifer water to the regional aquifer.

While the above analysis of trends in mean annual flows (Figure 20) suggests that there has not been a statistically significant declining trend in mean annual flows over the 1931-1985 period, other drainages in the region did experience shorter periods of drought within this longer period of record (Hereford, 1984). It does not, however, appear that declines in baseflows can be attributed to declines in overall runoff in the basin. Also, while unsubstantiated, we consider it unlikely that increases in phreatophyte use or losses to the regional aquifer have significantly affected baseflows. Thus, it can be deduced that either ground-water pumping in the floodplain aquifer, reduced recharge from the regional aquifer (related either to either ground-water pumping or climate influences), or a combination of both have contributed to the lower baseflows recorded at both gages (see Ground Water chapter). As described above, it is very difficult to make meaningful deductions about the possible influence of climate. Also, as described in the Ground Water chapter, water tables have declined—both along the river and elsewhere in the regional aquifer—during the period of declining baseflows.

Cross Section Rating Curves

Indirect rating curves were developed at all surveyed cross sections using the Manning Equation and a computer program described by Parsons and Hudson (1985). Streamgage data at Palominas and Charleston suggests that a Manning's n value between .02 and .025 is appropriate for most conditions. All cross-section rating data and discharge rating curves are provided in Figures 29a-g, and Appendix II. Estimated depths of the 2-year, 10-year, 50-year, and 100-year flows at each surveyed cross section were overlayed on the cross-section profiles (Figures 14a to g).

Figure 29. (a-g) Indirect discharge rating curves for San Pedro River cross sections.

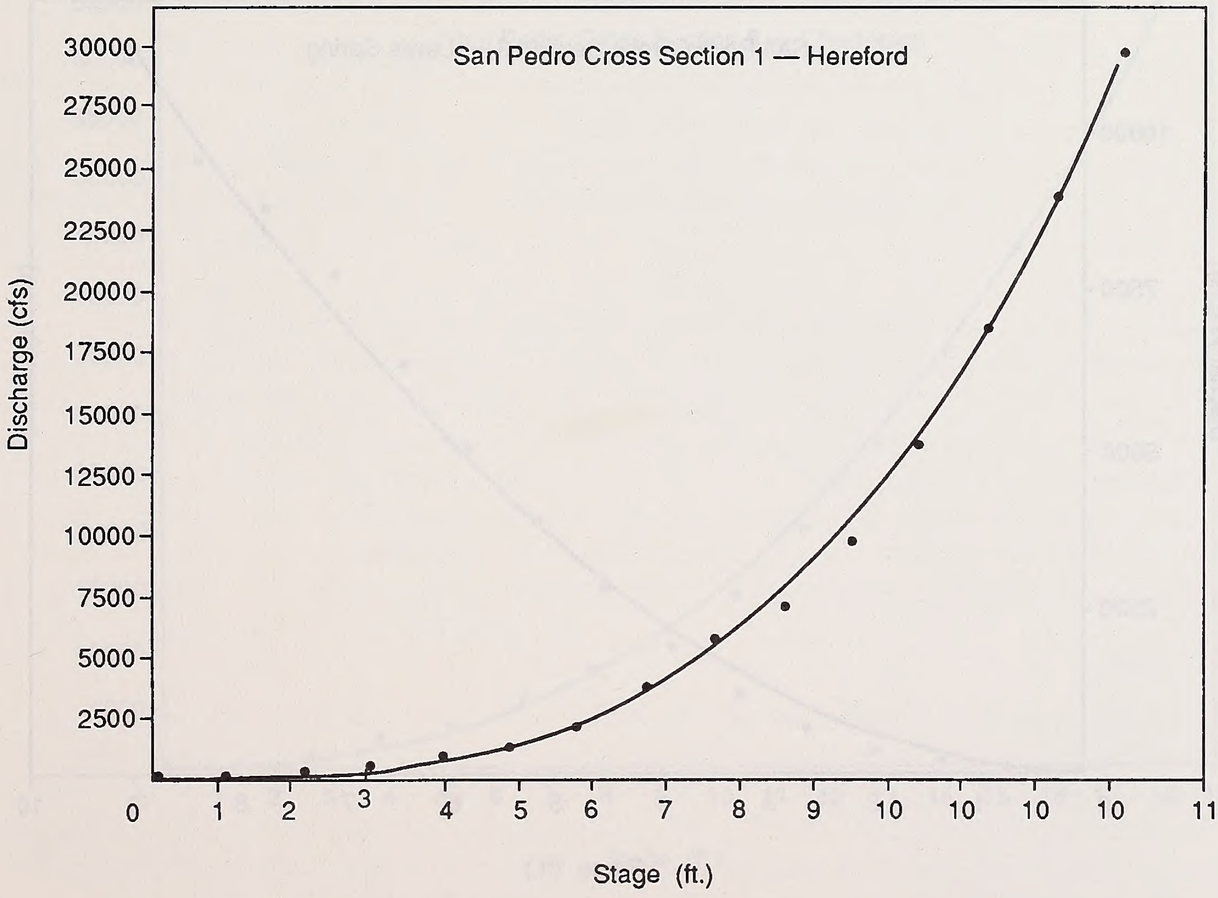


Figure 29a.

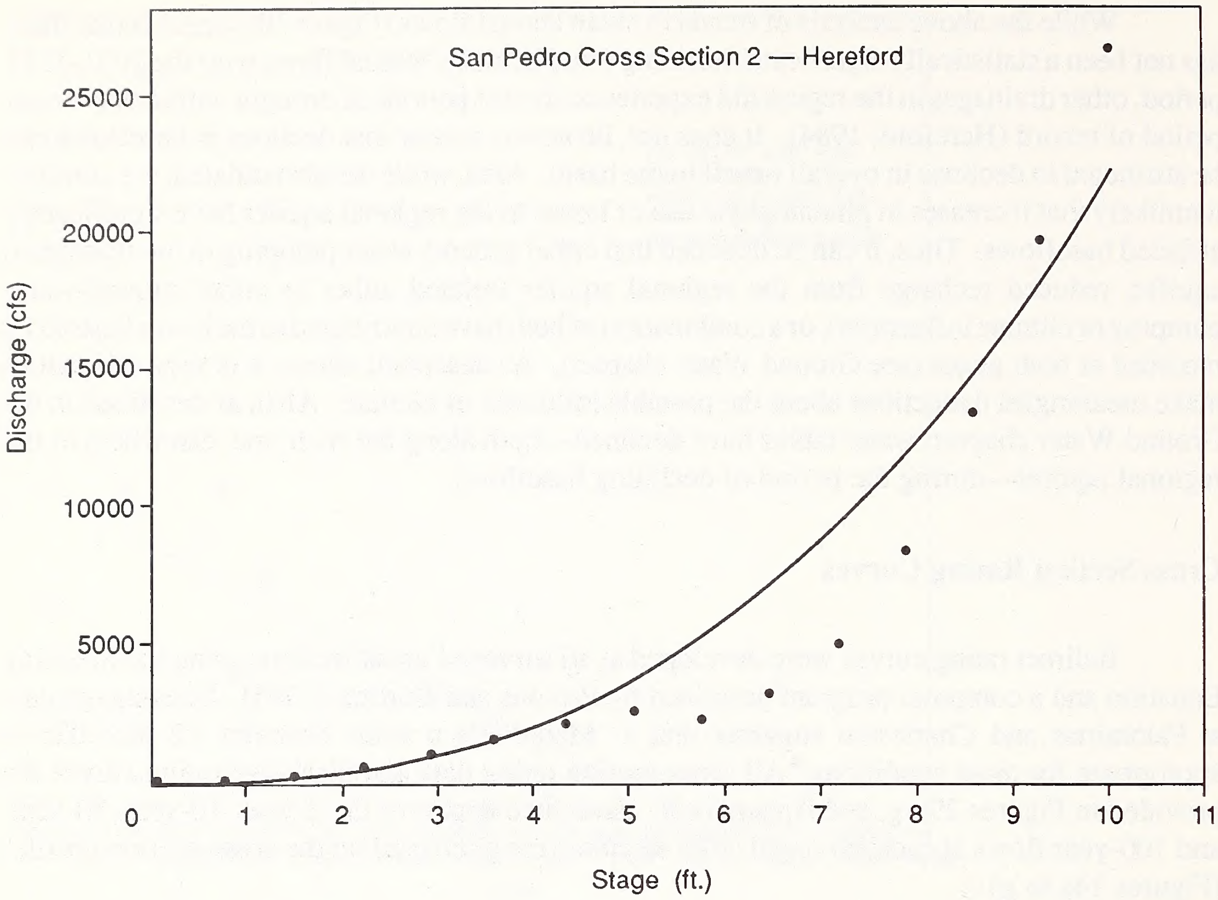


Figure 29b.

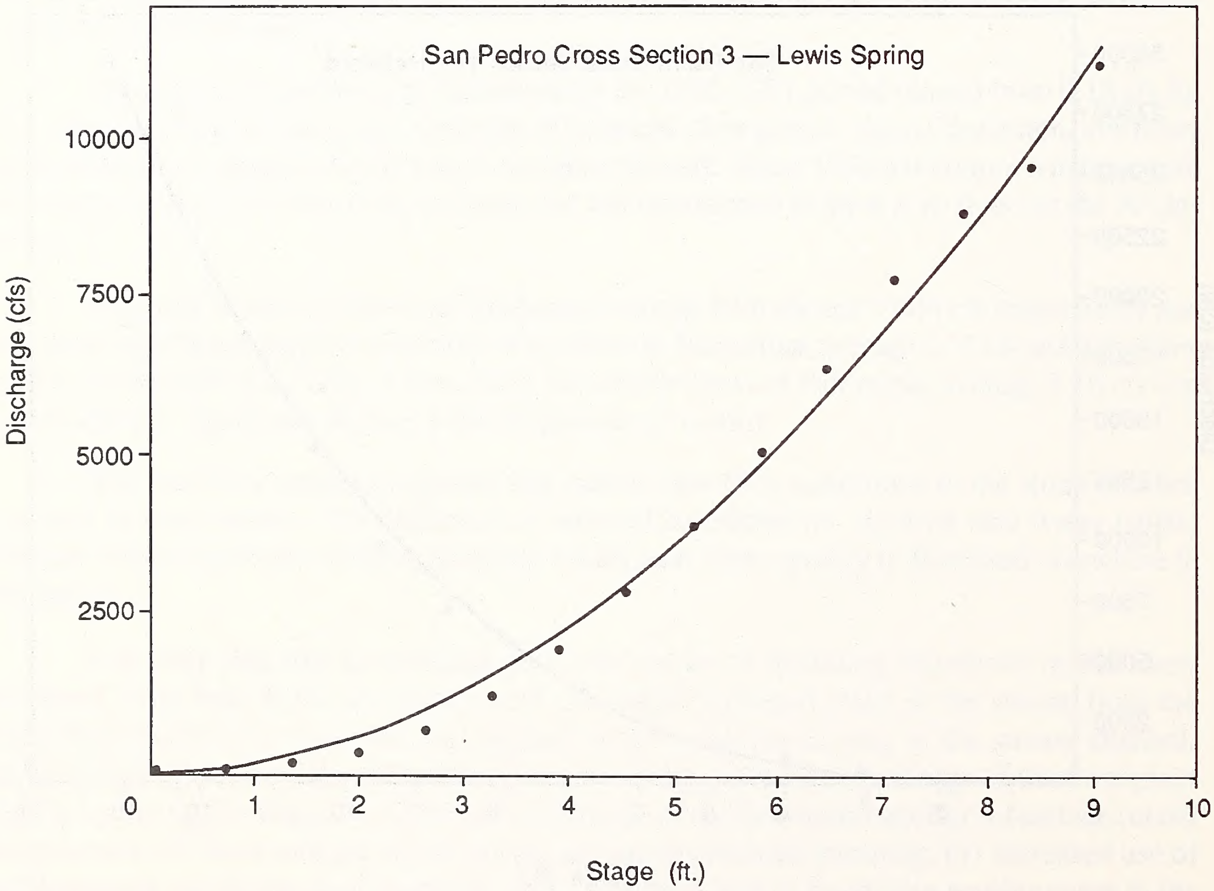


Figure 29c.

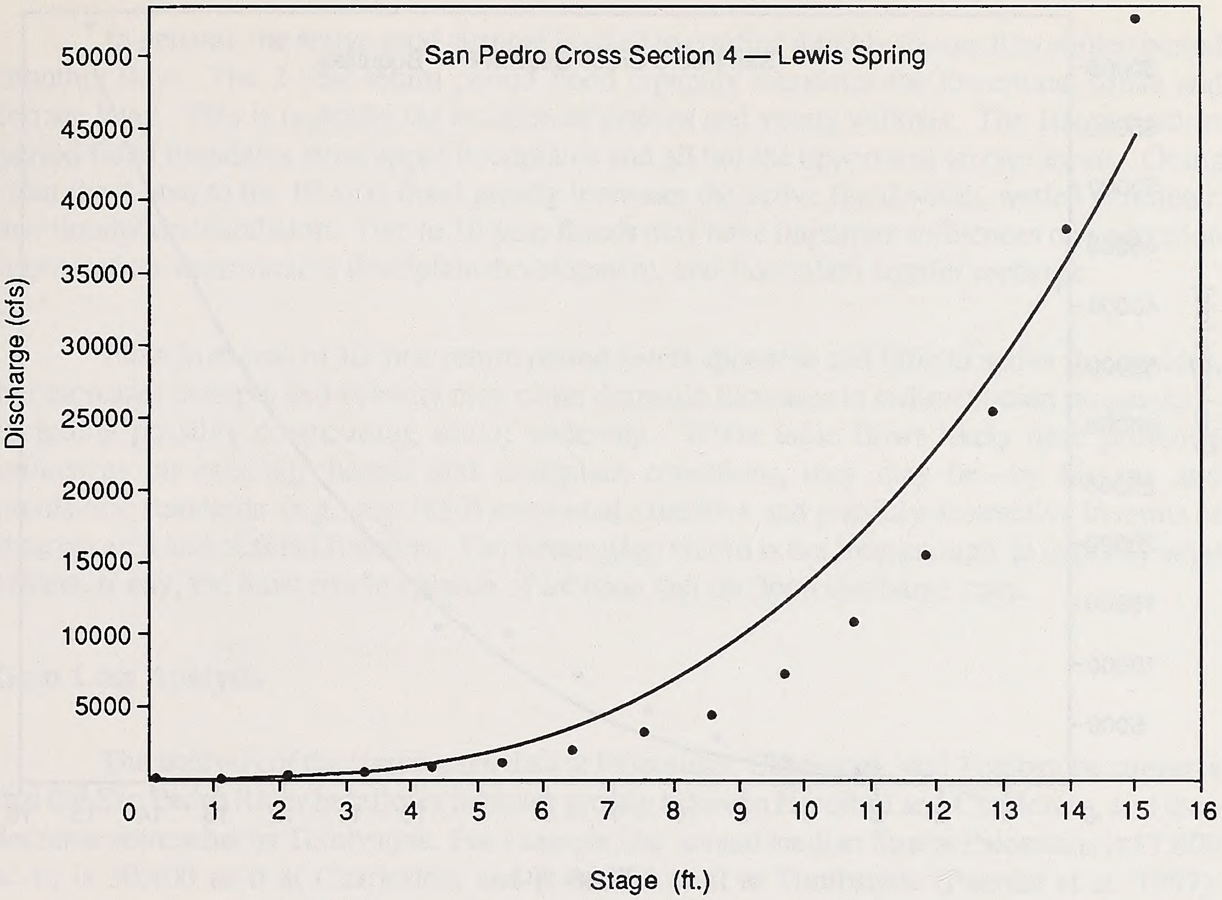


Figure 29d.

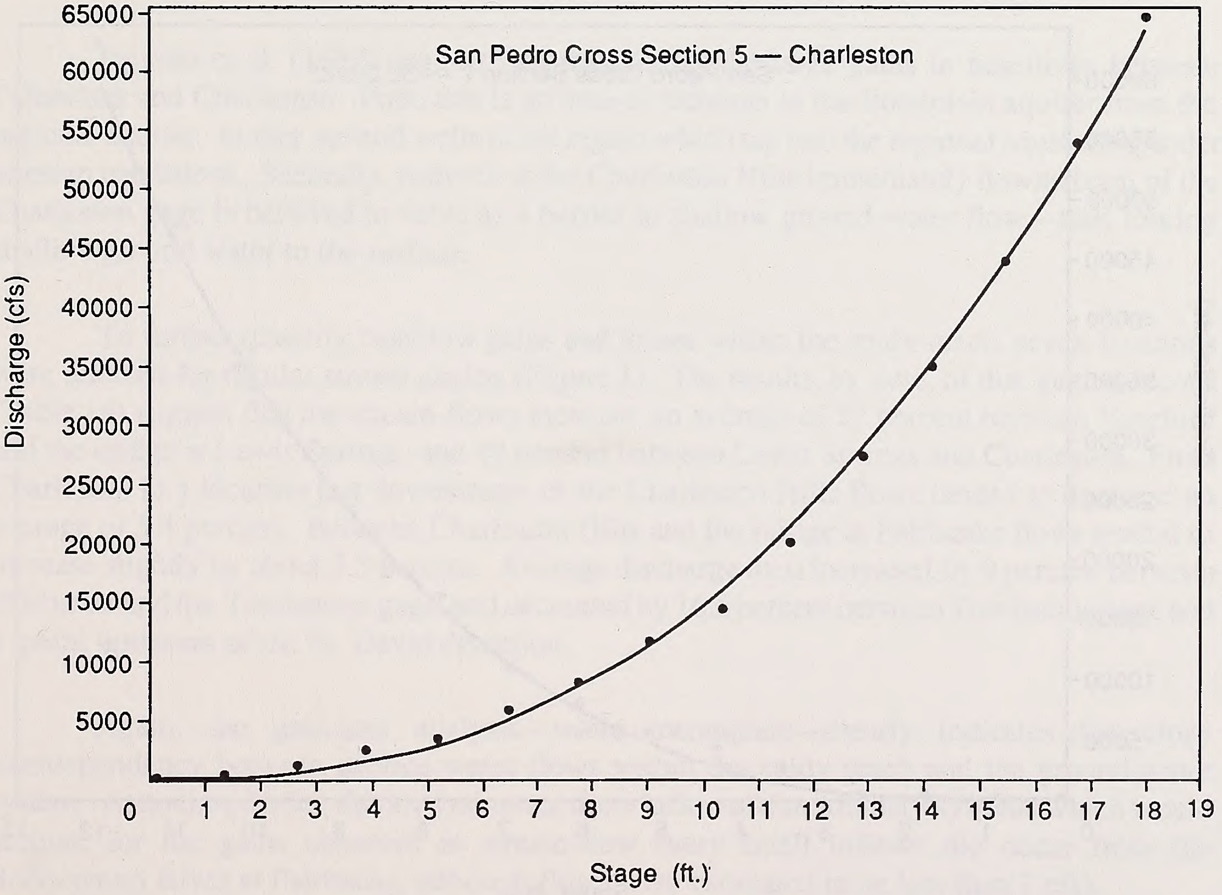


Figure 29e.

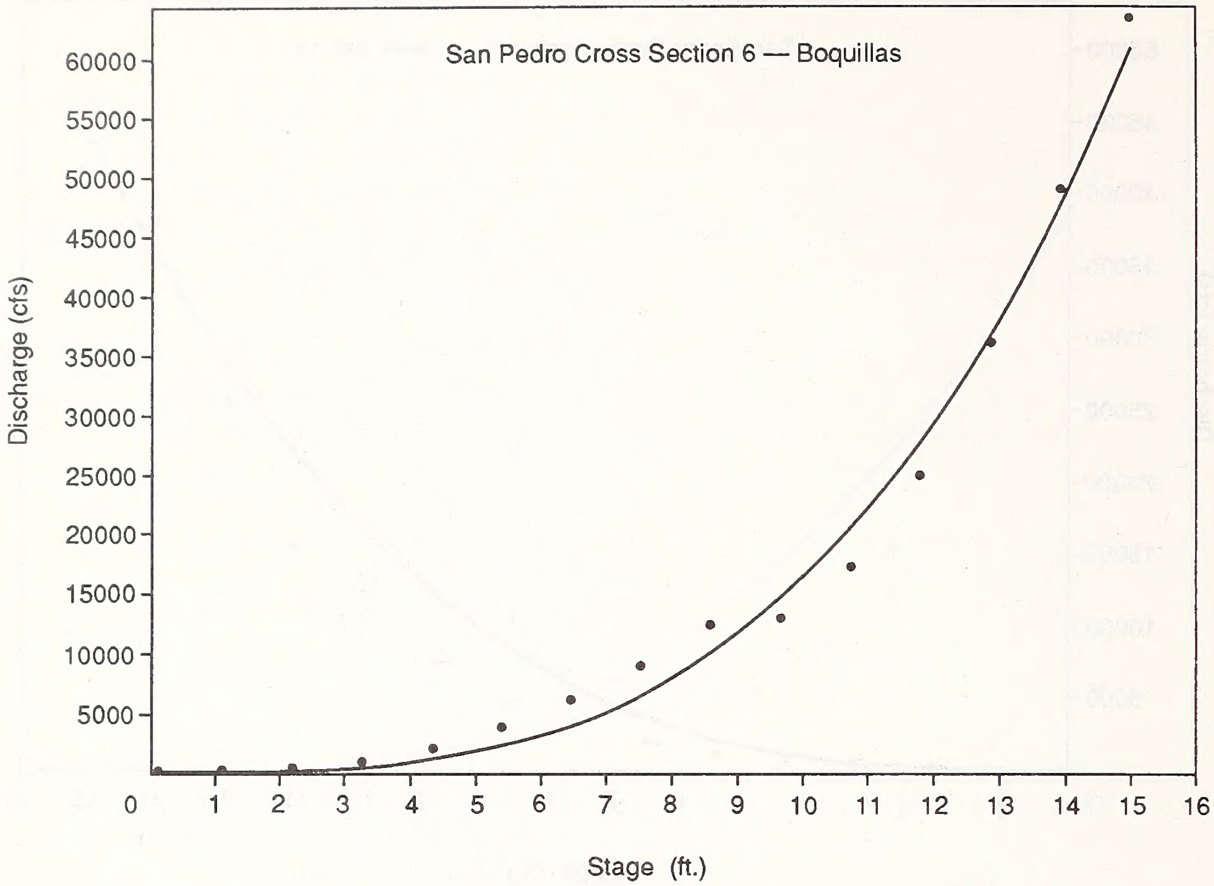


Figure 29f.

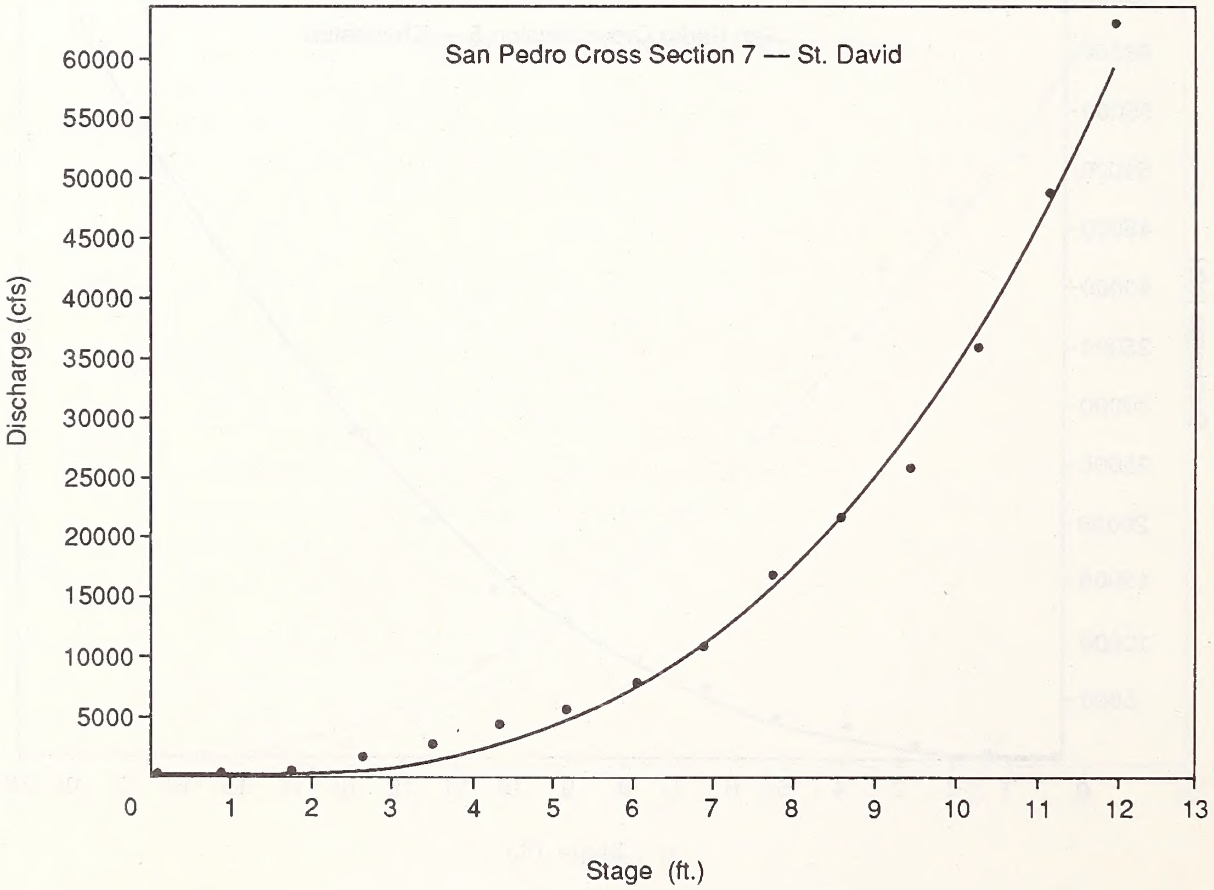


Figure 29g.

In general, the active sand channel is sized to confine roughly the median winter-period monthly flow. The 2-year return period flood typically inundates the lowermost banks and terrace level. This is typically the location of grasses and young willows. The 10-year return period flood inundates most upper floodplains and all but the uppermost terrace levels. Going from the 2-year to the 10-year flood greatly increases the active flood width, wetted perimeter, and floodplain inundation. Two to 10-year floods may have important influences on vegetation regeneration, constructive floodplain development, and floodplain aquifer recharge.

Flow in excess of 10-year return period levels appear to add little to active flood width, but increases in depth and velocity may cause dramatic increases in sedimentation processes—including possibly downcutting and/or widening. While these flows likely have profound influences on existing channel and floodplain conditions, they may be—by historic and prehistoric standards (e.g., pre-1880) somewhat excessive and possibly destructive in terms of riparian area and channel function. The streamgage record is not long enough to quantify what effects, if any, the most recent episode of incision had on flood discharge rates.

Gain-Loss Analysis

The analysis of the streamgage data at Palominas, Charleston, and Tombstone suggests that the San Pedro River baseflows increase greatly between Hereford and Charleston, and then decrease somewhat by Tombstone. For example, the annual median flow at Palominas is 17,800 ac-ft; is 30,400 ac-ft at Charleston; and is 34,300 ac-ft at Tombstone (Putman et al. 1987). Similarly, 1-day, 7-day, 30-day, and 90-day low flows as well as mean May and November flows were shown above to increase greatly between Palominas and Hereford. Putman et al. (1987) found the average monthly gain in the San Pedro River discharge between Palominas and Charleston for December-March of the 1967-1981 period to be 635 acre-feet per month.

Putman et al. (1987) suggest two reasons for the large gains in baseflows between Palominas and Charleston. First, this is an area of recharge to the floodplain aquifer from the regional aquifer. In fact, several wells in the region which tap into the regional aquifer are under artesian conditions. Secondly, bedrock at the Charleston Hills immediately downstream of the Charleston gage is believed to serve as a barrier to shallow ground-water flow—thus forcing shallow ground water to the surface.

To further quantify baseflow gains and losses within the study reach, seven locations were selected for regular stream gaging (Figure 1). The results, to date, of that gaging record (Table 14) suggest that the stream-flows increase an average of 27 percent between Hereford and the bridge at Lewis Springs, and 49 percent between Lewis Springs and Charleston. From Charleston to a location just downstream of the Charleston Hills flows tended to decrease an average of 5.4 percent. Between Charleston Hills and the bridge at Fairbanks flows tended to increase slightly by about 5.3 percent. Average discharge then increased by 9 percent between Fairbanks and the Tombstone gage, and decreased by 16.6 percent between Tombstone gage and a point upstream of the St. David diversion.

Again, the gain-loss analysis—while incomplete—clearly indicates the close interdependency between surface water flows within the study reach and the ground-water system. At no time during this analysis were there inflows from tributary systems which would account for the gains observed in stream-flow (very small inflows did occur from the Bobocomari River at Fairbanks, although flows were estimated to be less than 1 cfs).

Table 14. Downstream variations in surface discharge, San Pedro River, Arizona.

	Discharge, cfs						
Location	Hereford Bridge	Lewis Spring Bridge	Charleston Bridge	Below Charleston Hills	Fairbanks Bridge	Tombstone Gage	St. David Diversion
Date							
12-11-86	7.1	8.5	17.1	14.0	—	13.7	—
1-6-87	13.6	17.7	19.4	20.9	12.4		
1-23-87	12.4	16.7	25.3	22.1	26.8	23.6	13.4
2-5-87	11.0	12.7	20.8	18.2	19.5	20.9	18.2
3-3-87	17.4	19.4	28.3	25.4	28.4	31.1	—
3-19-87	11.0	13.5	20.2	19.9	20.7	23.7	—
4-1-87	8.9	11.2	18.3	18.9	19.7	20.4	17.8
4-15-87	8.2	10.1	15.8	15.9	15.2	16.9	13.9
4-30-87	9.4	15.1	15.7	16.1	15.0	16.9	17.6

GROUND WATER

HYDROGEOLOGIC SETTING

The objective of the ground-water evaluation performed here is to evaluate the dependency of the surface flow in the San Pedro River on ground-water contributions. The analysis is based upon existing geologic, hydrogeologic and hydrologic information which was used to form a conceptualization of the stream-aquifer system in the Upper San Pedro Basin. Additional investigation, which would include stream-depletion modeling, coupled with more well data in the study area, is required to more precisely quantify the surface/ground water connection (see chapter on Recommendations).

The upper San Pedro basin contains several hundred feet of consolidated and unconsolidated sedimentary deposits most of which are capable of transmitting ground water. These deposits may be more than a thousand feet thick in the southern part of the upper San Pedro drainage basin, where Basin-and-Range type faulting has produced a deep graben structure allowing extremely thick deposits of sedimentary deposits to accumulate (Sumner and Halvorson 1983, p.9). The hydrostratigraphic units of importance in the study area are the lower and upper units of the basin fill, and the overlying floodplain deposits. These units form the regional and local aquifers, respectively.

The lower unit of the basin fill consists of interbedded sandstone and gravel that ranges in thickness from 250-500 ft. (Putman, et al. 1987). Gravels within this unit locally contain much silt and other fine-grained sediments; thus decreasing permeability in some zones. The upper basin fill overlies the lower basin fill, and consists of reddish-brown clayey and silty gravel beds near the mountains, changing laterally basinward into a more silty and sandy facies (Roeske and Werrell 1973). According to the USGS (1982), the upper and lower basin fill behave as one hydrogeologic unit. Vertical and horizontal facies changes within these units result in a very heterogenous system. This diminishes any hydrologic differences that might exist between the two units.

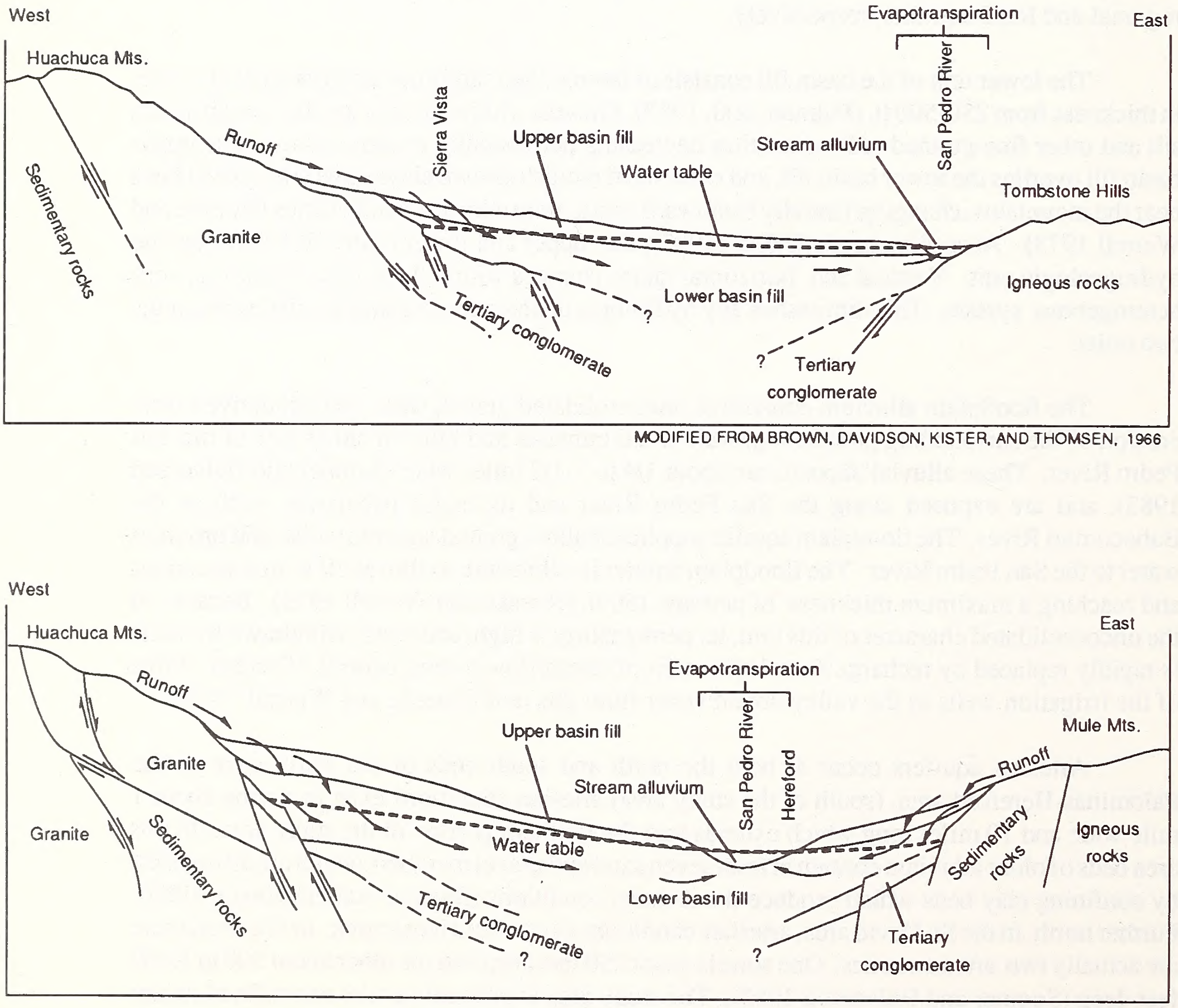
The floodplain alluvium consists of unconsolidated gravel, sand, and silt derived from erosion of the surrounding pediment gravels and mountains and hills on either side of the San Pedro River. These alluvial deposits are about 1/4 to 1-1/2 miles wide (Sumner and Halvorson 1983), and are exposed along the San Pedro River and its major tributaries, such as the Babocomari River. The floodplain aquifer supplies shallow ground water to wells, and provides water to the San Pedro River. The floodplain aquifer is a thin unit; as thin as 10 ft. in some areas, and reaching a maximum thickness of perhaps 150 ft. (Roeske and Werrell 1973). Because of the unconsolidated character of this unit, its permeability is high, and water withdrawn by wells is rapidly replaced by recharge from infiltration of streamflow during periods of runoff. Most of the irrigation wells in the valley obtain water from this unit (Roeske and Werrell 1973).

Artesian aquifers occur at both the north and south ends of the study area; in the Palominas-Hereford area, (south of the study area) artesian conditions exist in a zone about 1 mile wide and 10 miles long which extends into the southern portion of the study area. In this area beds of older alluvium contain at least seven sand and gravel members which are all overlain by confining clay beds which produce the artesian conditions (Sumner and Halvorson 1983). Further north, in the St. David area, artesian conditions exist over a larger area. In this area, there are actually two artesian zones. One zone is about 250 feet deep and the other about 500 to 1,400 feet deep (Sumner and Halvorson 1983). The study area is primarily under unconfined (water table) conditions, and water freely moves into, or out of the San Pedro River, depending on the water level within the floodplain aquifer.

Perched aquifers are likely to be present locally at various places in the basin. These aquifers are sufficient to provide water wells with limited yields; several ranches in the San Pedro Basin are believed to be supplied with water from these sources. Perched aquifers may be more common in this area than once surmised. Certainly the interbedded clay deposits which are common in this hydrogeologic setting, provides the framework for the existence of perched aquifers. The location and extent of these aquifers is not documented in the literature, and the goal of this study was not to study the perched aquifer system. Further study needs to be done to more precisely define these aquifers and the role they have in supplying water to ranches in the Upper San Pedro Basin.

Ground-Water/Streamflow Relationship

The saturated basin fill is an integral part of the ground-water/stream-flow regime in the Upper San Pedro Basin. Ground water contributes flow to the San Pedro River from two sources: (1) by contributions of flow from the basin fill and (2) contribution from underflow within the floodplain aquifer, which originates in the watershed in Mexico. Cross-sections drain across the San Pedro Basin as well as longitudinally (Figures 30 and 31) show the hydrogeologic units and ground water flow system as interpreted by the U.S. Geological Survey (Freethey 1982). The USGS study corroborates conditions observed and data gathered during this study. That is, flow



MODIFIED FROM BROWN, DAVIDSON, KISTER, AND THOMSEN, 1966

MODIFIED FROM DREWES, 1980

Figure 30. Diagrammatic sections representing hydrogeologic conditions in the San Pedro Basin.

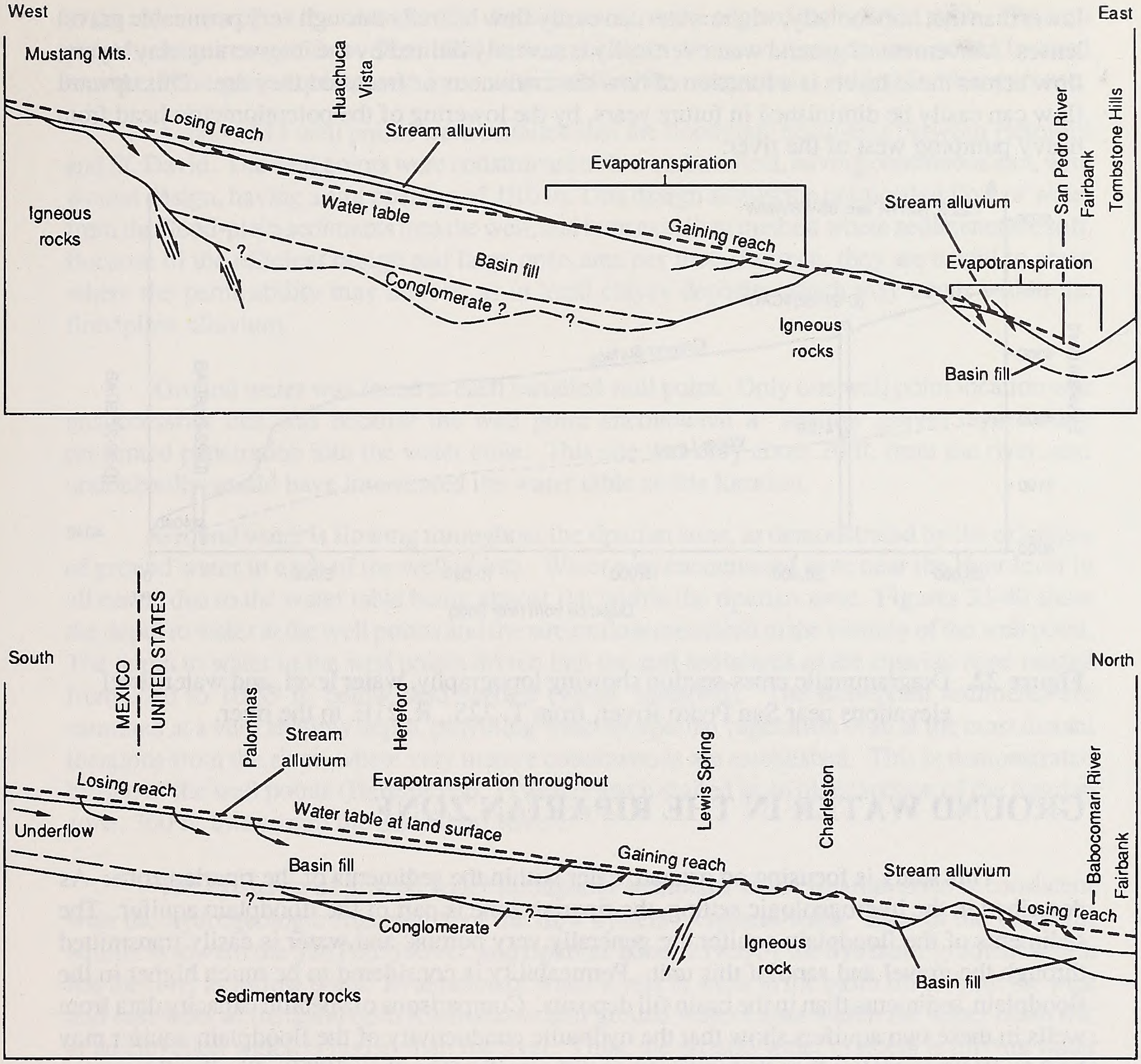


Figure 31. Diagrammatic sections representing hydrogeologic conditions beneath the Bobocomari and San Pedro Rivers.

in the San Pedro River is supplied due a great degree to contributions from ground water. The stream/aquifer relationship is shown diagrammatically by the cross-section of the basin-fill in Figure 32. Ground water occurs in the basin fill at an elevation higher than the river, and flows downgradient towards the river, discharging into the floodplain aquifer.

Ground-water recharge to the basin fill occurs in two ways: 1) percolation into the sediments along the mountain fronts, and 2) infiltration of precipitation into the floodplain aquifer from gullies and washes that have incised into the porous sediments of the floodplain aquifer. Ground water moves downgradient from the mountain fronts toward the San Pedro River which is the discharge point for most of the ground-water system. Here the ground water flows into the more porous sediments of the floodplain aquifer, discharging into the San Pedro river channel and maintaining its flow. Where artesian conditions exist, water is discharged to the San Pedro River from the basin fill via vertical leakage upward through overlying confining beds of clay and silty clay. This contribution to the flow of the San Pedro River is very minimal, because of the hydraulic characteristics of the bedded sedimentary deposits such as those that are found here. The hydraulic conductivity of these deposits in the vertical plane is generally much lower than that horizontally, where water can easily flow laterally through very permeable gravel lenses. Movement of ground water vertically is severely limited by the intervening clay layers; flow across these layers is a function of how discontinuous or fractured they are. This upward flow can easily be diminished in future years, by the lowering of the potentiometric head from heavy pumping west of the river.

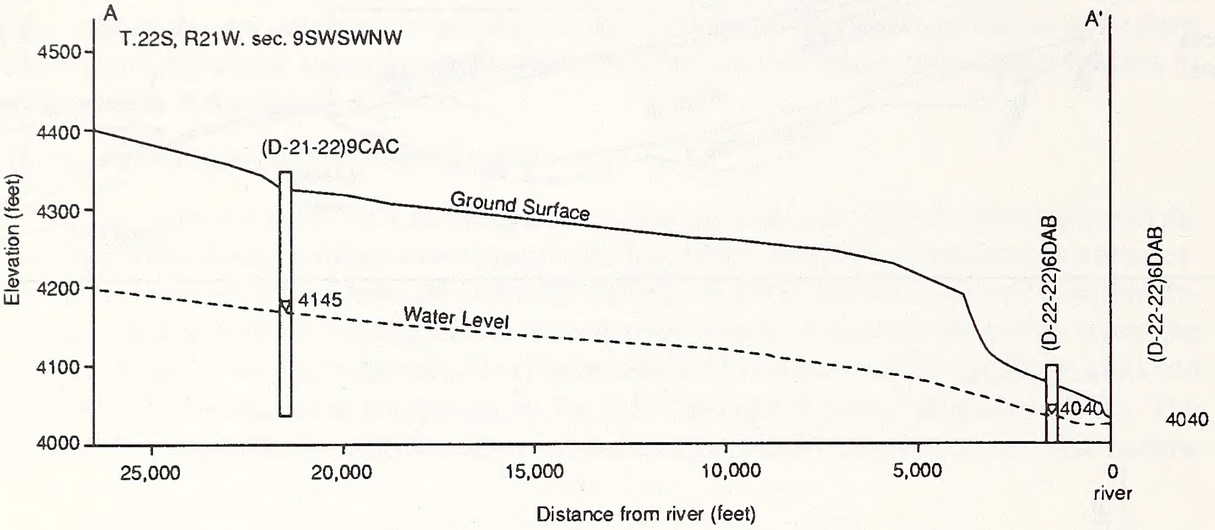


Figure 32. Diagrammatic cross-section showing topography, water level, and water-level elevations near San Pedro River, from T. 22S., R. 21E. to the river.

GROUND WATER IN THE RIPARIAN ZONE

This study is focusing on ground water within the sediments of the riparian zone. As described in the hydrogeologic setting, the riparian zone is part of the floodplain aquifer. The sediments of the floodplain aquifer are generally very porous, and water is easily transmitted through the gravel and sand of this unit. Permeability is considered to be much higher in the floodplain sediments than in the basin fill deposits. Comparisons of specific capacity data from wells in these two aquifers show that the hydraulic conductivity of the floodplain aquifer may be 2 to 10 times higher than that in the basin-fill aquifer (Freethey 1982). Similar figures are given in the study by Roeske and Werrell (1973).

The riparian zone of the San Pedro River is contained within the floodplain aquifer. Of central interest in this study is the existence and extent of ground water within the sediments of the riparian zone, how the ground water in these sediments related to streamflow of the San Pedro River, and how the ground-water system of the basin might support the riparian system on the river.

At the outset of this study, it was not known at what depth the ground water existed within the floodplain aquifer on the San Pedro River. Very little research is available in the literature on specific studies of riparian ground-water relationships. The ground-water regime of the riparian zone and its relationship to the basin ground-water system must be evaluated. Nearby pumping for irrigation and for municipal water supply are also of interest.

In order to evaluate and document the existence of ground water within the riparian zone, a series of well points were installed along the river within the floodplain sediments. Well points are an easy and inexpensive way to evaluate shallow ground water. Locations were selected which would provide ground-water information to complement the streamflow measurements and the geomorphic cross-sections of the river bed. Well points were installed at locations close to the river as well as at a considerable distance away, at the edge of the riparian zone. The well point locations ranged from 58 to 1060 ft. from the river. Some well points were driven by hand into the flood-plain aquifer, and some were installed into auger holes drilled for this purpose.

A total of 11 well points were installed into the floodplain sediments between Hereford and St. David. The well points were constructed of low carbon steel, having continuous slot, wire wound design, having a slot opening of .010 in. This design allows the unimpeded flow of water from the flood-plain sediments into the well, and is an excellent method where sediments are soft. Because of the efficient design and large open area per foot of screen, they are useful in areas where the permeability may be low, as in local clayey deposits which may occur within the floodplain alluvium.

Ground water was found at each installed well point. Only one well point location was unsuccessful; this was because the well point encountered a shallow gravel layer which prevented penetration into the water table. This site was only about 20 ft. from the river, and undoubtedly would have intercepted the water table at this location.

Ground water is flowing throughout the riparian zone, as demonstrated by the existence of ground water in each of the well points. Water was encountered at or near the river level in all cases, due to the water table being almost flat within the riparian zone. Figures 33-40 show the depth to water at the well points and the streamflow measured in the vicinity of the well point. The depth to water in the well points driven into the soft sediments of the riparian zone ranged from 3.80 to 10.85 ft. below land surface (when installed). The floodplain sediments are saturated at a very shallow depth, providing water to riparian vegetation even at the most distant locations from the river, where very mature cottonwoods are established. This is demonstrated by one of the well points (Hereford no. 1) which was installed in an older section of the riparian zone, 360 ft. away from the San Pedro River.

The existence of ground water throughout sediments in the riparian zone is consistent with the hydrogeologic framework of the flow system. Ground-water flow in the basin-fill aquifer is toward the San Pedro River, and riparian zone, driven by the hydraulic gradient which has the river as its low point. Evaluation of water levels in wells in the basin fill on both the west and east sides of the San Pedro River shows that ground water exists within the upper basin fill, at an elevation which is higher than the river. Thus, the ground-water gradient is driving water laterally within the upper basin fill toward the river, draining into the floodplain aquifer, through direct hydraulic connection. Construction of a flow net based on water level contours of the basin fill aquifer (Freethey 1982 and Roeske and Werrell 1973) shows the movement of ground water from the basin fill aquifer to the San Pedro River. Because of the high hydraulic conductivity of the floodplain sediments, water flows easily into these sediments from the basin fill aquifer.

Basin Fill/Floodplain Aquifer Interactions

The upper and lower basin fill deposits form the primary aquifer within the San Pedro basin. The floodplain aquifer is of local importance along the San Pedro River and other major tributaries. Ground water is transferred to the floodplain aquifer in three ways:

(1) by vertical leakage upward through clay layers, because of the higher potentiometric level in the basin fill aquifer,

(2) by the effect of bedrock outcrops near Charleston which forces water in the basin fill aquifer upward into the floodplain aquifer, and into the San Pedro River, and

(3) by lateral flow of water from the regional aquifer into the flood-plain aquifer.

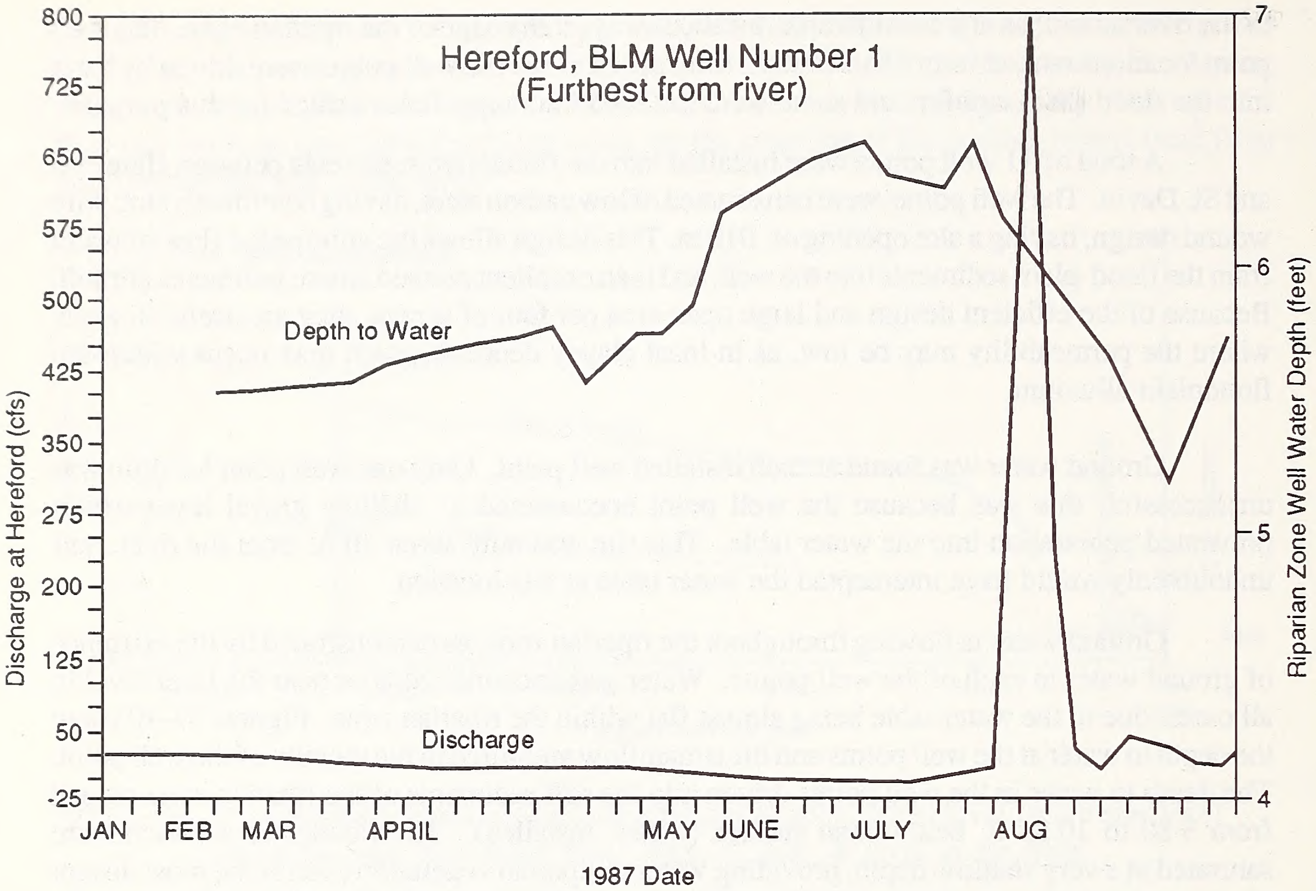


Figure 33. Depth to ground water in the riparian zone and river discharge, at T. 23S., R. 22E., sec. 9 NESENE (distance from river: 360 ft.).

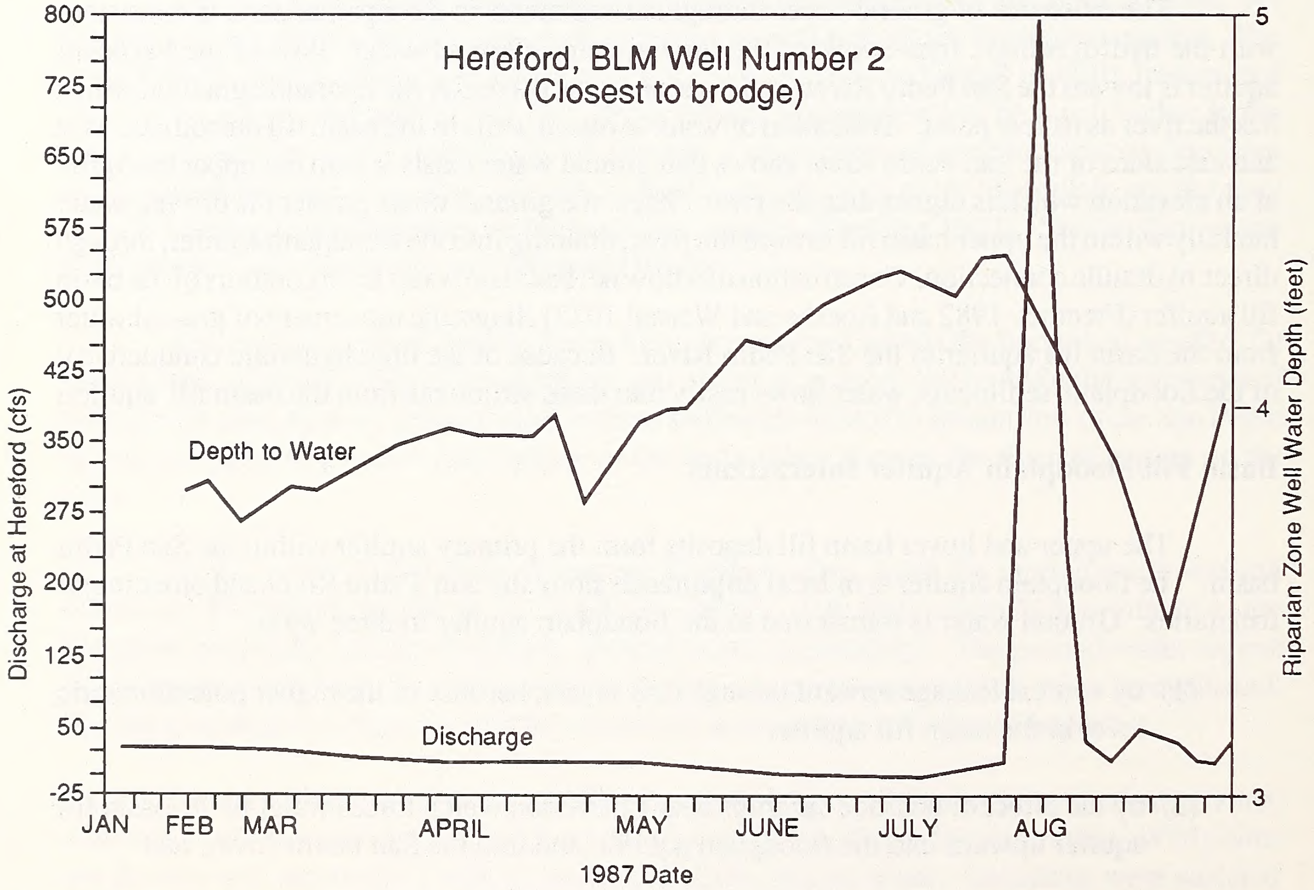


Figure 34. Depth to ground water in the riparian zone and river discharge, at T. 23E., R. 22S., sec. 10, SWSESE (distance from river: 128 ft.).

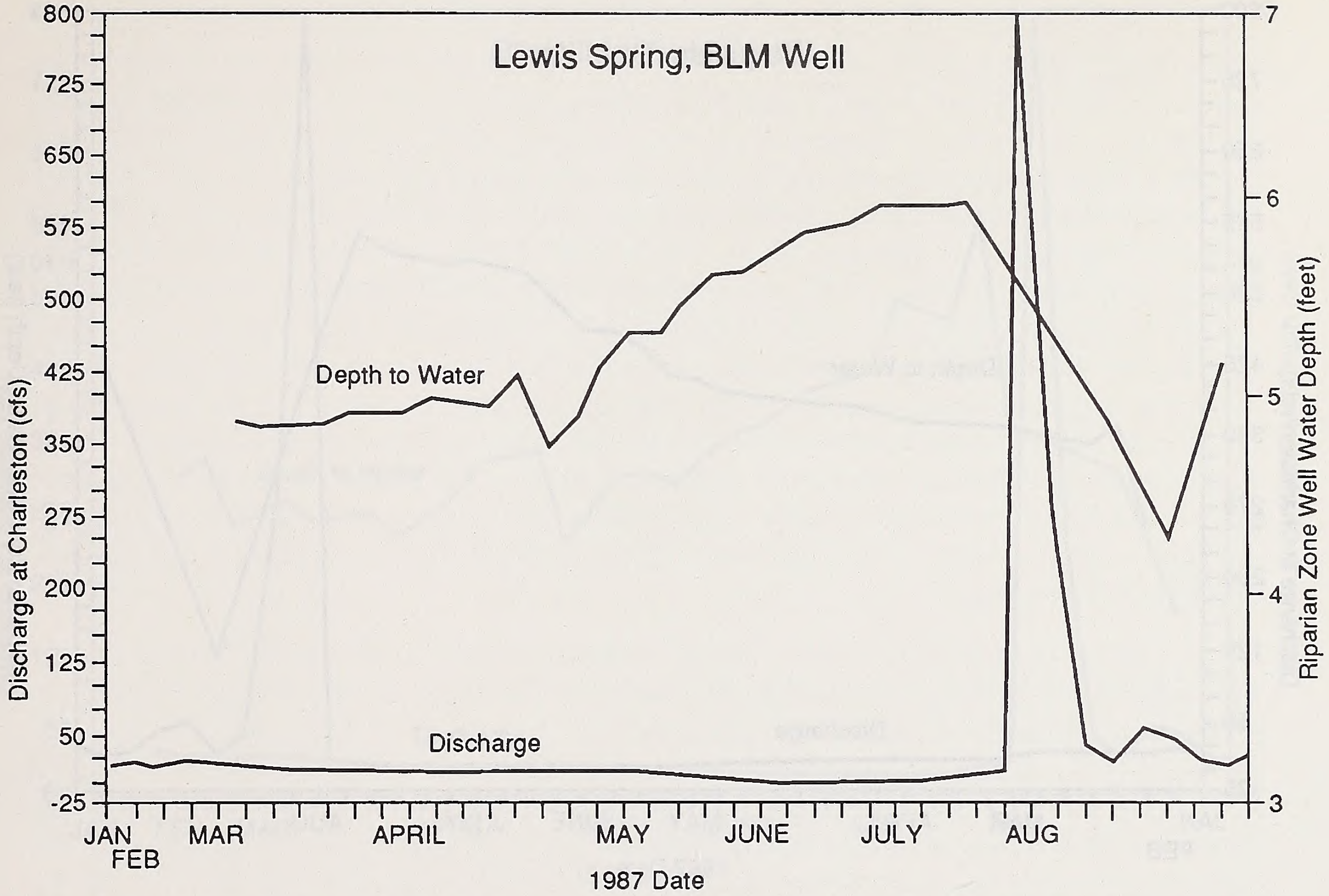


Figure 35. Depth to ground water in the riparian zone and river discharge, at T. 21S., R. 22E., sec. 31, SESESE (distance from river: 242 ft.).

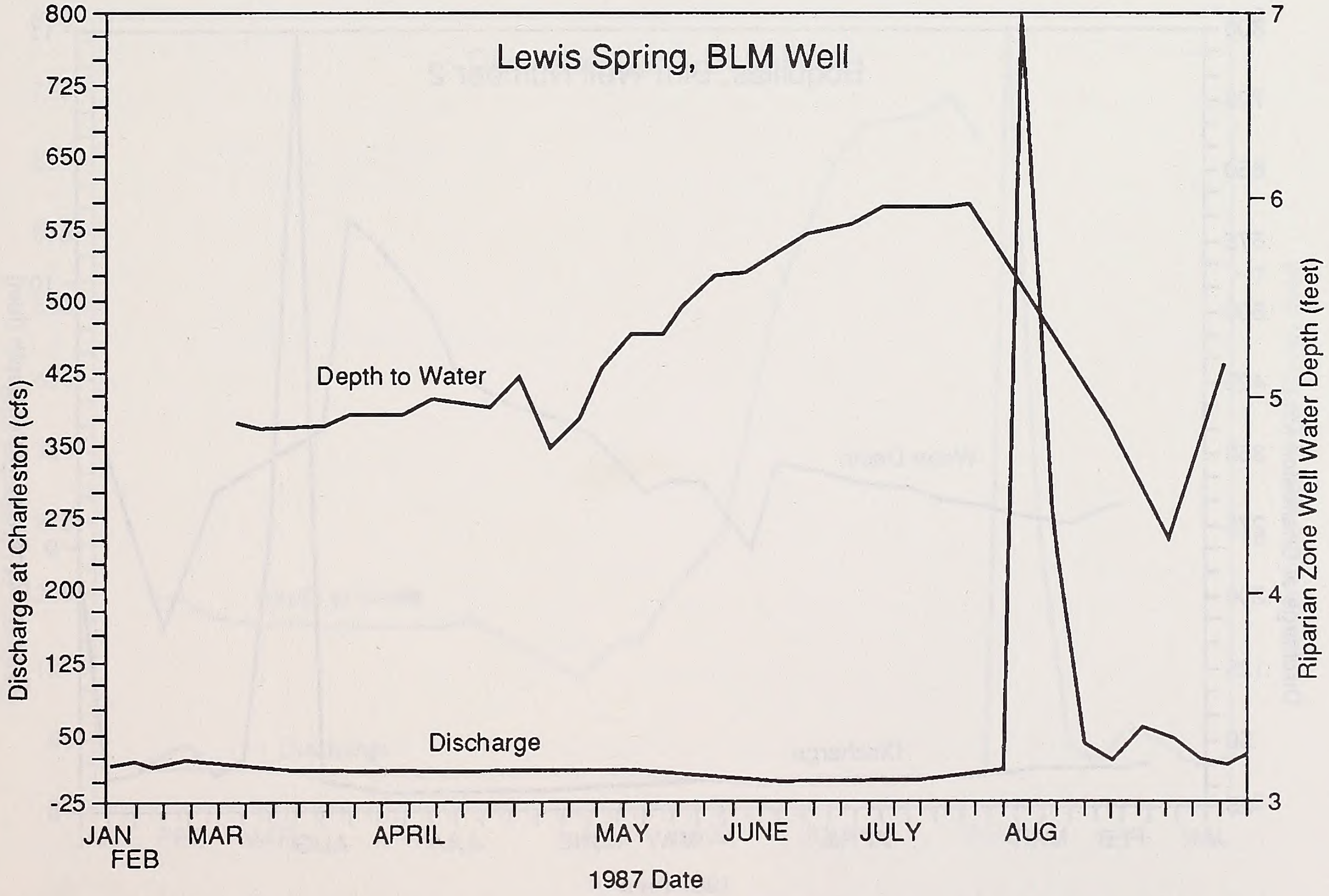


Figure 36. Depth to ground water in the riparian zone and river discharge, at T. 22S., R. 22W., sec. 17, SWSWNE (distance from river: 58 ft.).XX

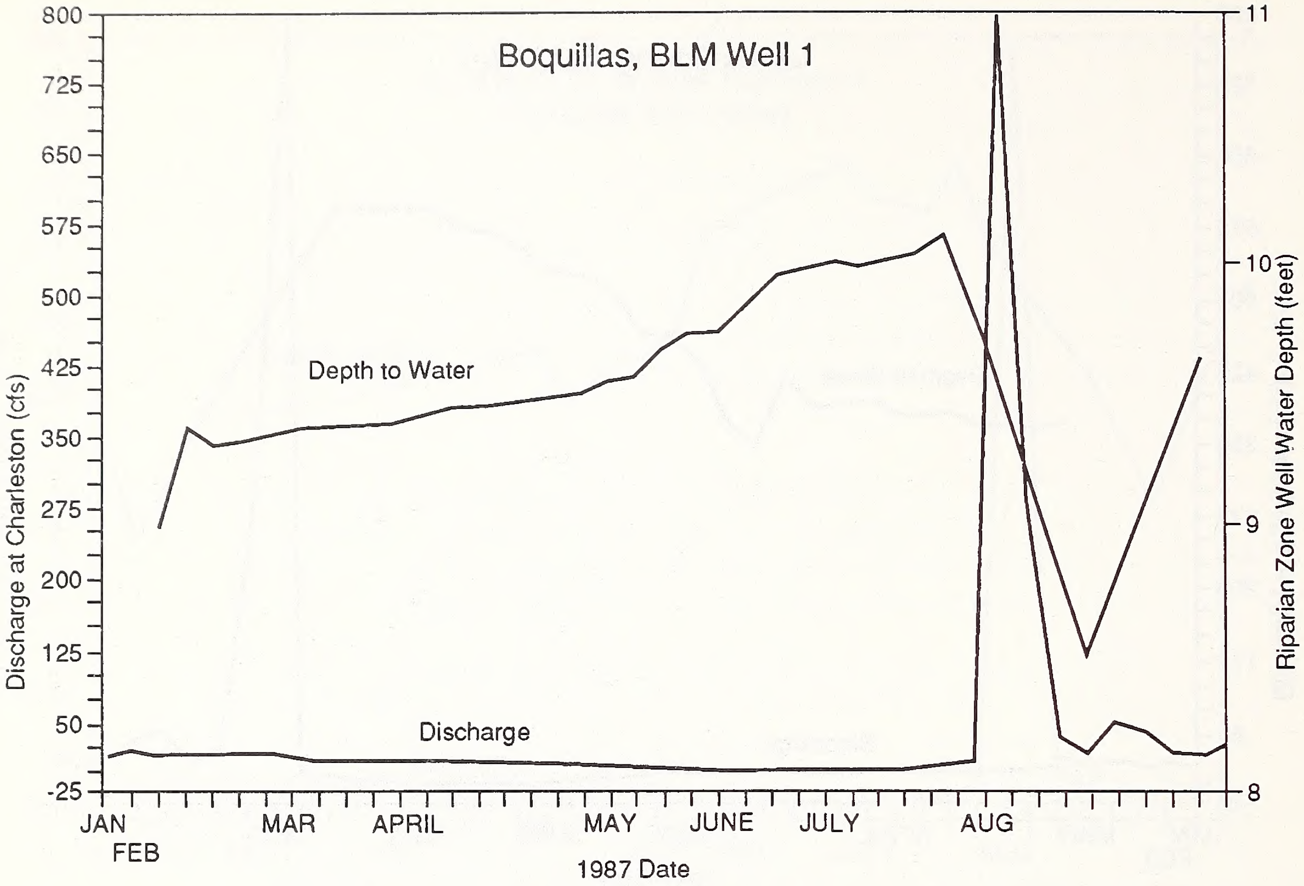


Figure 37. Depth to ground water in the riparian zone and river discharge, at T. 20S., R. 22E., sec. 15, SENWSE (distance from river: 139 ft.).

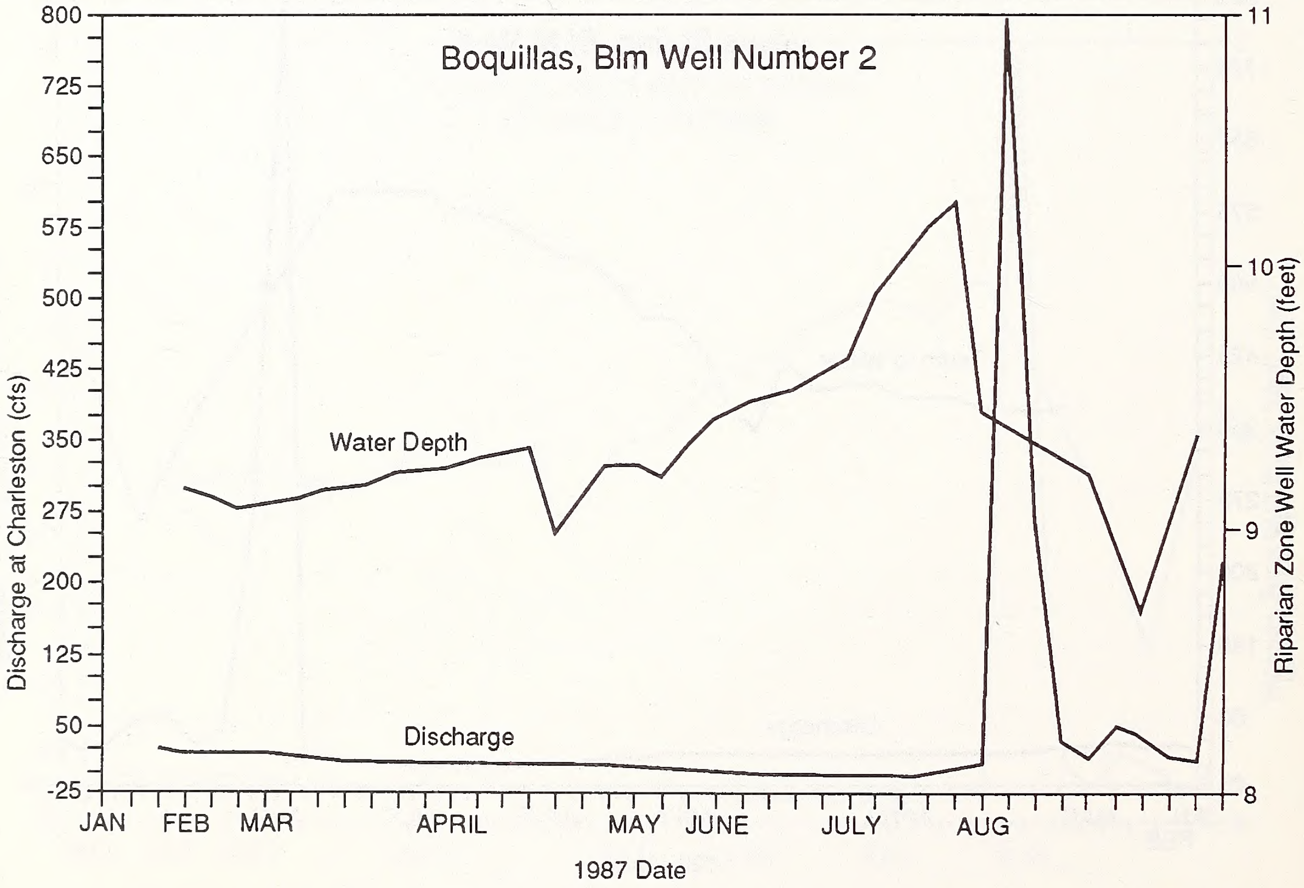


Figure 38. Depth to ground water in the riparian zone and river discharge, at T. 20S., R. 22E., sec. 22, SENENW (distance from river: 178 ft.).

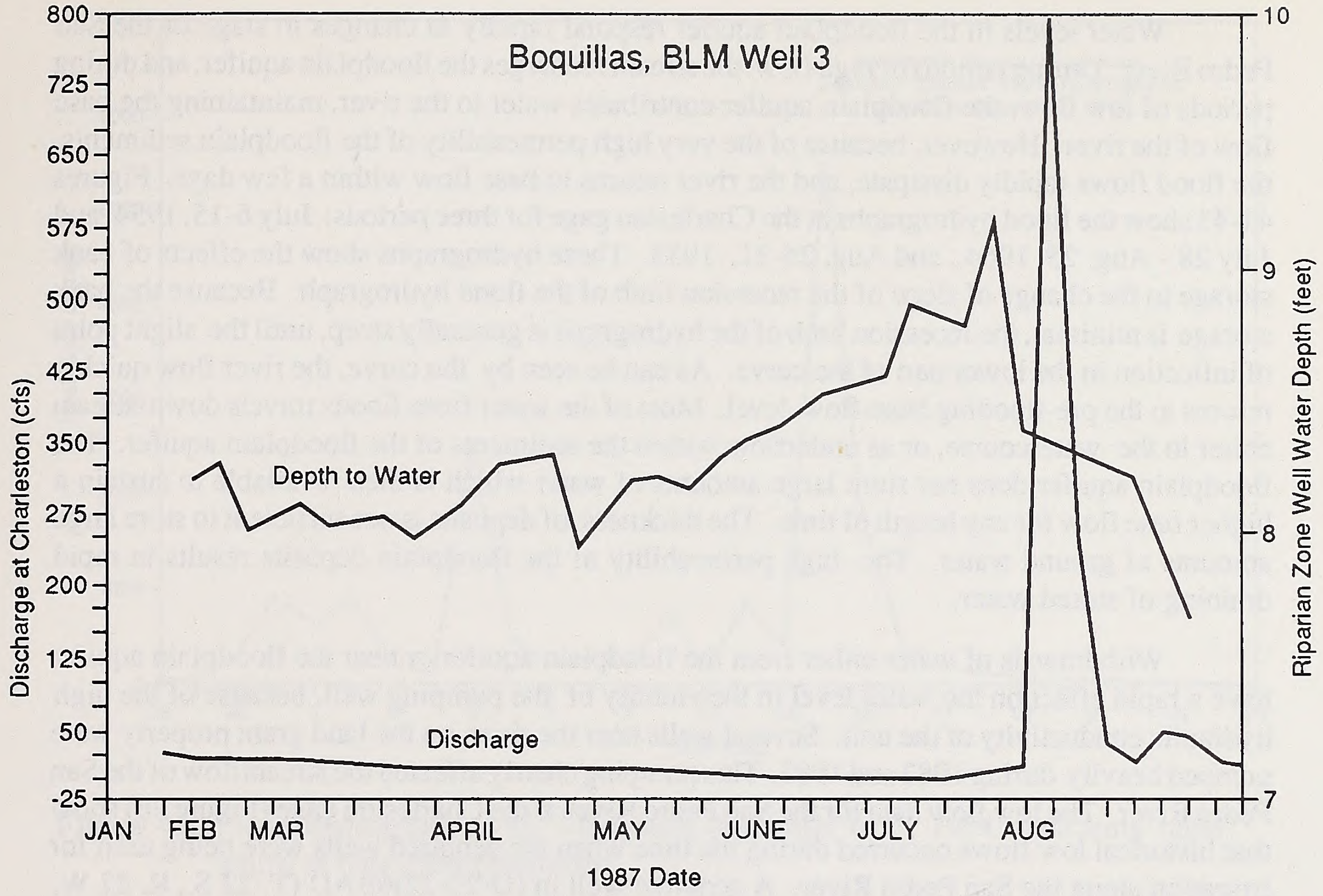


Figure 39. Depth to ground water in the riparian zone and river discharge, at T. 20S., R. 22E., sec. 22, SENENW (distance from river: 129 ft.).

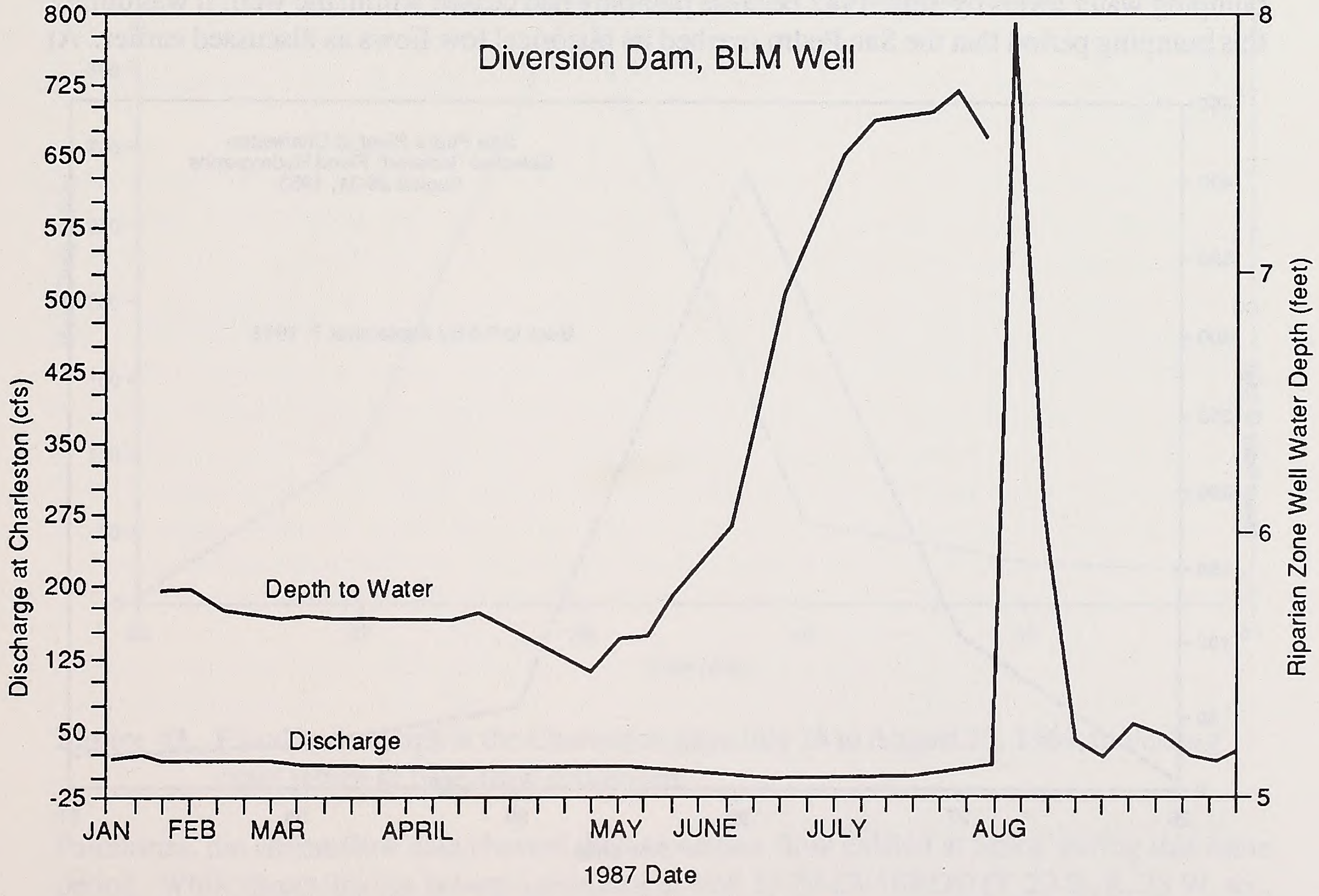


Figure 40. Depth to ground water in the riparian zone and river discharge, at T. 19S., R. 21E., sec. 4, SESWSW (distance from river: 305 ft.).

Water levels in the floodplain aquifer respond rapidly to changes in stage of the San Pedro River. During periods of high flow, the stream recharges the floodplain aquifer, and during periods of low flow, the floodplain aquifer contributes water to the river, maintaining the base flow of the river. However, because of the very high permeability of the floodplain sediments, the flood flows rapidly dissipate, and the river returns to base flow within a few days. Figures 41-43 show the flood hydrographs at the Charleston gage for three periods: July 6-15, 1954, and July 28 - Aug. 25, 1964 , and Aug. 26-31, 1953. These hydrographs show the effects of bank storage in the change of slope of the recession limb of the flood hydrograph. Because the bank storage is minimal, the recession limb of the hydrograph is generally steep, until the slight point of inflection in the lower part of the curve. As can be seen by the curve, the river flow quickly returns to the pre-flooding base-flow level. Most of the water from floods travels down-stream either in the watercourse, or as underflow within the sediments of the floodplain aquifer. The floodplain aquifer does not store large amounts of water which is then available to sustain a higher base flow for any length of time. The thickness of deposits is not sufficient to store large amounts of ground water. The high permeability of the floodplain deposits results in rapid draining of stored water.

Withdrawals of water either from the floodplain aquifer or near the floodplain aquifer have a rapid effect on the water level in the vicinity of the pumping well, because of the high hydraulic conductivity of the unit. Several wells near the river, on the land grant property were pumped heavily during 1982 and 1983. This pumping clearly affected the streamflow of the San Pedro River. The low flow data for the San Pedro River at the Charleston gage (Figure 26) show that historical low flows occurred during the time when the acquired wells were being used for irrigation along the San Pedro River. A acquired well in (D-22-22)6BAD (T. 22 S., R. 22 W. Sec. 6 SENENW) which was being used for irrigation, shows a 17.5 ft. decline in water level due to pumping between Dec. 1981 and March 1982. This well is 715 ft. deep, and penetrates sediments below the floodplain aquifer. Water level elevations had fully recovered nearly to pre-pumping water levels by Sept. 1982 because pumping had ceased within the well. It was during this pumping period that the San Pedro reached its historical low flows as discussed earlier. At

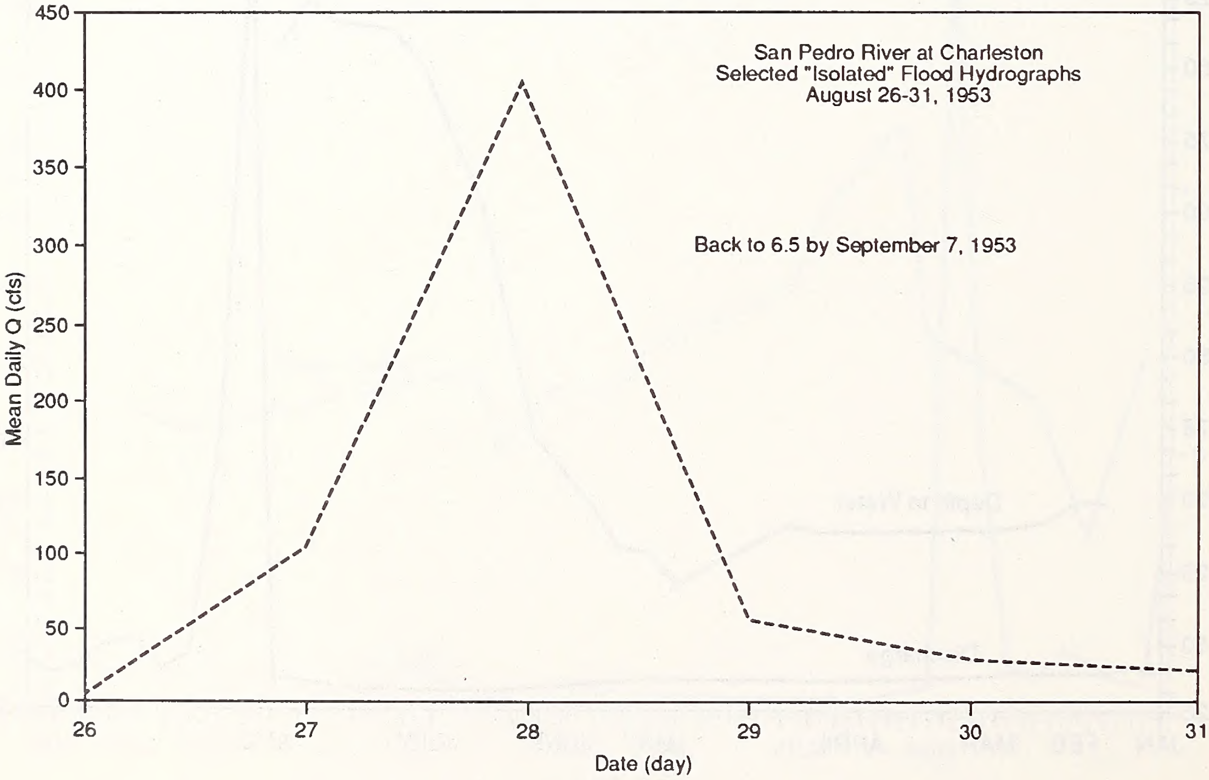


Figure 41. Flood hydrograph at the Charleston gage August 26-31, 1953, indicating rapid return to base-flow conditions.

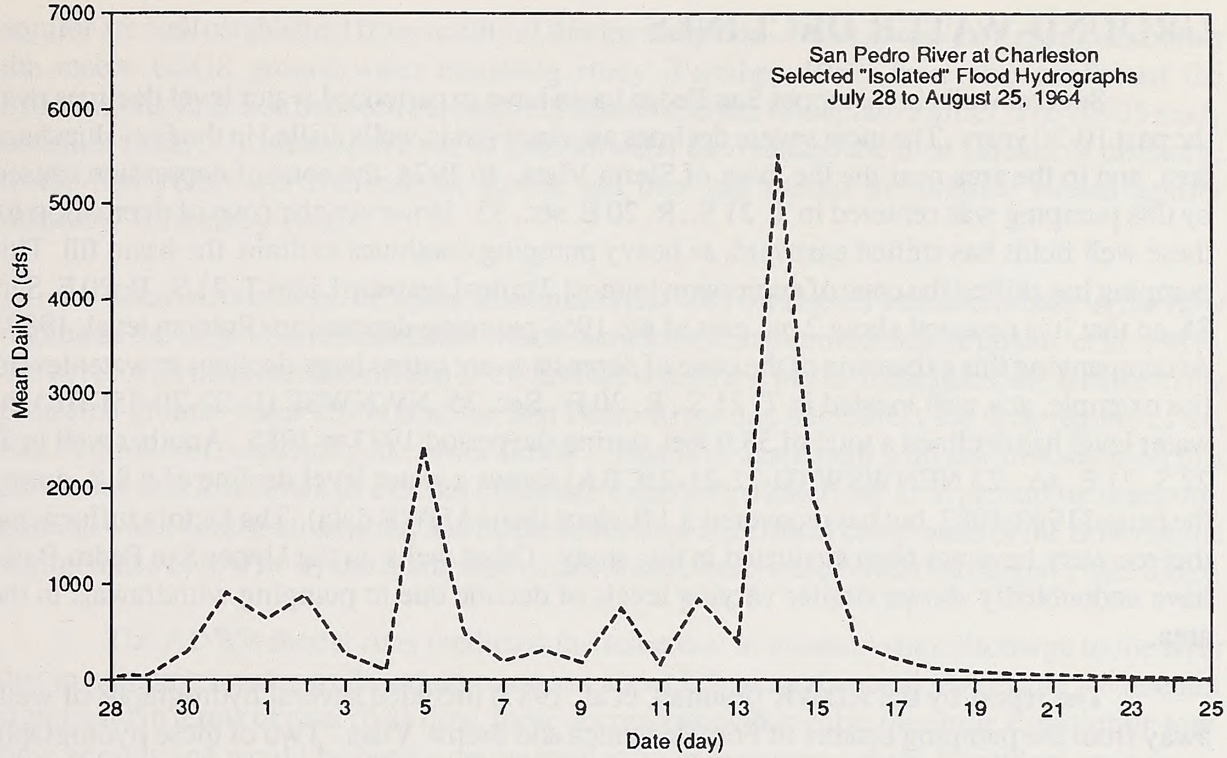


Figure 42. Flood hydrograph at the Charleston gage July 6-15, 1954, indicating rapid return to base-flow conditions.

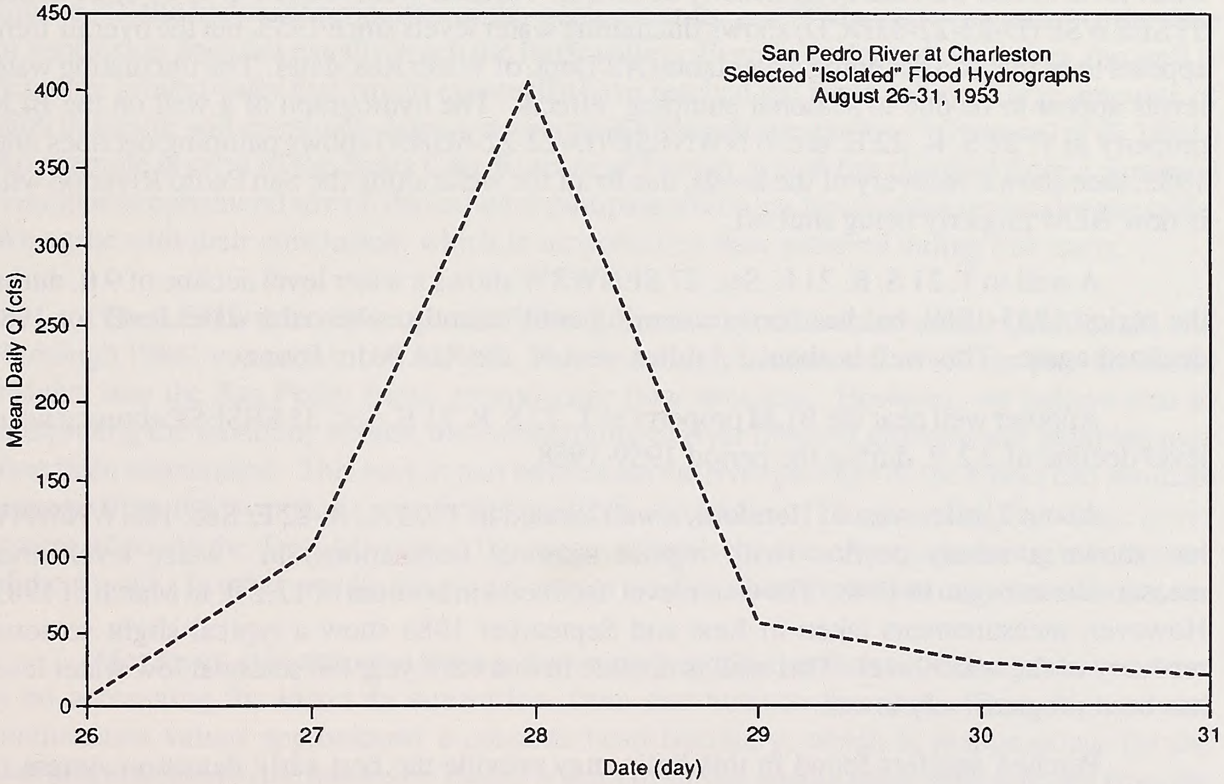


Figure 43. Flood hydrograph at the Charleston gage July 28 to August 25, 1964, indicating rapid return to base-flow conditions.

Palominas, the streamflow data showed that no surface flow existed at times during this same period. While direct linkage between pumping at well D-22-23-16BDD (T. 22 S., R. 23 W. sec. 16 SESENW) and the data at Charleston cannot be made, the data are noteworthy, and are believed to be significant.

GROUND-WATER DECLINES

Several wells in the upper San Pedro basin have experienced water level declines over the past 10-20 years. The most severe declines are observed in wells drilled in the Fort Huachuca area, and in the area near the the town of Sierra Vista. In 1974, the cone of depression caused by this pumping was centered in T. 21 S., R. 20 E. sec. 33. However, the cone of depression for these well fields has shifted eastward, as heavy pumping continues to drain the basin fill. This pumping has shifted the cone of depression [almost 2 miles] eastward, into T. 21 S., R. 20 E. Sec. 35. so that it is centered about 2 mi. east of the 1968 pumping depression (Putman, et al. 1987). Accompanying this expansion of the cone of depression are rather large declines in water levels. For example, at a well located in T. 21 S., R. 20 E., Sec. 35 NWNWSE (D-22-20-35DBB) the water level has declined a total of 53.9 feet during the period 1973 to 1985. Another well in T. 22 S. 21 E. sec. 23 NENWSW (D-22-21-23CBA) shows a water level decline of 6.8 ft. during the period 1963-1983, but has recovered 3.1 ft. since then (ADWR data). The factors influencing this recovery have not been evaluated in this study. Other wells in the Upper San Pedro Basin have undoubtedly shown similar varying levels of decline due to pumping withdrawals in the area.

The report by the ADWR (Putman, et al. 1987) included several hydrographs of wells away from the pumping centers of Fort Huachuca and Sierra Vista. Two of these hydrographs in the southern part of the study area near Palominas may be showing the effects of irrigation pumping. A well in T. 23 S. R. 22 E. sec. 18 SWSWSW (D-23-22-18BBB)shows a maximum 14.9 ft. (March 1983) decline in water level since 1948; the most recently available water level (Sept. 1983) shows a decline of 8.72 ft. Except for seasonal fluctuations due to pumping, the water level in this well has been steadily declining. Another well, located in T. 23 S. 22 E. sec. 33 SESWSE (D-23-22-33DCD) shows fluctuating water levels since 1953, but the overall trend appears to be that of a declining water table (AZ Dept. of Water Res. data). The fluctuating water levels appear to be due to seasonal pumping effects. The hydrograph of a well on the BLM property in T. 22 S. R. 22 E. sec. 6 NWNESE (D-22-22-6DAB) shows pumping declines until 1982, then shows recovery of the levels, due to all the wells along the San Pedro River on what is now BLM property being shut off.

A well in T. 21 S. R. 21 E. Sec. 27 SENWSW shows a water level decline of 9 ft. during the period 1965-1969, but has been recovering until recently, when the water level for 1980 declined again. This well is about 3.3 miles west of the San Pedro River.

Another well near the BLM property in T. 22 S. R. 21 E. Sec. 35 SESESE shows a water level decline of 2.2 ft. during the period 1959-1968.

About 2 miles west of Hereford, a well located in T. 23 S., R. 22 E. Sec. 18NWNWNW has shown a steady decline (with regular seasonal fluctuations) in water level since measurements began in 1948. The water level declined a maximum of 12.2 ft. in March of 1983. However, measurements taken in June and September 1983 show a typical slight seasonal recovery of the water level. This well is notable in that each year the seasonal low water level has been progressively lower.

Perched aquifers found in this basin may provide the best early detection system of general water level declines. These aquifers may be more prevalent than once thought; these should be identified if the basin is again studied in detail.

GROUND-WATER MODELING

In order to maintain the various resource values along the San Pedro River, maintenance of saturated conditions within the floodplain aquifer is essential. The connection between riparian habitat, streamflow, and ground water in both the floodplain aquifer and the basin fill aquifer are well established from results of this investigation. Other investigations, most notably the recent USGS ground-water modeling study (Freethey 1982) have also confirmed the hydrologic connection between the basin fill aquifer and the floodplain aquifer. The USGS study concluded that ..."Consumptive use of ground-water has reduced the total amount of discharge to the San Pedro and Babocamari Rivers and thus has altered the original stream-aquifer relations." (Freethey 1982).

The Arizona Dept. of Water Resources (ADWR) conducted a detailed study of the flow regime of the Upper San Pedro Basin which included extensive modeling (Putman, et al. 1987). We agree with their conclusion that .."the ground water flow model indicates some change in the projected ground water levels near the San Pedro River that may affect the flow regime of the San Pedro River, especially the lower flows". This is in agreement with our investigation that concludes that low flows in the San Pedro are extremely vulnerable to depletion by pumping. Ground water contribution to the San Pedro River flow is a critical component of the flow regime during times of low flow, and disruption of this source has a major effect on the river hydrology.

The ADWR model runs predicted the reduction in ground water discharge to the river due to pumping nearby wells would equate to about 2% of total annual river flow. While not significant in terms of total river flow, these decreases could involve the entire flow during low-flow periods and would be highly detrimental to river resources values dependent upon them, as discussed elsewhere in this report.

In the discussion of ground-water pumping in the Upper San Pedro River Basin, the ADWR report states that because of such factors as (1) the distance of a well from the flood-plain aquifer, (2) the hydraulic properties of the geologic units, and (3) the pumping rate, " ... the cone of depression does not usually reach the inner valley. Even in such cases, however, the well is pumping groundwater that would eventually have reached the inner valley. Large amounts of such pumping will eventually have a measurable effect on streamflow." (Putman, et al. 1987.) An example is cited of the Santa Cruz River near Tucson, which has changed from a perennial river into an ephemeral stream due to heavy pumping which has lowered the regional water table. We agree with their conclusion, which is supported by data gathered during this study.

The USGS three-dimensional finite-difference ground-water model (McDonald and Harbaugh 1984) was used in the ADWR. This is a widely used model which can provide useful insights into the San Pedro Basin groundwater flow situation. However, we believe that in interpreting the modeling results, the vulnerability of river flows to groundwater pumping may have been understated. This may in part be because the river package of the model can simulate seepage from the river that exceeds the available streamflow. The modeled river stage never lowers, although the depth of water in the stream controls the rate of seepage through the bottom of the stream. In other words, the model cannot predict when the stream may actually dry up.

Moreover, even though a leakage factor can be applied at each node along the river, there is no accounting for losses in streamflow from one node to the next. Thus, high stream conductance values approximate a constant head boundary, which is inappropriate for the hydrologic system in the San Pedro Basin. Values of stream conductance were selected from the USGS modeling study (Freethey 1982) which was conducted to improve understanding of the hydrogeology of alluvial basins through computer modeling. Leakance values are computed in the model based on head difference and stream conductance. It appears that the values for leakance from the river computed in the ADWR study far exceed the available streamflow during much of the year. Thus, the effect is much the same as using a constant head boundary in the model. However, the water supply in the stream simply is not available in the quantity required to recharge the floodplain aquifer in the event the water table in the regional aquifer is lowered to a point below the river or below the floodplain sediments.

One phase of the ground-water study conducted by the ADWR included modeling which simulated pumping of the acquired wells which are on the property that BLM recently acquired along the San Pedro River. This modeling suggested that increased infiltration from the stream into the ground water system would result, and that "...The likely effect of such infiltration is to reduce low flows in the river to slightly lower levels." (Putman, et al. 1987). However, data reviewed from the modeling study conducted by the USGS (Freethey 1982), and our own calculations of projected drawdown at the river suggests otherwise. Careful evaluation of the ADWR model graphical results suggests that the river will be depleted, based on lowered ground water levels. If the ground-water contours as plotted by the computer model (Putman, et al. 1987) are evaluated, the results show that the river will be depleted substantially, and perhaps even dry up. For example, the water level contour (the year 2000) just south of Charleston is for elevation 3950 ft. This is about the elevation of the river at this location. Thus, the ground-water recharge into the floodplain aquifer will be minimal, because of the lowered ground-water level adjacent to the river. Stream flow, if not completely diminished, will certainly be severely reduced. Similarly, the water level contour (for the year 2000) shown by the ADWR model just south of Lewis Springs is approximately 4030 ft.; the river currently is at about elev. 4025 ft. at this location. Thus, the stream might be substantially effected or possibly dry up at this location, if the water level in the aquifer dropped to or beyond the level as suggested by the aquifer simulation.

A second scenario for modeling, which used discontinuance of pumping of the acquired wells but with continued pumping of wells further away, shows similar results. The main difference in this scenario is that the water level contours are shifted southward slightly, which indicates a lessening of the effect on streamflow. However, the improvement is not substantial. Thus, pumping of wells located far away from the river (near Ft. Huachuca and Sierra Vista) can also have an effect on ground water levels at the San Pedro River as shown by the model.

The model used for the ADWR study is an excellent model which has been well tested and used extensively in ground water science. However, because of how the model functions, it has less applicability in situations where influent (losing) streams exist. This is because the model assumes that there is always enough water in the river to supply the aquifer (McDonald and Harbaugh 1984). In hydrogeologic situations such as those in the Upper San Pedro River Basin, this is not the case. The effect of the model is similar to having a constant head boundary, which supplies an infinite source of water to the system, although a constant head boundary is not used mathematically in the model.

The analysis conducted for this study does not support the contention that low flow will be only slightly affected by pumping. Our streamflow analysis, for example, shows that streamflow has declined over the years, and that baseflow is of extremely low volume (as low as .5 cfs in some months; see section on Streamflow) and pumpage could reduce the flow of the river for substantial periods during the year. Additionally, in regard to ground water, the saturated sediments of the floodplain aquifer become thinner northward from Hereford, thus reducing the amount of ground water in storage in these deposits. This reduces the amount of water available for recharge back into the basin-fill aquifer. Heavy pumping of wells in the basin fill a few miles to the west could lower the water table in the basin fill, and induce flow from the floodplain aquifer, draining it either substantially or completely and possibly drying up the San Pedro River. Some reaches of the river are more vulnerable than others for this occurrence.

The ADWR report concludes its discussion of the hydrology of the floodplain aquifer by stating that the river flow may be sufficient to offset the effects of pumpage near the river. The streamflow data evaluated during this study indicate that low flow of the river is fully supported by contributions from the floodplain aquifer. As noted previously, ground water is migrating laterally from the basin-fill aquifer into the floodplain aquifer. If heavy pumpage is continued from wells in the basin-fill aquifer, the supply of ground water to the floodplain aquifer must diminish. The only possibility for maintaining the river baseflow would be by vertical leakage upward from the deep aquifer. This contribution would be minimal because the hydraulic conductivity of the fluvial sediments is much lower in the vertical direction than horizontally. (These highly anisotropic conditions favor ground-water flow laterally along the sand and gravel units.) Hydraulic conductivity in the vertical plane can be as much as 10-50 times lower than in the horizontal plane. This hydrogeologic situation prevents any large amounts of water from leaking upward into the floodplain aquifer.

In this investigation, we evaluated the potential drawdown scenario using analytical models to simulate the effects of prolonged or increased pumpage on the flow regime of the San Pedro River (Rovey 1987). The Theis method of predicting drawdown was used. This technique does not account for any seepage of water from the river into the regional ground-water system. It is really the opposite end of the ground-water flow analysis spectrum, from using detailed numerical models which attempt to account for stream losses into the underlying aquifer. The assumptions (idealizations of the physical system) upon which the Theis equation is based are: (1) the aquifer is assumed to be of uniform thickness, is homogeneous, isotropic, and infinite in areal extent, and (2) the initial water table (before pumping begins) is assumed to be horizontal. Although actual field conditions do not match these idealizations, the hydrogeology is such that the method can be used for a first approximation of drawdowns due to pumping. Using the Theis method of calculating drawdowns and the principal of superposition to estimate the cumulative effect of more than one pumping well on the ground water system, drawdowns due to pumping near Fort Huachuaca and Sierra Vista were projected for locations along the river.

The following excerpt from Dr. Rovey's report describes the analytical modeling conducted for this study:

> "The Theis method for estimating the decline in potentiometric surface surrounding a pumping well is described in numerous ground water textbooks (e.g., Walton 1970). The Theis well field simulator employs the principle of superposition to estimate the cumulative effect of more than one pumping well on heads at selected observation points within the aquifer. The simulator has been converted into a BASIC computer program, to facilitate the numerous repetitive computations required to obtain estimates of cumulative head declines at each production well and observation point.
>
> For this analysis, effects of pumping were considered only for the Fort Huachuca-Sierra Vista area, although substantial amounts of pumping occur elsewhere in the Upper San Pedro Basin. In addition, average pumping rates for the 1966-85 period are used, instead of accounting for probable increased pumpage due to anticipated population increases in the future. Because this assumption underestimates the real pumping rates, both present and future, the analysis results are expected to produce conservatively low estimates of impacts of ground water pumping on the San Pedro River.
>
> Pumping rates used in the Theis analysis were derived from pumpage figures presented by ADWR (1987). Table 7 of that document includes a record of annual pumpage for Fort Huachuca for the twenty-year period from 1966 through 1985. The mean annual withdrawal is about 2800 acre feet. Based on comparison of Sierra Vista with Fort Huachuca 1985 pumpage a representative pumping rate for the 1966-85 period of 3200 acre feet was derived for Sierra Vista. This number is probably conservatively low. Both figures are conservatively low when used to project future stream depletions or ground water declines.
>
> The estimated annual pumping rates were converted to gpm, assuming a constant, year-round pumping schedule, and were divided among ten wells - five for Fort Huachuca, and five for Sierra Vista. The wells were located within the cone of depression that is apparent from 1978 water table contour maps, and near the east gate of Fort Huachuca.
>
> A representative range of values for aquifer transmissivity and storage coefficient were used to

> ensure that the first of these assumptions did not result in an overestimate of the impact of well pumping on the river. Transmissivity values of less than 1000 and as much as 15,000 ft^2/day were reported in the Fort Huachuca area by ADWR (1987). Representative values were in the range of 4000 to 8000 ft^2/day. Similarly, values for storage coefficient varied over a considerable range (ADWR, 1987); the narrower, probable range used in this analysis is 0.12 to 0.15.
>
> Observation points were located at township corners over an east-west distance of fifteen miles, and a north-south distance of thirty miles, centered around the Fort Huachuca-Sierra Vista area. The San Pedro River crosses the area from southeast to northwest. A line of observation points was located along the river, to obtain ground water declines that would occur at that location, assuming the river did not contribute leakage to the system (this condition could exist if the river is dry, or if the stream is losing and the permeability of the riverbed is very low.)
>
> Results of the 50-year simulation using a transmissivity (T) value of 8000 ft^2/day and a storage coefficient (S) value of 0.12 are perhaps the most notable, and are used for discussion here. The significant feature of the output data is that it shows head declines of as much as 5.3 feet at central locations along the river, as it passes near the Fort Huachuca-Sierra Vista well field. A comparable run using the "low" combination of T (4000 ft^2/day) and S (0.15) produces estimated head declines in this same vicinity of about 2.7 feet.
>
> Head declines over the range predicted by the well field simulator are large, relative to the depth of flow in the stream. (At the present time, field observations indicate that the San Pedro River is shallow enough to wade across at most locations.) Thus, ground water declines in the range of 2.7 to 5.3 feet (comparable to actual stream depth) are considered of sufficient magnitude to have the potential for drying up the stream (Rovey 1987)."

A second analysis was also made, simulating the effect of hypothetical new wells being pumped in an area which conceivably could experience development. In this analysis, values of transmissivity were varied between 4,000 ft^2/day and 8,000 ft^2/day The storage coefficient was held constant at 0.15..

In this second analysis, two hypothetical wells were located about 3 miles west of the San Pedro River, south of highway 90 in T. 23 S. R. 21 E. sec. 36 SWSWSW and sec. 24 NENENE. Each well was pumped at a rate of 800 gpm, and drawdowns were calculated at the river. The analysis using T = 8,000 ft^2/day showed drawdowns ranging from about 1.5 ft. three mi. north of Hereford, to about 7.5 ft. south of Lewis Springs. For the analysis using T = 4,000 ft^2/day drawdown at the river is projected to range from about 1.3 feet near Hereford, to about 11.2 feet near Lewis Springs (Rovey 1987). These drawdown figures may be slight overestimates, because the mathematical technique does not provide for any leakage contributions from the river.

ANALYSIS OF FLOODPLAIN WELL DATA

Floodplain well data were analyzed to determine 1) the depth to ground water within the riparian zone, 2) seasonal variations in riparian zone ground-water elevations, and 3) correlations—if any—between riparian zone ground-water elevations and streamflow. In addition, data from selected wells in the floodplain aquifer were analyzed to determine if any trends existed over time in ground-water elevations and if changes in ground-water elevation might correspond to changes in either mean monthly flow or to base flows (defined as the 90-day annual low flow).

The analysis of well data is hindered by the short period of record available for the BLM-riparian zone observation wells, and by both the short period of record and the erratic frequency of record (especially when compared to surface flow records) available for deeper wells in the floodplain aquifer. The short period of record makes trend analyses difficult. The erratic and intermittent frequency of data makes correlations with stream-flow difficult to detect. In addition, the storage capacity of the floodplain aquifer makes it effective in buffering abrupt changes in streamflows—another factor which confounds relationships between stream discharge and water table elevations.

BLM Riparian Observation Wells

Eleven well points were installed, all reaching ground water in the near-stream riparian zone. All well points were hand-driven except for three in which holes were drilled using an auger drill (Figure 44). Water elevations in the wells were measured at seven wells periodically beginning in February 1987. The stream was gaged at all BLM gage sites at roughly the same time that water table elevations were observed.

As described above, all riparian zone observation wells encountered the water table at approximately the same elevation as the stream water surface. During the February dormant vegetation season, small ground-water gradients toward the stream existed. These gradients support the notion, described above, that lateral inflows from the regional aquifer play an important—and measurable—role in maintaining base flows. As vegetation begins to utilize water in March and April, riparian water tables began to decline (Figures 33-40). These declines corresponded to general declines in streamflow. The depth to ground water between wells varied, of course, depending upon the geomorphic position of the wells. Continued monitoring of well water elevations will be required to develop annual patterns of ground-water elevation change. The current data are too sparse to show any long-term trend, but the mechanism of water use in the riparian zone is emerging.

Deep Floodplain Aquifer Wells

Three wells were identified which had sufficient data for analysis. Wells (D-22-22)06DAB and (D-23-22)16BDD are located on the BLM properties (Table 1). Water levels in those wells was read roughly three times per year between 1981 and 1986. Well (D-23-22)33DCD2 is located near Palominas, just south of the BLM properties. Water level in that well was read monthly from 1954 to 1963, and was read roughly annually from 1966 to 1986.

Water table elevations in wells (D-22-22)06DAB and (D-23-22)16BDD were plotted over time and compared to a plot of mean monthly flow (at Charleston) over the same period of time (Figures 45 and 46). Ground-water levels in these two irrigation wells did not correlate statistically with instantaneous daily discharge at either Charleston or Tombstone on the day of the well water level readings. However, when the well water levels are overlayed on the plot of mean monthly discharge, some very general patterns can be observed.

The generally lower water levels in 1981-1982 appear to reflect lower overall flow regimes and the fact that aquifer recharging high flows were smaller and occurred only during the summer high flow season. Beginning in 1983 there were two distinct high flow seasons as high winter flows occurred in addition to high summer flows. This appears to be reflected in generally higher well water levels from 1984 on. These two wells also appear to indicate recharge following specific periods of very high streamflows (e.g., June 1982; March 1983; August 1983-March 1984; July 1984-May 1986). The very wet period beginning in July 1984 resulted in the highest measured water levels in these two wells. The two lowest well water levels (4028 ft.) correspond to very low streamflow periods, but are probably the result of localized drawdowns caused by operation of the acquired irrigation pumps.

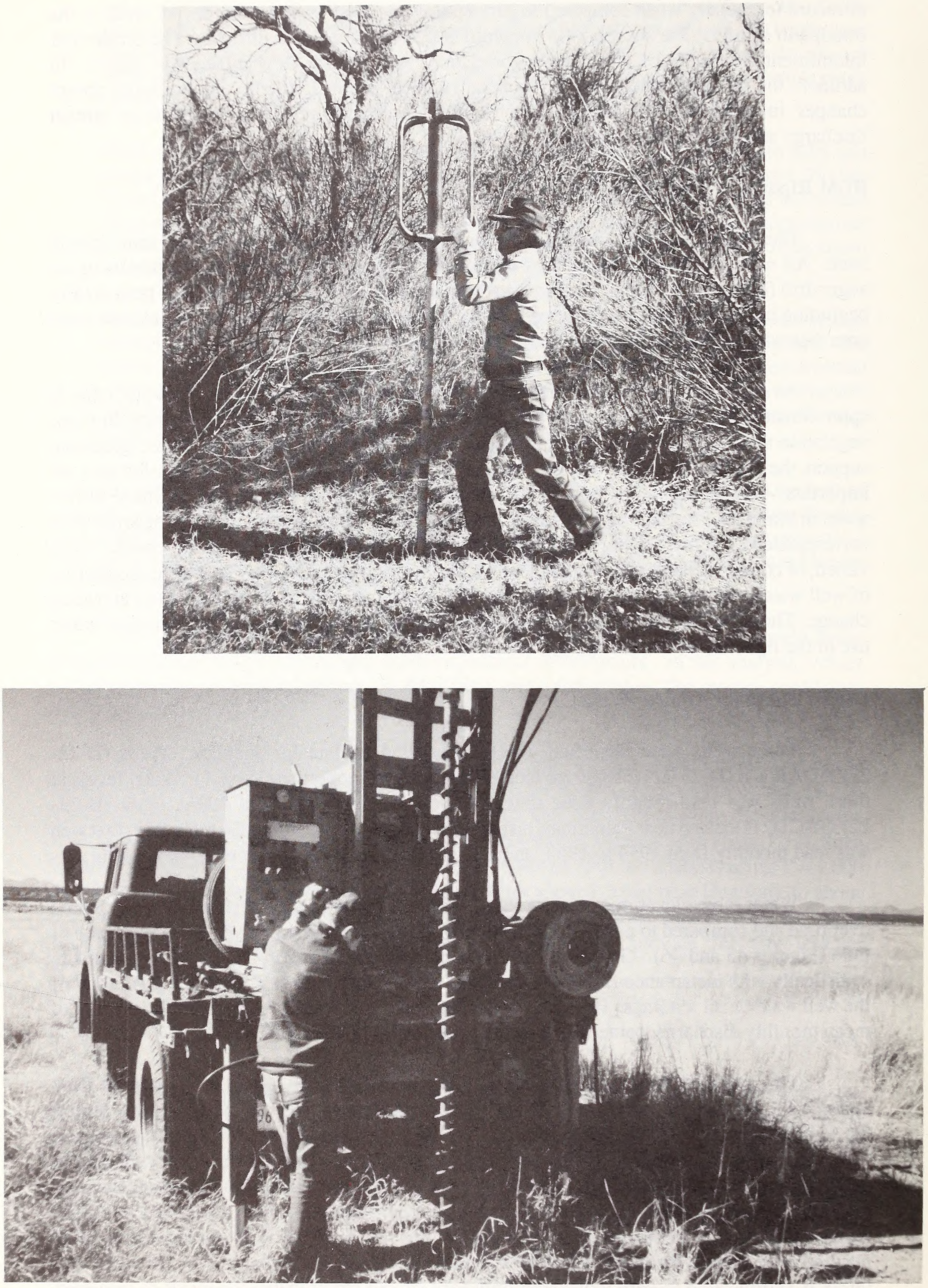


Figure 44. Photographs of BLM well-point installation D(23-22)33DCD2 near Palominas for the 1954-1986 period.

Well water table elevations in well (D-23-22)33DCD2 were plotted over time and compared to a plot of the annual 90-day low flow over the same period of time. Again, statistically significant correlations between well water level and corresponding streamflow (at Palominas) did not exist. However, some general changes in well water levels between the 1954-1963 period and the 1966-1981 did occur, and those changes corresponded to similar changes in base flows between the same periods.

Ground-water level elevations between 1954-1963 averaged 4210.94 feet (s = .89 feet) and averaged 4209.07 feet (S = 2.92 feet) and 4208.57 feet (S = 3.14 feet) for the 1966-1981 and the 1966-1986 periods respectively. Water levels for both the 1966-1986 and 1966-1981 periods were significantly (p = 0.99) lower than during the 1954-1963 period. Mean 90-day low flows also declined significantly (p = 0.90) during the 1966-1981 period when compared to the 1954-1963 period. Thus, significant declines were observed in both base flows and water table elevations between the two periods. The decline of 1.87 feet in average water table elevation corresponds to a decline of 1 cfs in mean 90-day low flow. The 1-cfs decline in 90-day low flow represents a 65% decline in that flow parameter between the two periods. When 1954-1986 ground-water elevations are analyzed for trends over time, a highly significant (p = 0.99) decline is observed (Figure 47). Again, all indications are that the long-term declines in base flows (see the Surface Water Hydrology chapter) are a reflection of lower ground-water levels along the river.

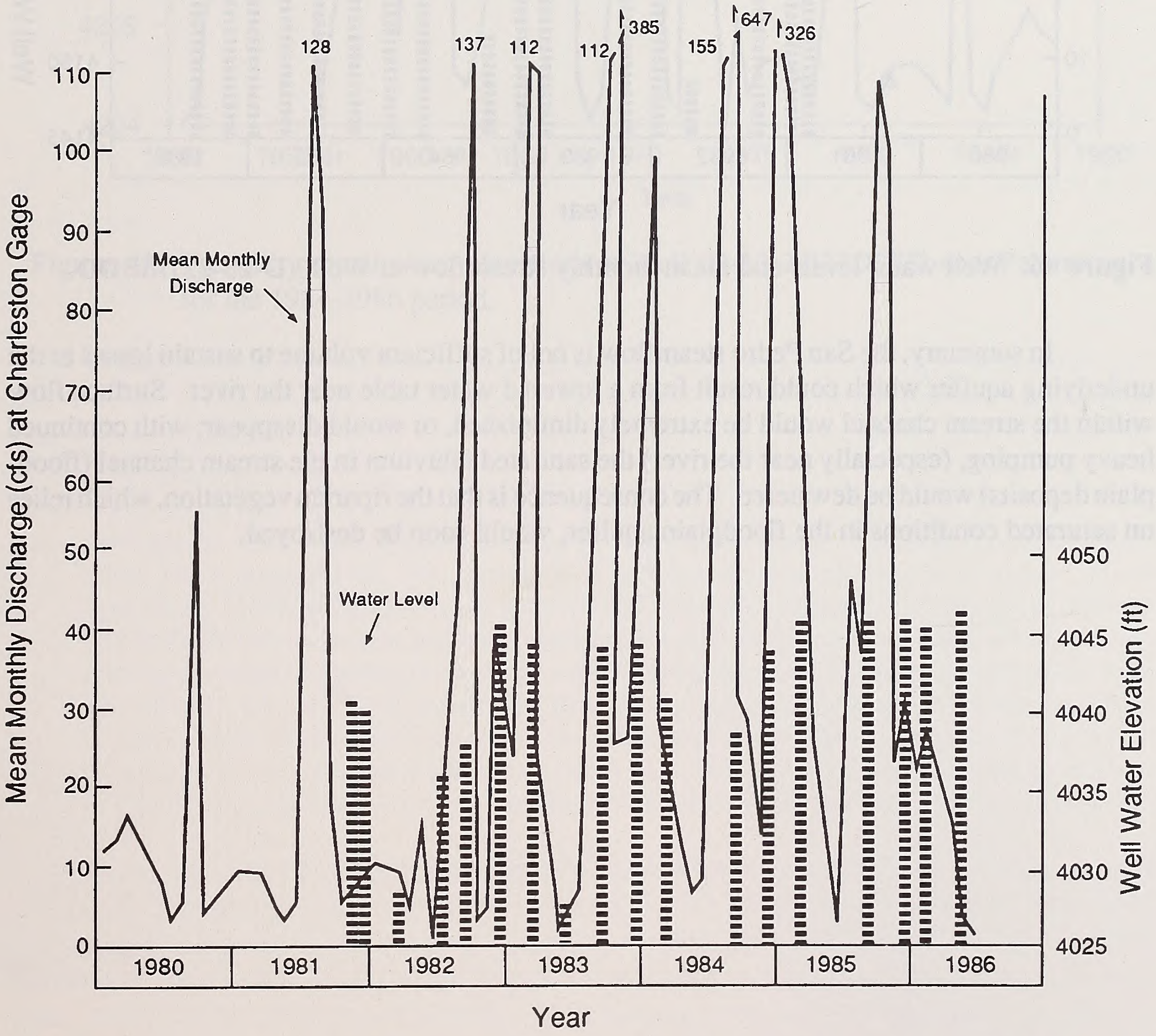


Figure 45. Well water levels and mean monthly streamflow at Well (D-22-22)06DAB.

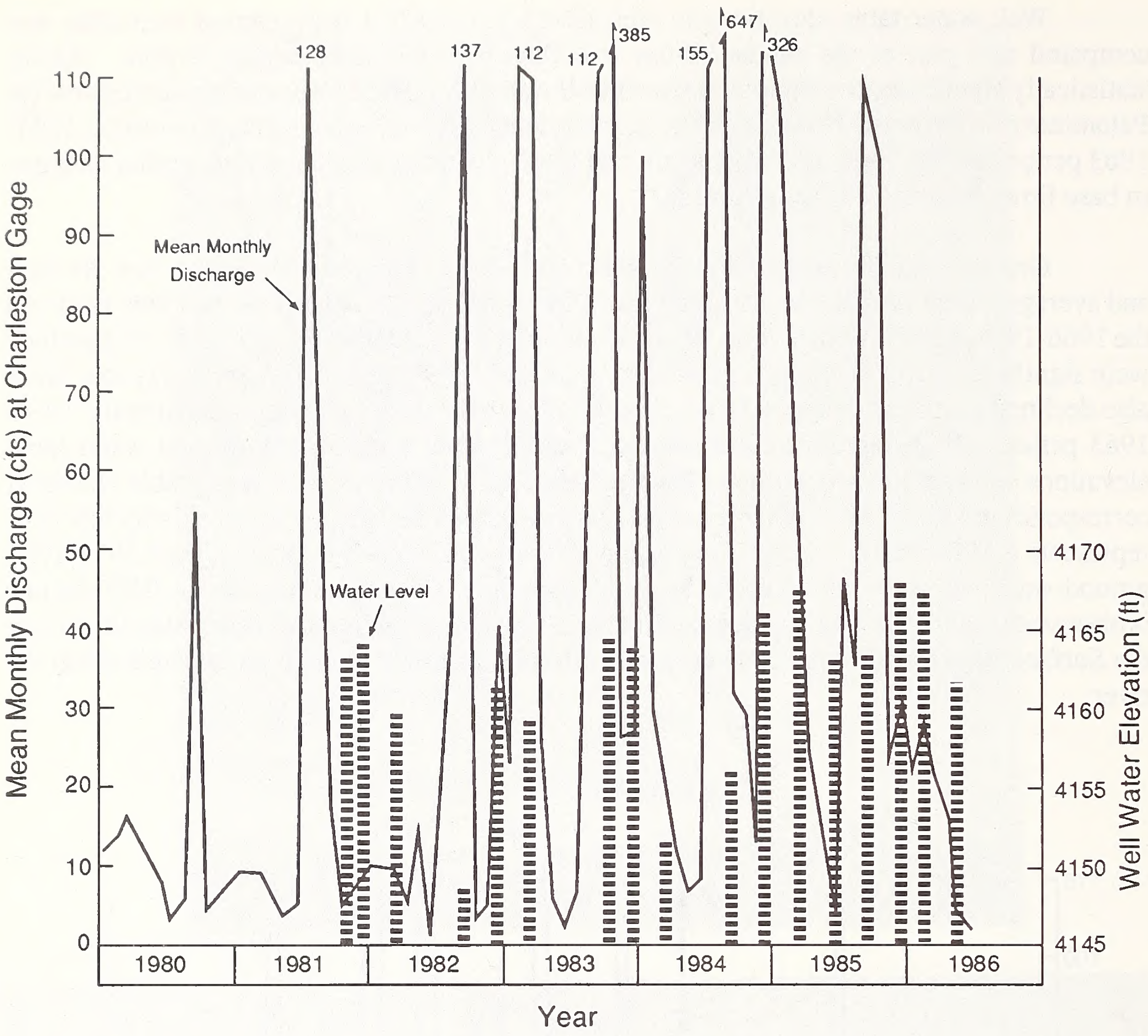


Figure 46. Well water levels and mean monthly streamflow at Well (D-23-22)16BDD.

In summary, the San Pedro steamflow is not of sufficient volume to sustain losses to the underlying aquifer which could result from a lowered water table near the river. Surface flow within the stream channel would be extremely diminished, or would disappear; with continued heavy pumping, (especially near the river) the saturated alluvium in the stream channel (floodplain deposits) would be dewatered. The consequence is that the riparian vegetation, which relies on saturated conditions in the floodplain aquifer, would soon be destroyed.

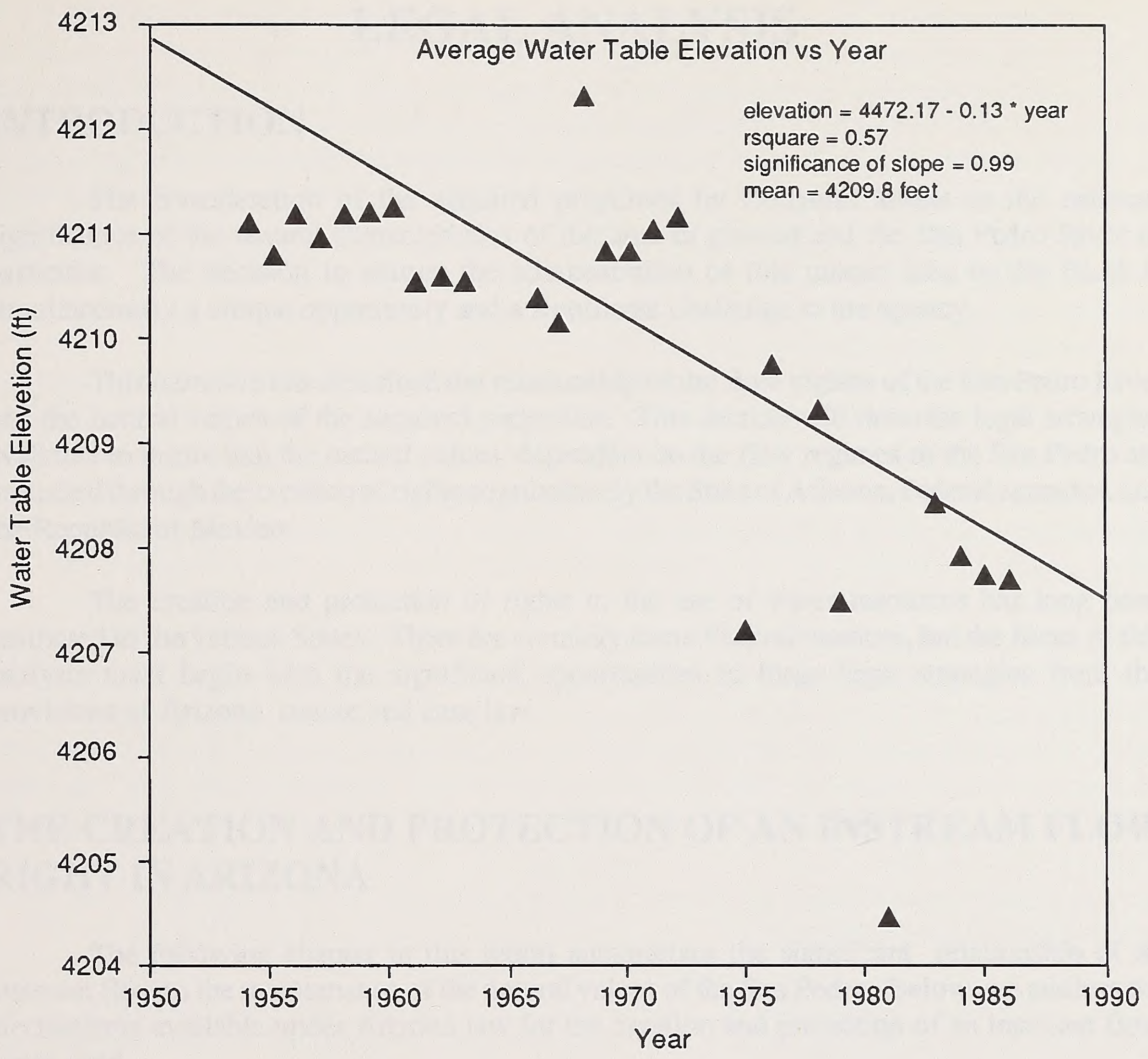


Figure 49. Trend in ground-water elevations at Well (D-23-22)33DCD2 near Palominas for the 1954-1986 period.

LEGAL ANALYSIS

INTRODUCTION

The consideration of the acquired properties by Congress attests to the national significance of the natural characteristics of the area in general and the San Pedro River in particular. The decision to entrust the administration of this unique area to the BLM is simultaneously a unique opportunity and a significant challenge to the agency.

This narrative has described the relationship of the flow regime of the San Pedro River and the natural values of the acquired properties. This section will describe legal strategies available to insure that the natural values dependent on the flow regimes of the San Pedro are protected through the creation of rights cognizable by the State of Arizona, Federal agencies, and the Republic of Mexico.

The creation and protection of rights to the use of water resources has long been attributed to the various States. There are certainly some Federal nuances, but the focus of this analysis must begin with the significant opportunities to forge legal strategies from the provisions of Arizona statute and case law.

THE CREATION AND PROTECTION OF AN INSTREAM FLOW RIGHT IN ARIZONA

The following chapter in this report summarizes the significant relationship of an instream flow to the maintenance of the natural values of the San Pedro. Below, we address the mechanisms available under Arizona law for the creation and protection of an instream flow water right.

A. Creation

Arizona does not have an instream flow law penned by the State legislature and sanctified by the signature of the Governor. The authority of the State to grant an instream flow right is derived from an Arizona Supreme court decision *M^cClellan v. Jantzen* 547, P.2d 494, 496 (1976), which states:

> "However, in 1941 when 'wildlife including fish' and in 1962 when 'recreation' were added to the purposes for appropriation, the concept of in situ appropriation of water was introduced —it appearing to us that these purposes could be enjoyed without a diversion. We find nothing, however which would indicate that the legislature intended that such an in situ appropriation would not carry with it the exclusive vested rights to use the water for these purposes. We therefore, find that by these amendments, the legislature intended to grant a vested right to the State of Arizona to subject unappropriated water exclusively to the use of recreation and fishing. Conceivably then, and assuming a first in right appropriation, the Game and Fish Department could prohibit the draining of a lake for irrigation purposes for example, if that draining interfered with the fish therein."

The significance of this language to the body of water law in Arizona has been debated at length. The case did not rely on a finding that the State could create an instream flow right, but rather whether or not the State would have to apply for a water right for fisheries and recreation. This subtle distinction between a rule of law and advice from the court offered gratuitously can be extremely significant. If this language is merely advice or dicta, the BLM's ability to rely on the strength of this finding by the court is substantially diminished.

Professor John D. Leshy of Arizona State University emphasized in a letter to Joseph E. Clifford, Assistant Attorney General, Arizona, the strength of the authority found in *M^cClellan*: "... is excellent authority for instream flows." Though there, the instream appropriation was of waters of a lake rather than a stream, surely that cannot be legally significant. The controlling Arizona statute lumps lakes and streams together, allowing appropriation of the "waters of all sources, flowing in streams, ... and of lakes, ponds, and springs on the surface ... A.R.S. 45-131A. Nowhere is any distinction drawn in the kind of appropriation allowed in these different types of water bodies .... Contrary to Mr. Clifford's assertion, this language is free from ambiguity: instream appropriations are lawful in Arizona."

This confidence in the strength of Arizona case law is reflected in the fact that the Arizona Department of Water Resources *In the Matter of Applications to Appropriate Nos. 33-78419 and 33-78421* (Ramsey Canyon Decision) granted The Nature Conservancy an instream flow right to "be used in situ for wildlife habitat preservation." There are 32 instream flow applications presently pending before the Department of Water Resources including a BLM filing on the San Pedro.

As of this moment, there is de facto instream flow protection on the San Pedro through the acquired properties. The Saint David Irrigation District holds a water right which dates back to 1881, located at the northern end of the acquired properties. Historically that right has taken the available flow of the San Pedro River 10 months of the year and pumped ground water when surface flow was unavailable. The flow in the canal has been measured as high as 19 cfs. Saint David's records indicate that approximately 500 acre-feet are taken each month when the San Pedro has surface flow. This kind of a water right immediately below the acquired properties acts as a water magnet drawing the available flows of the San Pedro through the critical stream sections to the benefit of BLM.

The BLM Application to Appropriate No. 33-90103 was originally filed by the Huachuca Audubon Society, Chiricahua Sierra Club, and Defenders of Wildlife on August 12, 1985 and assigned to the BLM on May 25, 1986. That application asks for an instream flow for "Wildlife protection pursuant to A.R.S. 45-141 (A)" in the following amounts:

Segment 1 Amount Month/Day	Segment 2 Amount Month/Day
4.19 cfs from 10/1 to 10/31	25 cfs from 10/1 to 10/31
6.30 cfs from 11/1 to 11/30	4.54 cfs from 11/1 to 11/30
8.65 cfs fro 12/1 to 12/31	6.41 cfs from 12/1 to 12/31
9.5 cfs from 1/1 to 3/31	9.5 cfs from 1/1 to 3/31
6.15 cfs from 4/1 to 4/30	5.76 cfs from 4/1 to 4/30
3.89 cfs from 5/1 to 5/31	1.86 cfs from 5/1 to 5/31
5.73 cfs from 6/1 to 6/30	.26 cfs from 6/1 to 6/30
128 cfs from 7/1 to 7/31	233 cfs from 7/1 to 7/31
92.6 cfs from 8/1 to 8/31	168 cfs from 8/1 to 8/31
19.7 cfs from 9/1 to 9/30	40.2 cfs from 9/1 to 9/30

The quantities of water sought in the Application to Appropriate No. 33-90103 should be amended to more accurately conform to the findings of this study. Similarly, the application should be amended to reflect precisely the beneficial uses found in Arizona case law and statute (i.e., recreation and wildlife).

B. Protection

Surface water—Arizona water law relies on the Appropriation Doctrine for the administration of its water rights. The cornerstone of the Appropriation Doctrine is the axiom "first in time, first in right." Under Arizona law, where water is taken from a stream, the appropriator who can establish that he has the older water right (senior) will be entitled to fulfill his water right before a water right established later (junior) in time. The right of the senior appropriation is not a correlative (where the effects of a low flow are shared among water right holders) right. The senior appropriator is entitled to fill his decree to the exclusion of all the other water users on the stream if the available water is equal to or less than the amount to which the senior appropriator is entitled under his decree. Water available in the stream above the right with the best priority, is available to the right with the second best priority, etc.

An instream flow water right established by the BLM on the San Pedro will have a 1985 priority date or later. This is a very junior right. Fortunately for BLM, the senior surface water rights are located downstream of the acquired properties.

As noted before, senior water rights located below the BLM lands act as water magnets drawing the flow of the San Pedro through BLM lands. There is no guarantee that under Arizona law those senior water rights will always be below BLM. Under conditions prescribed by Arizona law, the rights could transfer to some point above BLM. Such a transfer would carry with it the terms of the senior decree i.e., priority and amount of entitlement, but with the limitation that there can be no injury to other vested water rights.

"The general rule is that given a right to the capture and use of water in an amount certain, one has the right to change the place of storage or diversion so long as other users' rights are not impaired." *Fritsche v. Hudspeth* 262 P.2d 243,245 (1953).

Holding a water right, albeit very junior, BLM is entitled to conditions on the stream as of the date of its appropriation. BLM could limit or condition any surface water right transfer considered by the Arizona Department of Water Resources which could impact BLM's instream flow rights.

Ground water—The San Pedro is the apex of a triangle of water whose sides slice into the alluvial (stream channel) aquifer and into the regional aquifer. Our ground water analysis has established that intrusions into this ground-water triangle are likely to be expressed in reductions in San Pedro surface flow. Furthermore, significant reductions in annual peak flow are shown to result in less alluvial aquifer recharge and lower ground-water levels along the river. The steady low flows which nurture the riparian vegetation and sustain the wildlife, fishery, and other natural values of the San Pedro are little more than a reflection of the amount of water represented in the alluvial and regional aquifers.

Our concern with ground water stems from the possibility that drafts from the alluvial and regional aquifers will reduce the flows in the San Pedro River necessary to sustain the natural characteristics of the acquired properties.

Historically, Arizona recognized two kinds of ground water, percolating and underground stream water. A landowner has an intrinsic right to develop the percolating ground water beneath his land. Underground streams on the other hand are subject to the rules of the Appropriation Doctrine discussed for surface waters above.

The presumption is that ground water is percolating in Arizona. To appreciate the broad expanse of this presumption the court in *Maricopa County MWCD v. Southwest Cotton Co.* 39

Arizona 65, 4 P.2d 369 (1931); modified, 39 Arizona. 367, 7 P.2d 254 (1932) states "the presumption is that underground waters are percolating in their nature;" to defeat the presumption, it must be shown by "clear and convincing evidence" that the aquifers at issue "have a definite bed, banks, and current" the location of which must be shown "with reasonable certainty."

In 1952, the Court decided *Bristor v. Cheatham* 73 Arizona 228, 240 P.2d 1, 85 in which ground water in Arizona was declared to be subject to the Appropriation Doctrine overruling *Southwest Cotton Co.* One year later, a new Supreme Court Justice was appointed, the court reversed itself and the standards of *Southwest Cotton Co.* were restored.

The development of percolating ground water in Arizona is limited only by the common law Doctrine of Reasonable Use. The Reasonable Use Doctrine was the dominant form of ground-water administration in Arizona until the passage of the Arizona Ground-water Management Act in 1980. The Reasonable Use Doctrine allows a landowner to use the ground water beneath his land in an amount necessary for a recognized beneficial use on his land. Waste or transport of water to unrelated lands, is contrary to the fundamental tenets of the Doctrine.

The legal definition of percolating ground water segregates this resource administratively from underground water in a defined channel and surface water. The ground water in the San Pedro River has been treated historically as percolating ground water. Therefore, a well adjacent to the stream would be entitled to pump ground water under the Doctrine of Reasonable Use to the detriment of surface water rights established at an earlier date (unless the surface water appropriator can overcome the rigorous percolating ground-water presumption in *Southwest Cotton*).

In Arizona, the right to develop percolating ground water is independent of the rights of surface or tributary ground-water users. For the purposes of this analysis, it is absolutely critical to establish that ground water in the San Pedro Basin is not percolating. If we can not establish the connection between ground-water depletions from the regional and/or alluvial aquifers and stream flows in the San Pedro, we will have no mechanism for protecting any instream flow rights we may perfect.

There are two mechanisms for establishing this connection between ground-water depletions and stream flows. The common law (case law) mechanism involves overcoming the *Southwest Cotton* presumption, i.e., establishing that there is an underground stream with a definable bed, bank, and direction of flow. We are extremely fortunate in that the most recent analysis of the San Pedro Basin done by the State of Arizona takes a tremendous step toward defining the San Pedro ground-water system in precisely those terms. *The Preliminary Hydrographic Survey Report for the San Pedro River Watershed* by the Arizona Department of Water Resources, January, 1987 describes the basin in terms of its depth, geographic extent, direction of flow, and even quantity of flow.

The technical avenue for establishing the ground-water/surface water connection at common law is in hand.

The Arizona Groundwater Management Act (1980) may, with some very significant legal massage, serve as the basis of a second legal mechanism for establishing the ground water/surface water connection. One of the operative facets of the law is the power to establish ground-water Active Management Areas (AMAs). The four AMAs which have been established in Arizona articulate limitations on ground-water overdraft within those AMA boundaries. The existing AMAs do not consider surface water resources.

We believe that the Arizona Groundwater Management Act is written broadly enough that it could consider, if not directly, at least indirectly surface water resources within the AMA. The AMA represents a uniform ground-water management framework which will overlay the basin. The BLM as a basin water user must actively participate in the design of any AMA proposal to insure that, to the greatest extent possible, instream flows in the San Pedro are considered and protected.

Once the connection between ground-water depletions and surface water flows is established, we will have accomplished a great deal on behalf of the resources associated with instream flows of the San Pedro River. The rules of the Appropriation Doctrine allow a surface water appropriator with a better priority date to protect his rights against junior ground water or surface water appropriators. The Arizona Supreme Court found in *Pima Farms v. Proctor* 245 p. 369, 1926:

> No person will be permitted to decrease the quantity of the underflow to the depletion of the surface stream, and thereby, destroy or render ineffective the prior appropriator's means of diversion. Section 1163, Vol. 2 (2d Ed.) Kinney on Irrigation and Water Rights. In other words, the appropriator does get something more than a water right; he gets an easement in the bed of the stream and the underflow to support and carry his water so that it may be used and enjoyed, and while he does not appropriate or apply to beneficial use, as that term is understood, the underflow, and while such underflow may be appropriated, those who appropriate it must adopt means to preserve the prior appropriator his rights without injury to him.

Utilizing either the common law or Arizona statute, we must establish the ground-water/ surface water connection. Once the connection is established, we may rely on the protections afforded by the Appropriation Doctrine. The protection afforded a water right with a 1985 or 1987 priority date is extremely small. We must therefore look at mechanisms for bolstering our priority date.

If the connection between surrounding ground-water depletions and the flow regime of the San Pedro is not recognized by the State, the ability of the BLM to protect instream flows in the San Pedro will be virtually non-existent. The further development of the adjacent ground-water aquifer is a certainty. If that development takes place without the consideration of resultant stream flow depletions in the San Pedro, the instream flow rights of the BLM will be of small consequence.

The BLM must develop sufficient ground-water data so that we will be able to overcome the presumption of percolating waters where ground-water depletions on adjacent lands threaten necessary streamflows in the San Pedro. Although the alternative of establishing a San Pedro AMA is attractive, we must prepare for a more probable eventuality—litigation and negotiation. Agreements between the water interests in the San Pedro basin could be utilized in lieu of AMA designation. Ground-water data must be available to support any management alternative which would consider an agreement between water users.

Acquired Wells and Other Associated Water Rights—If BLM is able to establish the connection between a surface water instream flow and ground-water depletions, we will have relied upon the Appropriation Doctrine. The cornerstone axiom of this Doctrine is "First in time, first in right." Our 1985 priority date (from our existing instream flow application) standing by itself would fare poorly as compared with ground-water appropriations initiated even as late as the 1960s or 1970s. The unsettling result of establishing the surface water/ground-water nexus is that we would have a poor priority date.

A side note is that a Federal Reserved right would give us an even lower priority date. This will be discussed later.

It might be possible to rely on the Saint David Ditch water magnet to be a legal "fix." This alternative might work providing Saint David asserted their rights to water at their headgate utilizing their legal expertise and their money. A more reliable solution to this dilemma should be considered.

Along with the acquired properties, BLM acquired a battery of wells once utilized for irrigation purposes and various surface water rights.

The transfer of these water rights to an instream flow use would serve as a powerful tool in maintaining the integrity of our instream flow appropriation once the connection between ground-water depletions and surface water flows has been established through the establishment of an AMA.

The acquired wells are very important to the BLM. Although the BLM may never irrigate an acre of land, these rights may serve as the basis of an instream flow right in the San Pedro. The well rights must therefore never be allowed to lapse. The wells should be maintained, periodically pumped, and the water applied to a beneficial use to avoid any implication of abandonment.

Further, the formula for determining the amount of water which can be transferred from a well to an alternative use such as an instream flow is dependent upon the amount of water applied to a beneficial use for the 5 years prior to establishment of the AMA. Strict compliance with the letter of Arizona law may require that the BLM pump the aquifer on a regular basis to maintain the viability of the rights to the acquired wells.

FEDERAL RESERVED WATER RIGHTS

When Congress acts to set aside a parcel of land from the public domain for a particular purpose, there arises by implication, a water right of sufficient quantity to satisfy the primary purposes of the reservation in and to waters unappropriated at the time of the reservation

The facts of *Cappaert v. United States* 426 U.S. 128 (1976) are technically similar to the facts which surround a potential reserved water right on the San Pedro River. This discussion is predicated on the creation of the San Pedro Riparian National Conservation Area.

In *Cappaert* a 40-acre parcel of land was designated a National Monument in 1952. The purpose of this designation was to protect a cavern full of water which is home to the Devil's Hole pupfish. The Cappaert's owned an adjoining parcel of land which they irrigated utilizing a system of wells. The pumping of the wells drew down the water in the pool so that the primary purpose of the reservation, the maintenance of pupfish habitat, could not be realized.

If the San Pedro River is to become a part of the San Pedro Riparian National Conservation area a reserved water right would be created absent any indication to the contrary by Congress. The creation of a reserved water right does not necessarily require the assertion of a reserved water right as we are discovering in the wilderness reserved water right case *Sierra Club v. Block* Civil Action No. 84K2. In his decision Judge Kane found the existence of a reserved water right irrefutable, but reasoned the protection of the values associated with that water right might be protected through other mechanisms.

If the San Pedro River and its adjacent lands become a part of a Federal reservation, the resultant reserved water right would have some interesting characteristics:

1. The right would be created in and to waters unappropriated as of the time of reservation. Our reserved water right would have a priority date of 1987. We would not antedate anyone. We would be the last appropriator in line. Our State law based instream flow appropriation would have a priority date 2 years earlier.

2. The right would be for the primary purposes of the reservation. The flow regime necessary to sustain the riparian character of the river would be substantially different than the flow regime described in our instream flow application. Other than the high-end flows necessary for Cottonwood reproduction, we would be entitled to less water utilizing a reserved water rights argument.

3. A reserved water right exists in the face of State law to the contrary. The problems regarding the ground-water/surface water connection would be resolved more favorably to BLM utilizing a reserved water rights theory. State law cannot be construed to defeat a Federal property right. Strangely, this argument from the Federal Supremacy Clause may be available whether or not a reserved water right is created. Theoretically, if Congress purchases an area to protect its riparian values, State law cannot be construed to diminish the values of an area purchased by Congress for a specific purpose.

Under the circumstances, the best that can be said for a reserved water right is that it helps resolve the issue of ground-water/ surface water connection. A reserved water right, standing by itself would probably result in less water and a more junior priority date. However, if at some point in the future, the State refuses to recognize that ground-water depletions on adjacent lands in the San Pedro basin are having detrimental affects on the flows in the San Pedro River, a Federal water right will be an important resource protection tool.

The reserved water rights of the Gila River Indian Reservation may have an impact on BLM instream flow rights in the San Pedro River. As discussed earlier, downstream, senior water rights have the effect of drawing water to a point downstream. It is difficult to imagine the low and moderate flows of the San Pedro River having much of an impact on the Gila River. However, the high flows of the San Pedro, those that flush through drainage basin in the spring, distributing and embedding the seeds of the cottonwoods, later nurturing the seedlings—those flows may have been available historically to the Gila River Indian Reservation. Although these flows were available irregularly, they may be a significant part of any claim by the Gila River Indian Reservation. This kind of a claim would benefit the BLM. The Saint David Irrigating Company would claim low and moderate flows, the Reservation would claim the high flows, and BLM could leave the issue of ground-water/surface flow connection to the Reservation.

INTERNATIONAL LAW

Arizona water law, reserved water right claims, and any other Federal water right claims are rendered insignificant if the Republic of Mexico exercises its dominion over the headwaters of the San Pedro River. Regardless of the basis of the water right claim or its historic beneficial user in the United States, there are no limitations on Mexico's right to dry up the San Pedro River at the International Boundary.

According to USGS data, of the 4,483 square miles within the San Pedro drainage area, 696 square miles are located in Mexico. Yet, according to gaging records at Palominas, Arizona, and the Charleston Gaging Station—the flows from Mexico represent 61% of the flow in the San Pedro River at the Charleston Gage. The impact of a 61% reduction in flows on the San Pedro River would be very significant.

In addition, the ground-water flow from Mexico to the United States is estimated to be 3400 acre-feet per year. Fifty wells were recently drilled by the Cananea Mining Company near the City of Cananea, Sonora. The closest well to the international boundary is about 15 miles away. The total depletions projected from these wells is 40,000 acre-feet per year.

Predictions on how these depletions will affect the San Pedro River in the United States vary greatly. The critical point is that Mexico has every legal right to develop the subsurface source and the surface expression of the San Pedro River to extinction at the border and for some distance beyond.

In addition, there are no limitations on the quality of water entering the United States from Mexico. The Cananea Mine has been a source of heavy metal contamination in the San Pedro.

Beginning in mid-December 1977, and periodically through March 1979, overflow and seepage from the Cananea tailings ponds played havoc on the water quality of the San Pedro River. Efforts to correct the situation in Mexico have apparently met with some success. However, there are no international restrictions on the water quality in the San Pedro River.

The Treaty of 1944 between the United States and Mexico concerned the allocation of water from the Colorado River to Mexico. IWBC Minute 242 addresses the issue of salinity in the deliveries of water to Mexico. There is no provision in any agreement between the United States and Mexico which addresses the problems of the San Pedro River discussed above.

Unless some formal agreement between the United States and Mexico is reached concerning the allocation of surface and ground-water resources between the two countries and the related water quality problems, water development in Mexico, and/or water quality degradation in Mexico could render this conservation effort irrelevant. A formal agreement is no absolute guarantee that there will be flows of sufficient quality and quantity in the San Pedro to sustain the natural qualities of the area. However, we must pursue an agreement with the same enthusiasm with which we develop the area for the public.

LEGAL STRATEGIES

I. Status Quo

  A. Pursue the adjudication of Application to Appropriate Public Waters No. 33-90103

  B. If perfected, protect this right through full participation in the State water right administrative process.

  C. During periods of severe water shortfalls, the opportunity to pump the acquired wells may provide some short duration relief.

  D. Rely on the protection offered by the presence of downstream senior water rights.

  E. Utilize the information generated by this report to develop management alternatives for the riparian areas associated with the San Pedro.

Analysis: There is a de facto instream flow on the San Pedro as of this moment. A recognized water right would enhance our ability to protect instream flows on the San Pedro. The issue of ground-water depletions and the effect on surface water flows could be delayed until we had a measurable impact. The problem with this approach is once the percolating ground-water presumption is overcome (no mean feat). We have to prove which ground-water user is responsible for our injury. We may be able to go for years however, before this problem would confront us.

II. State Law, No AMA

A. Pursue formal agreement with the Republic of Mexico regarding water quantity/ quality of the San Pedro River.

B. Amend Application to Appropriate Public Waters No. 33-90103 to reflect the results of this study and purposes in complete conformance with Arizona water law. Purchase the St. David Irrigation Co. rights and deliver the historic appropriation to St. David at its headgate.

C. Perfect and protect the amended instream flow water right.

D. Negotiate an agreement with the major surface water/ground-water users in the San Pedro River Basin which would afford the instream flow protection from adjacent ground-water withdrawals.

E. Aggressively participate in the State water adjudication process.

F. Develop ground-water data in preparation for defending the instream flow in State Court or as the basis for a negotiated agreement.

Analysis: Any effort expended on developing the area for the benefit of the public should be matched by an effort working with the Congressional Delegation of Arizona to develop the terms of a formal agreement with the Republic of Mexico to protect water quantity and quality of the San Pedro River. We should amend our application to reflect more correctly the flow regime required to maintain the natural characteristics of the area, to conform more precisely to Arizona statutes, and to reflect our use of St. David water to bolster our priority date.

An agreement between the major water users in the basin and the BLM would be advantageous to all parties involved. The water users would be able to enjoy percolating waters without the restrictions of an AMA where surface water withdrawals may eventually have to equal ground-water recharge. The acquired wells may be utilized as bargaining chips in the negotiation of a water user agreement. We may agree to defer pumping to allow adjacent ground-water users to pump at certain times of the year, for example. It is very important that BLM develop good ground-water information to help formulate a strong negotiating position.

III. State Law, AMA

A. Pursue formal agreement with the Republic of Mexico regarding water quality/ quantity of the San Pedro River.

B. Amend Application to Appropriate Public Waters No. 33-90103.

C. Perfect and aggressively protect the amended instream flow appropriation.

D. Develop ground-water data to insure BLM's participation in the AMA process is informed and positive.

E. Rely on downstream senior water users and participate fully in the State water right administrative system.

F. Utilize acquired wells as facets of an augmentation plan on which rights may be transferred in exchange for other water rights on land.

Analysis: If the State initiates an AMA, BLM need only establish an informed position in the process and participate enthusiastically. Our work would be done for us in the engineering studies which would follow. The acquired wells (provided we have not abandoned them) will become extremely valuable both for our purposes and BLM's purposes of water development in the basin. BLM could utilize those rights to exchange for land or upstream rights. The senior nature of the acquired rights is a major plus for the BLM in an AMA process.

IV. Federal Law

A. Pursue formal agreement with the Republic of Mexico regarding water quantity/ quality of the San Pedro River.

B. Notify Arizona of BLM's intent to claim a Federal Reserved Water Right.

C. Quantify the reserved right utilizing the information generated from this document and notify the State.

D. Develop ground-water data necessary to establish whether or not ground-water depletions caused by other water users are infringing on the reserved right.

E. Actively participate in the State water administrative process.

F. Be prepared to utilize acquired wells for short-term water supply or facets in a plan of augmentation.

Analysis: The reserved water right BLM could claim in the event the area is set aside by Congress would have a less senior water right for a lower overall quantity of water than our State instream flow right. However, it would likely move the State toward recognition of the connection between ground-water depletions and surface flows. Once recognized, however, our reserved water right would be junior to all the rights with which we established a connection. We would need to augment the instream flows through the rights granted the acquired wells.

INSTREAM FLOW ANALYSIS

Instream flow recommendations are expressed as a percentage of the median of the daily flows for each month in the year averaged over the period of record. Median flows are believed to be more representative of daily flow conditions than mean flows because of the highly skewed nature of daily flow distributions. The annual San Pedro River flow regime was stratified into four distinct seasons to facilitate the instream flow analyses. The April-June spring season is the primary low-flow period, and the July-September summer season is the primary high (flood) flow period for the river. A secondary low-flow period occurs during the fall (October-November), and a secondary high-flow period occurs during the winter (December-March). Recommended instream flows are provided in Table 15 and justified below. All flow recommendations reflect consideration for historic base-flow declines.

Table 15. Recommended Instream Flows for the BLM San Pedro River Properties

Period	Month	Flow Recommendation, cfs	
		Palominas	Charleston/Tombstone
Fall	Oct.	3.7	12.2
	Nov.	3.6	13.6
	Dec.	5.5*	17.1*
Winter	Jan.	7.9*	19.5*
	Feb.	8.6*	20.3*
	Mar.	6.3*	18.9*
Spring	April	2.5*	12.2*
	May	1.2*	7.9*
	June	0.6*	4.2*
Summer	July	7.0*	19.0*
	Aug.	7.0*	19.0*
	Sept.	7.0*	19.0*

* *This value or runoff equating to that amount generated by 60% of the contributing basin being unimpounded or undiverted, whichever is greater, where contributing basin is defined in terms of water yield, not land surface area (see Figure 48.)*

Spring Period

Recommended spring-period (April-June) flows represent 100% of the average median daily flow for the period of record up to 1986. Where recommended flows are not naturally available, 100% of the instantaneous flow is recommended for instream purposes. Spring-period flows have declined to where present daily flows are less than the 50-year norm. Previously perennial reaches now become dry during this period. Thus, the overall length of perennial stream has decreased. This is an aesthetic factor impairing recreational use of the river. It may also adversely influence riparian vegetation seedling establishment by reducing the availability of required continuously moist surface soils. The spring period is a critical period for juvenile fish survival and fish growth, and is an important bird migration period. Recommended flows are required to prevent further loss of open water habitat for fish and wildlife. The general ground-water declines associated with decreased April-June flows probably have not seriously impacted established vegetation. However, local drawdowns due to pumping of the floodplain aquifer may have influenced vegetation survival. Cottonwood is probably the most sensitive species to localized ground-water declines. Further generalized ground-water declines may

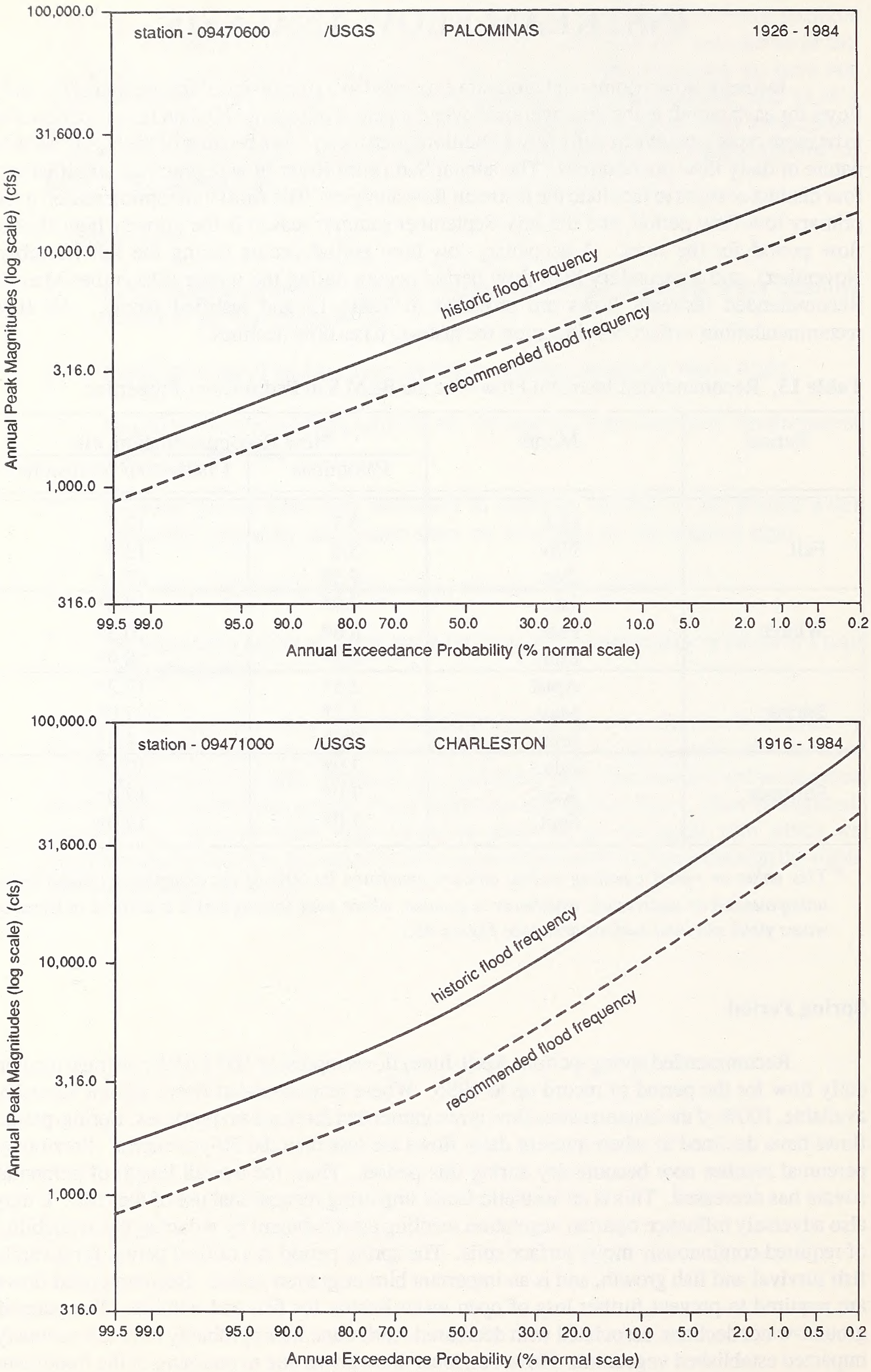


Figure 48. Recommended flood-frequency relationship for San Pedro River at Palominas and Charleston.

affect vegetation survival and would work against conditions which favor overall aggradation and development of floodplains. Recommended spring-period flows will provide for maintenance of a perennial stream throughout the study reach, and should correspond to stabilized ground-water levels. During April, May and June, 60 percent of the natural storm flow is required for purposes of cottonwood reproduction whenever that value exceeds the recommended flow.

Summer Period

Recommended summer-period (July-September) flows represent 60% of the natural storm flow or the mean winter period median monthly flow for the period of record up to 1986, whichever is greater. Summer-period peak flows are critical to the maintenance and evolution of geomorphic features—especially floodplains, point bars, and nursery bars. Summer floods are also required for the regeneration of riparian vegetation, and may stimulate reproduction of fishes. High (flood) flows are also shown to contribute—though briefly—to recharge of the floodplain aquifer and thus play a role in maintaining water tables, riparian vegetation, and stream flows during some low-flow periods.

Baseflow recommendations correspond to winter-period baseflow conditions and are considerably lower than median daily flow conditions in the summer period. However, it was judged that the higher summer period median flows—which largely reflect storm runoff—did not significantly enhance water-dependent resource values, and that all values were adequately maintained at winter-period median flow conditions.

While summer high flow is the critical parameter for this period, flow rates in excess of the present 10-year return period flood probably favor channel incision and may cause excessive riparian zone physical adjustments. However, if 2-10 year return-period flood peaks did not occur, healthy evolution and development of floodplains and, eventually, channels would be halted. This would inhibit riparian vegetation reproduction and succession, and would favor maintenance of older mature species over regeneration. Elimination of flooding would also reduce recharge of the floodplain aquifer, lowering water tables and reducing low flows. Restricting floodplain evolution and development would also impair recreation attributes—openness and ease of travel—and would influence wildlife habitat by reducing vegetation diversity. High flow recommendations equate to a 60% reduction in the flood-frequency relationship for the river. This corresponds roughly to a shifting of the 10-year flood to the 50-year return period.

It is important to understand that excessive flood volumes are not a problem—only excessive instantaneous flow rates. The best of all possible situations would be to maintain greater than 10-year return-period flood volumes while eliminating greater than 10-year return-period flood peaks. This ideal situation can be accomplished either through natural evolution of the channel, floodplain and riparian zone, or by properly located, designed, and operated detention structures. The summer-period high flow recommendation is provided as a minimum requirement for maintenance of riparian zone geomorphic processes in the event that future detention projects are proposed. The study team believes, however, that discharge data suggest that healthy evolution of the high (flood) flow regime is occurring in the absence of water storage structures.

Fall Period

Recommended fall-period (October-November) flows represent 100% of the average median daily flow for the period of record up to 1986. Where recommended flows are not naturally available, 100% of the instantaneous flow is recommended for instream purposes. The fall period is a secondary low-flow period, which like the spring period is a critical period of growth and productivity for fishes. The fall period is also an important bird migration period and potential recreation use period. Median daily flows during this period have also been reduced over historic norms. These reductions influence values in the same way as spring-period flow reductions, but the effects may be somewhat less than for comparable spring-period reductions. However, given the trend of historic declines in fall period flows, and the association between fall-period flows and riparian zone water tables, the study team judged that 100 percent of the median daily flow was required to prevent further resource degradation.

Winter Period

Recommended winter-period (December-March) flows represent 100% of the average median daily flow for the period of record[3] or 60% of the natural storm flow, averaged over a long (100 yr. +) period of record, whichever is greater. Where recommended flows are not naturally available, 100% of the instantaneous flow is recommended for instream purposes. Riparian zone ground-water gradients suggest that winter-period median flows largely reflect discharge to the stream from the regional aquifer. These flows are critical to maintaining fish, wildlife and aesthetic values in the stream corridor as well as for maintaining water table elevations in the riparian zone. Median daily winter flows are roughly twice those of fall-period flows and over four times those of the spring period. This is largely a reflection of reduced ground-water pumping and phreatophyte use during the winter period. Median winter-period flow reductions would correlate to measurable reductions in riparian zone ground-water levels and would cause unacceptable reductions in fish nursery habitat. In general, wetted perimeters decrease rapidly with decreases in discharge below the median winter flow rate (Appendix II). Cross-sectional flow area also decreases linearly with decreases in flow (Appendix II).

The winter period is also an important secondary high flow period. Winter high flows rework the channel and create ephemeral backwater areas critical to fish spawning and rearing. Winter is the key spawning season for San Pedro River fishes.

A summary of critical factors influenced by instream flow recommendations is provided in Table 16.

Table 16. Summary of critical factors influenced by Instream Flow recommendations.

Period				Critical Factors
Oct.-Nov.	Dec.-Mar.	April-June	July-Sept.	
X		X		Length of perennial stream
X	X	X	X	Riparian water table
X	X	X	X	Veg. maintenance
			X	Veg. reproduction
	X		X	Ground-water recharge
			X	Floodplain development
X		X		Fish maintenance, growth
X		X		Wildlife water
	X	X	X	Aesthetics
			X	Travel
			X	Camping
			X	Canoeing
	X			Fish reproduction

---

[3] *One extreme median flow value for January (1682 cfs at Palominas and 230 cfs at Charleston) was omitted from the analysis because it was considered to be well outside the normal range of median flow values for the month.*

RECOMMENDATIONS

WATER RIGHTS

Under the provisions of FLPMA, BLM can plan for and implement management alternatives which affect the surface and subsurface land resource. The BLM does not have an inherent right to use water in Arizona either by virtue of surface ownership or FLPMA. The flows of the San Pedro River necessary to sustain the natural values of the area are available to appropriation and may in fact already be committed to uses on adjacent private lands.

To maintain sufficient water supplies to sustain the natural values of the San Pedro River, the BLM must perfect a water right recognized under Arizona law. Whether that right is based in Federal law (reserved water right) or State law (instream flow appropriation), the BLM must have some cognizable right to the waters of the San Pedro River.

Surface water resources in Arizona are allocated and managed through the Appropriation Doctrine. The cornerstone axiom of this Doctrine is "first in time, first in right" In times of water shortage, water resources are managed so that the rights established earliest historically will be entitled to take their water allocation, while rights established later in time (junior priorities) may not receive any water.

The BLM Application to Appropriate No. 33-90103 was originally filed by the Huachuca Audubon Society, Chiricahua Sierra Club, and Defenders of Wildlife on August 12, 1985 and assigned to BLM on May 25, 1986. Although this is a very junior appropriation, there are no senior surface rights above the acquired properties or within the study corridor except for the St. David Irrigation Company located at the terminus of the study corridor.

BLM is confronted with two problems:

A. establishing the ground-water/surface water connection.
B. poor water right priority once that connection is established.

Surface Water/Ground-Water Connection

Under Arizona law, there is a strong presumption favoring the characterization of ground-water resources as percolating. Absent legislative directives to the contrary (the creation of an Active Management Area) or establishing that the ground-water basin is actually an "underground river" (Arizona case law), the effect of ground-water depletions on surface water supplies is not recognized by the State. The right to develop percolating ground water is a right of surface ownership limited only by the Doctrine of Reasonable Use. Under the Doctrine of Reasonable Use, a surface owner adjacent to the stream would be entitled to pump the stream dry. In a system like the San Pedro where the groundwater storage in the alluvial aquifer is small, ground-water depletions from lands adjacent to the stream will be quickly reflected in diminished streamflow.

In its *Preliminary Hydrologic Study Report*, Arizona recognized that ground-water development of the regional aquifer would eventually have an impact on the San Pedro River. However, as of the date of this analysis, ground water is administered by the State as percolating ground water.

In order to protect any instream flow appropriation on the San Pedro River, ground-water depletions must be administered under the same legal restrictions as surface rights. This can be done either through a basinwide water user agreement, the creation of an AMA, or the assertion of a reserved water right for an instream flow on the San Pedro.

A. Water User Agreement

A Water User Agreement with the major ground-water users in the basin looks very good on first glance. The best example would involve the community of Sierra Vista. Sierra Vista has fairly predictable ground-water drafts whose impact on the San Pedro River could be modeled. Those impacts would probably look like a sine wave with peaks and troughs at a given frequency. An agreement between BLM and Sierra Vista could consider these impacts and a plan could be developed which would coordinate the peak ground-water drafts with historical high-flow periods on the river. Surface water collection structures could account for slack rainfall years. It is conceivable that a technical solution exists to the water supply problem.

Unfortunately, the existing ground-water management of the San Pedro River Basin would not afford any protection to such an agreement. Any landowner between the San Pedro River and Sierra Vista could develop wells and negate any benefits which would derive from such an agreement. We would need to have a second agreement and more modeling. Eventually, there would need to be an agreement with every landowner in the basin. Such an undertaking is difficult to conceive and impossible to recommend.

To be an effective tool, a water-user agreement would need to be complemented either by some form of intermediate legislation limiting additional ground-water development in the basin or by an agreement with the State of Arizona to manage groundwater and surface water resources in the San Pedro River basin under the tenets of the Appropriation Doctrine.

B. Active Management Area

The creation of an Active Management Area (AMA) in the San Pedro River basin would be a substantial first step toward solving the technical/legal instream flow puzzle for the San Pedro River. The primary benefit of AMA designation is that the State manages the ground-water/surface water resource recognizing that ground-water depletions will have an effect on surface water resources. A priority system of rights is established. Ground-water development is limited in the sense that ground-water depletions must eventually recharge over a period of years. A secondary benefit is that the acquired wells become water rights of significant priority rather than holes in the ground drilled as a peripheral right of land ownership. At some date in the future, those well rights could be traded for land or other interests in land. Designation of the basin as an AMA would be extremely advantageous for BLM. The latitude for imaginative technical solutions to the water allocation problems in the basin is limited. However, the benefits which would derive from designation would far outweigh any disadvantages.

C. Federal Reserved Water Right

A Federal reserved water right is a right which can be created and exists in the face of State law to the contrary. The assertion of a water right for an instream flow in the San Pedro River would be a strong argument in favor of managing ground-water and surface-water resources in the basin under a comprehensive administrative mechanism. The BLM would be entitled to protect its instream flow water right despite Arizona ground-water law allowing the reasonable use of percolating ground water.

Priority

Once the groundwater/surface water connection is legally established, BLM is confronted with the priority of its instream flow water right. Under the best possible construction, the BLM would be awarded a 1985 priority water right under Application to Appropriate No. 33-901033. The priority date of any reserved water right would be even more junior.

The priority dates of the major adjacent ground-water users would reach back into the 1960s. These water users would be entitled to withdraw their allocation of water before the BLM received water for an instream flow in the San Pedro. However, the most senior right on the San Pedro belongs to the St. David Irrigation Co. (SDIC) located at the lower end of the study segment. If groundwater and surface water are managed under the Appropriation Doctrine, SDIC should be entitled to its allocation of water unencumbered by the depletions to the stream created by ground-water use.

Provided SDIC diligently protects its water rights and does not transfer its rights elsewhere, BLM's low priority date is of little consequence. SDIC will protect BLM's base flow requirements from ground-water depletions while the high-flow requirements are nearly independent of ground water table conditions. Thus, assertion of the SDIC water right is a component of the water rights protection afforded the BLM San Pedro River properties.

In conclusion, the BLM must be concerned with establishing the ground-water/surface-water connection and taking steps to bolster our insignificant priority dates through acquisition, transfer, or change in use of the acquired wells.

RESOURCE MANAGEMENT

During the course of this project, the study team developed the following miscellaneous resource management recommendations which support water conditions and water-dependent processes in the riparian zone.

1. **Land Acquisitions:** Acquisition of agricultural lands along the San Pedro River between the former acquired properties and the Mexican border is highly recommended. The BLM has already taken initiatives to acquire these properties. Ground-water pumping for irrigation of these lands has already contributed to reduced base flows in the river. Discontinuing irrigating of these properties should contribute to enhanced spring-period flows in the river.

2. **Ground-Water Pumping - BLM Wells:** Pumping of the acquired acquired wells will cause local water table drawdowns. This could adversely impact cottonwood survival in the vicinity of the wells. While very low pumping rates may not be a problem, we recommend against any significant ground-water pumping in the BLM properties.

3. **Livestock Grazing in the Riparian Zone:** Heavy livestock grazing reduces vegetation density and may restrict regeneration of woody riparian species including willow and cottonwood. This results in decreases in Manning's "n" and works against dissipation of flood energy and sediment deposition. The project team recommends that livestock grazing be managed to promote favorable vegetation conditions on the floodplain and to favor woody vegetation establishment.

4. **Channel Enhancement Structures:** Instream structures such as gabion steps or deflectors intended to promote channel conditions for fishes are generally incompatible with alluvial channels undergoing fairly rapid adjustments. Both the adjustable nature of the San Pedro River channel and the extremely high flood flows experienced periodically mean that most small instream structures would wash out. We recommend against the installation of small channel enhancement structures.

5. **Erosion Control Structures:** In certain places the San Pedro River is actively bank cutting. This is part of the normal process of widening and floodplain development which follows episodes of river entrenchment. We believe this process is beneficial to the river and floodplain and should not be controlled (an exception might be if continued widening threatened an important archaeological resource).

6. **Water Control Structures:** Large mainstem structures intended to detain runoff and induce sediment deposition could serve to improve hydrologic regime (if peak flows were reduced—not eliminated) and help create the cienega-type habitat which was lost during the past episode of river entrenchment. However, through the maintenance of instream flows and proper management of land uses in the riparian zone and adjacent watershed, natural adjustment process—over time—can achieve these same hydrologic/geomorphic objectives. While it is a philosophical topic, we believe that the natural healing and evolutionary processes now occurring along the San Pedro River are in themselves a resource value of particular scientific interest. Large detention structures would straightjacket those processes and force predetermined conditions upon the resource. We recommend against their use. However, in the event that groundwater tables decline to the point where the resource is critically threatened, use of carefully designed and located detention structures could serve to help augment baseflows with stored stormflow runoff.

7. **Vegetation Plantings:** While some selected planting of cottonwood or other riparian species may be considered for management or scientific purposes, we recommend against widespread artificial cottonwood planting along the San Pedro River at this time. Tree forestation along the river eventually results in bar building and stream course migration. Trees should not be planted until it is possible to predict the effects on channel adjustments and floodplain development. This will require additional study of the relationships between vegetation and channel dynamics. Natural reproduction and successional changes—aided by maintenance of instream flows and restricted livestock grazing—appears to be a prudent management strategy.

8. **Bridges:** Highway bridges serve to artificially constrict flood flows—thus working against sediment deposition. If at some time in the future bridges at Charleston, Lewis Springs, or Hereford are scheduled for replacement, BLM might wish to encourage designs which allow for normal spreading of floodflows.

9. **Intergovernmental Coordination:** This topic is discussed in detail elsewhere in this report. However, we wish to reiterate the importance of open dialog with city, county, State, and international agencies regarding the management of surface water and groundwater uses and water quality.

10. **Research:** A number of high-priority research topics were identified by the project team during the course of this study. Some of them are listed below:
    a. Additional modeling of the groundwater resource and the impacts of water

table drawdowns of riparian zone water conditions and instream flows is required. The modeling effort should include the Mexican portion of the watershed and should be coordinated with the city of Sierra Vista, the Fort Huachuga military base, the Arizona Department of Water Resources and possibly the U.S. Geological Survey. Use of University or consultant services might also be appropriate.

b. Additional research into the effects of water table declines on cottonwood survival is required. While it is generally known that cottonwoods are intolerant to drought, the rates of water table decline and total depths of decline which are critical to their survival need to be better quantified. This would allow the development of "threshold" water table conditions for riparian zone management and monitoring.

c. Additional research into fluvial geomorphic processes operating along the San Pedro River is required. Topics include 1) descriptions of historic adjustments following river entrenchment, 2) relationships between flow rates and sediment deposition processes, 3) predictive modeling of channel adjustments and floodplain development which considers interactions with vegetation (refer to recommendation 7).

d. Additional research on cottonwood reproduction along the San Pedro River is suggested. Variables which need to be better understood include the magnitude and timing of flows, required fluvial features, and interactions with other vegetation species.

e. If reestablishment of native fishes is desired, more information on habitat requirements and instream flow relationships will be required.

MONITORING

The project team judged that present discharge monitoring by the USGS is adequate for management purposes. However, it is important that the USGS not discontinue low-flow monitoring at the Palominas gage (budget reductions are currently reducing operation of that gage). Additional water-related monitoring requirements which need to be addressed by BLM are listed below. We did not address the topic of vegetation monitoring.

1. **Groundwater levels:** BLM should continue regular monitoring of water tables in the riparian zone observation wells until annual patterns of change are understood (this will probably require about 2 years of data). They should then be monitored roughly three times per year to determine that water tables are not declining out of their normal range.

   BLM should also begin a coordinated groundwater monitoring program with DWR and the USGS to develop good information on water tables both in the floodplain aquifer and the regional aquifer. The following wells should be monitored on at least an annual basis—and preferably more often that:

   a. T. 20 S. R. 21 E. sec. 16 SWSESE
   (designated also as [D-20-21] 16 ddc)

   b. T. 22 S. R. 22 E. sec. 30 SWSWNE
   (designated also as [D-22-22] 30 ACC)

c. T. 21 S. R. 21 E. sec. 27 SENWSW
(designated also as [D-21-21] 27 cbd)

d. T. 22 S. R. 22 E. sec. 6 NWNESE
(designated also as [D-22-22] 6 DAB)

2. **Sediment Deposition and Channel Adjustments:** At least four of the BLM-surveyed cross sections should be permanently benchmarked and staked (cross sections 1, 2, 6, and 7). They should be resurveyed every 5 years or following flood events of selected magnitudes. This will permit a careful assessment of the direction and rate of channel adjustments and sediment deposition in the riparian zone.

3. **Water Quality:** This study did not address the issue of water quality in any detail. However, this is an important management issue which relates to the maintenance of fish, wildlife, and vegetation. A thorough baseline water quality monitoring program is required.

LITERATURE CITED

AGFD. Statewide Fishery Investigations. 1977-1978. Fed. Aid Fish. Proj. F-7-R - 20), Phoenix.

—. Statewide Fishery Investigations. 1978-1979. Fed. Aid Fish. Proj. F-7-R - 21), Phoenix.

ANDERSON, R.M. 1978. The distribution and aspects of the life history of Meda fulgida in New Mexico. Unpubl. M.S. Thesis, N. Mex. St. Univ., Las Cruces.

ANDERSON, T.W. and N.D. WHITE. 1979. Statistical summaries of Arizona streamflow data. U.S. Geol. Surv. Wat. Resour. Invest. 79-5: 1-416.

— and —. 1986. Arizona surface water resources. USGS Water-Supply Paper 2300, National Water Summary, Arizona. pp. 145-150.

ANON. 1913. Farmers of the Gila Valley win suit with mines. Arizona Gazette 17 (June): 11.

—. 1980. Riparian habitat and instream flow studies lower Verde River Fort McDowell Reservation, Arizona. Riparian Habitat Analysis Group, Office of Environment, U.S. Fish and Wildlife Service, Region 2, Albuquerque, NM. 52pp.

ANTEVS, E. 1952. Arroyo-cutting and filling. J. Geol. 60:375-385.

BAIRD, S.F. and C. GIRARD. 1853. Descriptions of new species of fishes collected by Mr. John H. Clark, on the U.S. and Mexican Boundary Survey, under Lt. Col. Jas. D. Graham. Proc. Acad. Nat. Sci. Phila. 6: 387-390.

BARBER, W.E. and W.L. MINCKLEY. 1966. Fishes of Aravaipa Creek, Graham and Pinal counties, Arizona. Southwest. Nat. 11: 313-324.

— and —. 1983. Feeding ecology of a southwestern cyprinid fish, the spikedace, *Meda fulgida*. Southwest. Nat. 28: 33-40.

BARBER, W.E., D.C. WILLIAMS, and W.L. MINCKLEY. 1970. Biology of the Gila spikedace, *Meda fulgida*, in Arizona. Copeia 1970: 9-18.

BARLOW, G.W. 1958a. High salinity mortality of desert pupfish, Cyprinodon macularius. Copeia 1958: 231-232.

—. 1958b. Daily movements of desert pupfish, Cyprinodon macularius, in shore pools of the Salton Sea, California. Ecology 39: 580-587.

BARTLETT, J.R. 1854. Personal Narrative of Explorations and Incidents in Texas, New Mexico, California, Sonora, and Chihuahua, connected with the United States and Mexican Boundary Commission during the years 1850, '51, '52, and '53, Vols. I-II. D. Appleton and Co., N.Y. and London.

BELL, W.A. 1869. New Tracks in North America, Vols. I-II. Chapman and Hall, London.

BENNETT, E.F. 1977. An afternoon of terror: the Sonoran earthquake of May, 1877. Arizona and the West, Summer 1977: 107-120.

BOLTON, H.E. 1980. Coronado, Knight of Pueblos and Plains. Univ. N. Mex. Press, Albuquerque (3rd printing).

BRADY, W., D.R. PATTON, and JAY PAXSON. 1985. The development of Southwestern riparian gallery forests. Pp. 39-43, In R.R. Johnson, C.D. Ziebell, D.R. Patton, P.F. Ffolliott, and R.H. Hamre (tech. coords.). Riparian Ecosystems and Their Management: Reconciling Conflicting Uses. First N. Am. Riparian Conf., 16-18 Apr. 1986, Tucson, Arizona. USDA For. Serv., Gen. Tech. Rept. RM-120. 523 pp.

BRITT, K.D., Jr. 1982. The Reproductive Biology and Aspects of Life History of Tiaroga cobitis in Southwestern New Mexico. Unpubl. M.S. Thesis, N. Mex. St. Univ., Las Cruces.

BROOKS, J.E. 1985. Reintroduction of Sonoran topminnow, *Poeciliopsis o. occidentalis*, in Arizona. Ann. Rept. U.S. Fish. Wildl. Serv., Off. Endang. Spec., Albuquerque, NM. Ariz. Game Fish Dept., Phoenix.

—. 1986. Reintroduction of Sonoran topminnow, *Poeciliopsis o. occidentalis*, in Arizona. Ann. Rept. U.S. Fish. Wildl. Serv., Off. Endang. Spec., Albuquerque, NM. Ariz. Game Fish Dept., Phoenix.

—, B.L. JENSEN, J.E. JOHNSON, P.C. MARSH, and W.L. MINCKLEY. in preparation. Efforts toward recovery of razorback sucker, *Xyrauchen texanus* (Abbott), in the lower Colorado River Basin.

BROWN, D.E. (ed.). 1982. Biotic Communities of the American Southwest, United States and Mexico. Desert Plants 4: 4-431.

— and C.H. LOWE. 1978. Biotic communities of the American Southwest. USDA For. Serv. Gen. Tech. Rept. RM-41: map, scale, 1:1,000,000.

— and R.S. HENRY. 1981. On relict occurrences of white-tailed deer wiithin the Sonoran Desert in Arizona. Southwest. Nat. 26: 142-152.

BRYAN, K. 1925. Date of channel trenching (arroyo cutting) in the arid southwest. Science 62: 338-344.

—. 1928. Change in plant associations by change in ground-water level. 474-478 pp. Ecology Vol. IX.

BULL, W.B. 1979. Threshold of critical power in streams. Bull. Geol. Soc. Amer. Part I, V(90):453-464.

BULL, W.B. 1979. Threshold of critical power in streams. Bull. Geol. Soc. Amer. 86: 1489-1498.

—. 1981. Soils, geology, and hydrology of deserts. Pp. 42-58, In D.E. Evans and J.L. Thames (eds.). Water in Desert Ecosystems. Dowden, Hutchinson, and Ross, In., Stroudsburge, PA.

BURKHAM, D.E. 1976. Hydraulic effect of changes in bottomland vegetation on three major floods, Gila River in southeastern Arizona. USDI Geol. Surv. Prof. Paper 655-J, 14p.

CALVIN, R. 1946. River of the Sun—Stories of the Storied Gila. Univ. N. Mex. Press, Albuquerque.

CAROTHERS, S.W. and C.O. MINCKLEY. 1981. A Survey of the Fishes, Aquatic Invertebrates and Aquatic Plants of the Colorado River and Selected Tributaries from Lee Ferry to Separation Rapid. Final Rept. Contr. 7-07-30-X0026, U.S. Bur. Reclam., Lower Color. R. Reg., Boulder City, NV. Mus. N. Ariz., Flagstaff.

CHAMBERLAIN, F.W. 1904. Unpublished Arizona field notes. Smithson. Institut. Arch., Washington.

CLARKSON, R.W. 1982. Morphology and Feeding Behavior in Hybrids between Catostomus insignis and Pantosteus clarki (*Catostomidae*). Unpubl. M.S. Thesis, Ariz. St. Univ., Tempe.

COOKE, R.U. and R.W. REEVES, 1976. Arroyos and Environmental Change in the American Southwest. Clarendon Press, Oxford, England, 213p.

COWLES, R.B. 1934. Notes on the ecology and breeding habits of the desert minnow, *Cyprinodon macularius* Baird and Girard. Copeia 1934: 40-42.

CULLER, R.C., R.L. HANSON, R.M. MYRICK, R.M. TURNER, and F.P. KIPPLE. 1982. Evapotranspiration before and after clearing phreatophytes, Gila River floodplain Graham County, Arizona. 67p. USGS Professional Paper 655p.

CURRY, R.R. 1972. Rivers — geomorphic and chemical overview. Pp. 9-31, In R.T. Oglesby, C.A. Carlson, and J.A. McCann (eds.). River Ecology and Man. Academic Press, Inc., New York.

DAVIS, G.P. 1982. Man and Wildlife in Arizona — The American Exploration Period 1824-1865. N.B. Carmony and D.E. Brown (eds.). Ariz. Game Fish Dept., Phoenix.

DEACON, J.E. and W.L. Minckley. 1974. Desert fishes. Pp. 385-488, In G.W. Brown, Jr. (ed.). Desert Biology, Vol. II. Acad. Press, Inc., N.Y.

DEACON, J.E., G. KOBETICH, J.D. WILLIAMS, S. CONTRERAS—BALDERAS, and others. 1979. Fishes of North America: endangered, threatened, or of special concern. Fisheries (Am. Fish. Soc., Bethesda, MD) 4: 29-44.

DE MARAIS, B.D. 1986. Morphological Variation in Gila (*Pisces: Cyprinidae*) and Geologic History, Lower Colorado River. Unpubl. M.S. Thesis, Ariz. St. Univ., Tempe.

DOBYNS, H.F. 1981. From Fire to Flood: Historic Human Destruction of Sonoran Desert Riverine Oases. Ballena Press, Soccoro, NM.

DOUGLAS, P.A. 1952. Notes on the spawning of the humpback sucker, Xyrauchen texanus (Abbott). Calif. Fish Game 38: 149-155.

EBERHARDT, S. 1981. San Pedro River basin water quality status report for period 1973-1979. Rept. Bur. Wat. Qual. Contr., Ariz. Dept. Health Serv., Phoenix.

ECCLESTON, R. 1950. Overland to California on the Southwestern Trail, 1849. Diary of Robert Eccleston. G.P. Hammond and E.H. Howes (eds.). Univ. Calif. Press, Berkeley.

ELLIOTT, J.G. 1979. Evolution of large arroyos—the Rio Puerco of New Mexico. Unpub. M.S. Thesis, Colorado State University, Ft. Collins, Colorado, 106p.

EMORY, W.H. 1857. Report on the United States and Mexican Boundary Survey, Vols. I-II. U.S. 34th Congr., 1st Sess., Senate Exec. Doc. 108, Washington.

ETZ, D.B. 1938. Untitled, unpublished manuscript. Ariz. Hist. Soc., Tucson.

EVANS, G.W.G. 1945. Mexican Gold Trail. G.S. Dumke (ed.). The Huntington Library, San Marino, CA.

EVERMANN, B.W. 1905. Report on inquiry respecting food-fishes and the fishing grounds. Pp. 54-574, In Reports of the United States Department of Commerce and Labor for the year ending June 30, 1904. U.S. Govt. Print. Off., Washington.

— and C. RUTTER. 1895. The fishes of the Colorado Basin. Bull. U.S. Nat. Mus. 14(1884): 487-499.

FENNER, P., W.W. BRADY, and D.R. PATTON. 1984. Observations on seeds and seedlings of Fremont cottonwood. 1984.(???) Desert Plants Vol. 6 No. 1. pp. 55-58.

—, —, and —. D.R. PATTON. 1985. Effects of regulated water flows on regeneration of Fremont cottonwood. Journal of Range Management 38(2). pp. 135-138.

FISHER, S.G. and W.L. MINCKLEY. 1978. Chemical characteristics of a desert stream in flash flood. J. Arid Environ. 1: 25-33.

FISHER, S.G., D.E. BUSCH, and N.B. GRIMM. 1981. Diel feeding chronologies in two Sonoran Desert stream fishes, *Agosia chrysogaster* (Cyprinidae) and *Pantosteus clarki* (Catostomidae). Southwest. Nat. 26: 31-36.

FOGEL, M.M. 1981. Precipitation in the desert. pp. 219-234, In D.E. Evans and J.L. Thames (eds.). Water in Desert Ecosystems. Dowden, Hutchinson, and Ross, Inc., Stroudsburg, PA.

FREETHY, G.W. 1982. Hydrologic analysis of the upper San Pedro basin from the Mexico-United States International Boundary to Fairbank, Arizona. U.S. Geol. Survey Open-File Report 82-752. 63pp.

GERKING, S.D. and D.V. PLANTZ. 1980. Size-biased predation by the Gila topminnow *Poeciliopsis occidentalis* (Baird and Girard). Hydrobiologia 72: 179-1919.

GILBERT, C.H. and N.B. SCOFIELD. 1895. Notes on a collection of fishes from the Colorado basin in Arizona. Proc. U.S. Nat. Mus. 20: 487-499.

GIRARD, C. 1857. Researches upon the cyprinoid fishes inhabiting the fresh waters of the United States of America, west of the Mississippi Valley, from specimens in the museum of the Smithsonian Institution. Proc. Acad. Nat. Sci. Phila. 8(1856): 165-213.

—. 1859. Ichthyology of the Boundary. U.S. and Mex. Bound. Surv. 2(2): 1-85.

GRAHAM, J.D. 1852. Report of Lieutenant Colonel Graham on the Subject of the Boundary Line Between the United States and Mexico. 32nd Congr., 1st Sess., Exec. Doc. 121, Washington.

GRANGER, B.H. 1960. Will C. Barnes' Arizona Place Names, Revised and Enlarged. Univ. Ariz. Press, Tucson.

HAIR, J.D., G.T. HEPP, L.K. LUCKETT, K.P. REESE, and D.K. WOODWARD. 1979. Beaver pond ecosystems and their relationships to multi-use natural resource management. pp. 80-92. In R.R. Johnson and J.F. McCormick (tech. coords.). Strategies for Protection and Management of Floodplain Wetlands and Other Riparian Ecosystems. Proc. Symp. 11-13 Dec. 1978, Calaway Gardens, GA. USDA For. Serv. Gen. Tech. Rept. WO-12. 410pp.

HAMMAN, R.L. 1981. Spawning and culture of Colorado squawfish in raceways. Prog. Fish-cult. 43: 173-177.

—. 1985. Induced spawning of hatchery-reared razorback sucker. Prog. Fish-cult. 47: 187-189.

HANSON, R.L. and D.R. DAWDY. 1976. Accuracy of evapotranspiration rates determined by the Water-Budget method, Gila River floodplain, Southeastern Arizona. USGS Professional Paper 655-L. 35pp.

HARRELL, H.L. 1978. Response of the Devil's River (Texas) fish community of flooding. Copeia 1978: 60-68.

HARVEY, M.D., C.C. WATSON, and S.A. SCHUMM. 1985. Gully erosion. USDI Bureau of Land Management Tech. Note 366. Bldg. 50, Federal Center. Denver 80225. p. 181.

HARVEY, M.D., J. PITLICK, and J. LAIRD. In press, 1987. Temporal and spatial variability of sediment storage in Ash Creek, Arizona. Erosion and Sedimentation in the Pacific Rim. IAHS, Corvallis, Oregon.

HASTINGS, J.R. 1959. Vegetation change and arroyo cutting in southeastern Arizona. J. Ariz. Acad. Sci. 1: 60-67.

—. 1962. Historical Changes in the Vegetation of a Desert Region. Unpubl. Ph.D. Dissertat., Univ. Ariz., Tucson.

— and R.M. TURNER. 1965. The Changing Mile. Univ. Ariz. Press, Tucson.

HAYNES, C.V. 1968. Preliminary report on the Late Quaternary geology of the San Pedro Valley, Arizona. pp. 79-96 In S.R. Titley (ed.), Arizona Geological Society southern Arizona Guidebook 3, Tucson.

HEEDE, B.H. 1980. Stream dynamics: an overview for land managers. USDA Forest Service Gen. Tech. Rep. RM-72, Ft. Collins, Colorado, 26pp.

HENDRICKSON, D.A., W.L. MINCKLEY, R.R. MILLER, D.J. SIEBERT, and P.H. MINCKLEY. 1981. Fishes of the Rio Yaqui basin, Mexico and United States. J. Ariz.-Nev. Acad. Sci. 15 (1980): 66-106.

HENDRICKSON, D.A. and W.L. MINCKLEY. 1985. Cienegas —vanishing climax communities of the American Southwest. Desert Plants 6(1984): 141-175.

HERBOLD, B. and P.B. MOYLE. 1987. Introduced species and vacant niches. Am. Nat. 28, in press.

HEREFORD, R. 1984. Climate and ephemeral-stream processes: twentieth-century geomorphology and alluvial stratigraphy of the Little Colorado River, Arizona. Geol. Soc. of America Bull. V. 95, 654-668.

HJULSTROM, F. 1939. Transportation of detritus by moving water. In: Recent Marine Sediments, edited by P. Trask, Am. Assoc. Petroleum Geologists.

HOLDEN, P.B. and C.B. STALNAKER. 1975a. Distribution and abundance of mainstream fishes of the middle and upper Colorado River basins, 1967-1973. Trans. Am. Fish. Soc. 104: 217-231.

— and —. 1975b. Distribution fishes of the Dolores and Yampa River systems of the upper Colorado basins. Southwest. Nat. 19: 403-412.

HUBBS, C.L. 1954. Establishment of a forage fish, the red shiner, *Notropis lutrensis*, in the lower Colorado River system. Calif. Fish Game 40: 287-294.

—. 1964. History of ichthyology in the United States after 1850. Copeia 1964: 42-60.

— and R.R. MILLER. 1941. Studies of the fishes of the order Cyprinodontes. XVII. Genera and Species of the Colorado River system. Occ. Pap. Mus. Zool. Univ. Mich. 433: 1-9.

—, R.R. MILLER, and L.C. HUBBS. 1974. Hydrographic history and relict fishes of the north-central Great Basin. Calif. Acad. Sci. Mem. 7: 1-259.

HUTTON, N.H. 1859. Engineers report —El Paso and Fort Yuma wagon road. In Records of the Office of the Secretary of the Interior relating to wagon roads, 1857-1881. Nat. Arch. Film Microcopies M95: roll 3.

HYNES, H.B.N. 1970. The Ecology of Running Water. Univ. Toronto Press, Toronto, Canada.

JAMAIL, M.H. and S.J. ULLERY. 1979. International water use relations along the Sonoran Desert borderlands. Arid Lands Resour. Pap. 14. Univ. Ariz., Off. Arid Lands Stud., Tucson.

JENNINGS, M.R. 1987. Frederic Morton Chamberlain (1867-1921), pioneer fishery biology of the American West. Fisheries (Am. Fish. Soc., Bethesda, MD), in press.

JOHN, K.R. 1963. The effect of torrential rains on the reproductive cycle of *Rhinichthys osculus* in the Chiricahua Mountains, Arizona. Copeia 1963: 286-291.

—. 1964. Survival of fish in intermittent streams of the Chiricahua Mountains, Arizona. Ecology 45: 112-119.

JOHNSON, J.E. 1985. Reintroducing the natives —razorback sucker. Proc. Des. Fish. Counc. 13: 73-79.

JOHNSON, R.R. and D.A. JONES, Tech. Coord. 1977. Importance of preservation and management of riparian habitat: a symposium. (Tucson, Ariz., July 9, 1977) USDA For. Serv. Gen. Tech. Rep. RM-43. Rocky Mt. For. and Range Exp. Stn., Fort Collins, CO. 80521. 217pp.

JONES, J.E. 1977. Calculation of evapotranspiration using color-infrared photography. USGS, Professional Paper 655-9. 45pp.

KEPNER, W.G. 1982. Reproductive Biology of the Longfin Dace, Agosia chrysogaster, in a Sonoran Desert Stream, Arizona. Unpubl. M.S. Thesis, Ariz. St. Univ., Tempe.

KINO, E.F. 1919. Kino's Historical Memoir of Pimeria Alta, Vols. 1-11. H.E. Bolton (transl. and ed.). A.H. Clark Co., Cleveland.

KOEHN, R.K. 1965. Development and ecological significance of nuptial tubercles of the red shiner, *Notropis lutrensis*. Copeia 1965: 462-467.

KOSTER, W.J. 1957. Guide to the Fishes of New Mexico. Univ. N. Mex. Press, Albuquerque.

LA BOUNTY, J.F., J.J. SARTORIS, L.D. KLEIN, E.F. MONK, and H.A. SALMAN. 1975. Assessment of heavy metal pollution in the upper Arkansas River of ColoraDo. U.S. Bur. Reclam., Appl. Sci. Br., Denver, CO.

LACEY, R.L. and H.W. HJALMARSON. 1977. Effects of phreatophyte removal on water quality in the Gila River phreatophyte project area, Graham County Arizona. USGS Professional Paper 655-M. 23pp.

LEACH, J.B. 1858. Itinerary of the El Paso and Fort Yuma wagon road expedition. Nat. Arch. Film Microcopies M95: roll 3.

LEWIS, M.A. 1977. Influence of an Open-pit Copper Mine on the Ecology of an Upper Sonoran Intermittent Stream. Unpubl. Ph.D. Dissert., Ariz. St. Univ., Tempe.

LOWE, C.H. 1964. The Vertebrates of Arizona. Univ. Ariz. Press, Tucson.

—, D.S. HINDS, and E.A. HALPERN. 1967. Experimental catastrophic selection and tolerances to low oxygen concentration in native Arizona freshwater fishes. Ecology 48: 1013-1017.

MARSH, P.C. 1987. Digestive tract contents of adult razorback sucker in Lake Mohave, Arizona-Nevada. Trans. Am. Fish. Soc., in press.

MARSH, P.D. and D. Langhorst. 1987. Foods and fate of larval razorback sucker in Lake Mohave, Arizona-Nevada. J. Fish Biol., in press.

MARTIN, P.S. 1964. The last 10,000 years: A fossil pollin record of the American Southwest. Univ. of Arizona Press, Tucson, Arizona.

McAda, C.W. and R.S. WYDOSKI. 1980. The razorback sucker, *Xyrauchen texanus*, in the upper Colorado River basin, 1974-1976. Tech. Pap. U.S. Fish. Wildl. Serv. 99:1-15.

McCARTHY, M.S. 1986. Age Determination in Razorback Sucker, Xyrauchen texanus (Abbott), from Lake Mohave, Arizona-Nevada. Unpubl. M.S. Thesis, Ariz. St. Univ., Tempe.

McCARTHY, M.S. and W.L. MINCKLEY. 1987. Age estimation for razorback sucker (Pisces: Catostomidae) from Lake Mohave, Arizona-Nevada. J. Ariz.-Nev. Acad. Sci., inpress.

McCLINTOCK, J.H. 1916. Arizona: Prehistoric; Aboriginal; Pioneer, Modern, Vols. I-III. S.J. Clarke, Publ., Chicago.

McCLINTOCK, J.H. 1921. Mormon Settlements in Arizona. Manufacturing Stationers, Phoenix.

McDONALD, Michael A. and A. W. HARBAUGH. 1984. A Modular Three Dimensional Finite-Difference Ground Water Flow Model: U.S. Geol. Survey Open-File Report 85-875. 528 p.

McNATT, R.M. 1979a. Possible strategies for preservation of the San Pedro River riparian community. pp. 201-206. In R.R. Johnson and J.F. McCormick (tech. coords.). Strategies for Protection and Management of Floodplain Wetlands and Other Riparian Ecosystems. USDA, For. Serv., Gen. Tech. Rept. WO-12, Washington.

—. 1979b. Discovery and loss of a new locality for the Gila topminnow, *Poeciliopsis occidentalis occidentalis*. Southwest. Nat. 24: 555-556.

McQUEEN, I.S. and R.F. MILLER. 1972. Soil-moisture and energy relationships associated with riparian vegetation near San Carlos, Arizona. USGS Professional Paper 655-E. 51pp.

MEFFE, G.K. 1983a. Ecology of Species Replacement in the Sonoran Topminnow (*Poeciliopsis occidentalis*) and the Mosquitofish (*Gambusia affinis*) in Arizona. Unpubl. Ph.D. Dissertat., Ariz. St. Univ., Tempe.

—. 1984. Effects of abiotic disturbance on coexistence of predatory-prey fish species. Ecology 65: 1525-1534.

—. 1985. Predation and species replacement in American Southwestern fishes: a case study. Southwest. Nat. 30: 173-1534.

— and W.L. MINCKLEY. 1986. Persistence and stability of repeatedly disturbed animal assemblages in a Sonoran Desert stream. Am. Midl. Nat. 109: in press.

MEFFE, G.K., D.A. HENDRICKSON, W.L. MINCKLEY, AND J.N. RINNE. 1983. Factors resulting in decline of the endangered Sonoran topminnow *Poeciliopsis occidentalis* (Atheriniformes: Poeciliidae) in the United States. Biol. Conserv. 25: 135-159.

MELTON, M.A. 1965. The geomorphic and paleoclimatic significance of alluvial deposits in southern Arizona. The Journal of Geology 73(1), 1-38.

MILLER, R.R. 1943. The status of *Cyprinodon macularius* and *Cyprinodon nevadensis*, two desert fishes of western North America. Occ. Pap. Mus. Zool. Univ. Mich. 473: 1-25.

—. 1954. A drainage map of Arizona. Syst. Zool. 3: 80-81.

—. 1955. Fish remains from archaeological sites in the lower Colorado River basin, Arizona. Pap. Mich. Acad. Sci., Arts, Lett. 45: 125-136.

—. 1959. Origin and affinities of the freshwater fish fauna of western North America. pp. 187-222, In C.L. Hubbs (ed.). Zoogeography. Am. Assoc. Adv. Sci. Publ. 51, Washington, DC.

—. 1961. Man and the changing fish fauna of the American Southwest. Pap. Mich. Acad. Sci., Arts, Lett. 46(1960): 365-404.

—. 1981. Coevolution of desert and pupfishes (genus *Cyprinodon*) in the American Southwest. pp. 39-94. In R.J. Naiman and D.L. Soltz (eds.). Fishes in North American Deserts. John Wiley and Sons, Inc., New York.

— and H.W. WINN. 1951. Additions to the known fish fauna of Mexico: three species and one subspecies from Sonora. J. Wash. Acad. Sci. 41: 83-84.

MILLER, R.R. and C.L. HUBBS. 1960. The spiny-rayed cyprinid fishes (*Plagopterini*) of the Colorado River system. Misc. Publ. Mus. Nat. Hist. Univ. Mich. 115: 1-39.

MILLER, R.R. and C.H. LOWE. 1964. Part 2. Annotated checklist of the fishes of Arizona. pp. 133-151. In C.H. Lowe (ed.). The Vertebrates of Arizona. Univ. Ariz. Press, Tucson (reprinted, 1967, as "Part 2. Fishes of Arizona," op cit.).

MINCKLEY, W.L. 1969a. Aquatic biota of the Sonoita Creek basin, Santa Cruz County, Arizona. Ecol. Stud. Leaflet (Nature Conserv.) 15: 1-8.

MINCKLEY, W.L. 1969b. Attempted re-establishment of the Gila topminnow within its former range. Copeia 1969: 193-194.

—. 1973. Fishes of Arizona. Ariz. Game Fish Dept., Phoenix.

—. 1980a. *Agosia chrysogaster* (Girard), longfin dace. p. 141; 1980b. *Tiaroga cobitis* Girard, loach minnow. p. 365; 1980c. *Catostomus clarki* Baird and Girard, desert sucker. p. 373; 1980d. *Catostomus insignis* Baird and Girard, Sonoran sucker. p. 380; 1980e. *Cyprinodon macularius* Baird and Girard, desert pupfish. p. 497; and 1980f. *Poeciliopsis occidentalis* (Baird and Girard), Gila topminnow. p. 553. All In D.S. Lee et al. (eds.). Atlas of North American Freshwater Fishers. N. Car. St. Mus. Nat Hist., Raleigh.

—. 1980g. Morphological Variation in Catostomid Fishes of the Grand Canyon Region, Middle Colorado River Basin. Final Rept. Nat. Park Serv., Grand Canyon Nat. Park, Grand Canyon, AZ. Ariz. St. Univ., Tempe

—. 1981. Ecological studies of Aravaipa Creek, Central Arizona, Relative to Past, Present, and Future Uses. Final Rept. Contr. YA-512-CT6-98, U.S. Bur. Land Mgmt, Safford, AZ Distr., Ariz. St. Univ., Tempe.

—. 1983. Status of the Razorback Sucker, *Xyrauchen texanus* (Abbott), in the lower Colorado River basin. Southwest Nat. 28: 165-187.

—. 1985. Native Fishes and Natural Aquatic Habitats of U.S. Fish and Wildlife Service Region II West of the Continental Divide. Rept. U.S. Fish Wildl. Serv., Albuquerque, NM. Ariz. St. Univ., Tempe.

— and J.E. DEACON. 1968. Southwestern fishes and the enigma of "endangered species." Science 159: 1424-1432.

MINCKLEY, W.L. and W.E. BARBER. 1971. Some aspects of the biology of the longfin dace, a cyprinid fish characteristic of streams in the Sonoran Desert. Southwest. Nat. 15: 459-464.

MINCKLEY, W.L. and G.D. CONSTANTZ. 1974. A Physico-chemical and Biological Assessment of the Influence of Tailings Water on Upper Cocia Wash, Pima County, Arizona, with Special Reference to the Gila topminnow and its habitat. Rept. Am. Smelt. Refin. Corp., Tucson, AZ. Ariz. St. Univ., Tempe.

MINCKLEY, W.L. and R.W. CLARKSON. 1979. Fishes. pp. 510-531. In W.L. Minckley and M.R. Sommerfeld (eds.). Resource Inventory for the Gila River Complex, eastern Arizona. Final Rept. Contr. YA-512-CT6-216, U.S. Bur. Land Manag., Safford, AZ, Distr., Ariz. St. Univ., Tempe.

MINCKLEY, W.L. and J.E. BROOKS. 1986. Transplantations of native Arizona fishes: records through 1980. J. Ariz.-Nev. Acad. Sci. 20(1985): 73-89. (errata, J. Ariz.-Nev. Acad. Sci. 21[1987], in press).

MINCKLEY, W.L. and G.K. MEFFE. 1987. Differential selection for native fishes by flooding in streams of the American Southwest. In press. In W.J. Matthews and D.C. Heins (eds.). Evolutionary and Community Ecology of North American Stream Fishes. Univ. Okla. Press, Norman.

MINCKLEY, W.L., J.N. RINNE, and J.E. JOHNSON. 1977. Status of the Gila topminnow and its co-occurrence with mosquitofish. USDA For. Serv. Res. Pap. RM-198: 1-8.

MINCKLEY, W.L., D.A. HENDRICKSON, and C.E. BOND. 1986. Geography of western North American frewshwater fishes: description and relationships to intracontinental tectonism. pp. 519-613 + Lit. Cited. In C.H. Hocutt and E.O. Wiley (eds.). Zoogeography of North American Freshwater Fishes. John Wiley and Sons, Inc., New York.

MOYLE, P.B. 1986. Fish introductions into North America; patterns and ecological impact. In press, In H. Mooney (ed.). Biological Invasions in North America. Springer-Verlag.

MOYLE, P.B., H.W. LI., and B.A. BARTON. 1986. The Frankenstein effect: impact of introduced fishes on native fishes in North America. pp. 415-426. In R.H. Stroud (ed.). Fish Culture in Fisheries Management. Fish Cult., Fish Manag. Sects., Am. Fish. Soc., Bethesda MD.

MUELLER, G.A. 1984. Spawning by *Rhinichthys osculus* (Cyprinidae) in the San Francisco River, New Mexico. Southwest. Nat. 29: 354-356.

NETER, J. and W. WASSERMAN. 1974. Applied Linear Statistical Models. Richard D. Irwin, Inc. Homewood, Ill. 842pp.

NEVE, L.C. 1976. The Life History of the Roundtail Chub, *Gila robusta grahami*, at Fossil Creek, Arizona. Unpubl. M.S. Thesis, North. Ariz. Univ., Flagstaff.

OSBORN, H.B. and L.J. LANE. 1984. Climatic change and streamflow in the Southwest. Amer. Society of Civil Engineers, Irrigation and Drainage Dev., 1984 Specialty Conf. Flagstaff, AZ. July 24-26, 1984. p. 11.

PAGE, H.G. 1963. Water regimen of the inner valley of the San Pedro River near Mammoth, Arizona. USGS Supply Paper 1669-I. pp. 11-122.

PARKE, J.G. 1857. Report of explorations for railroad routes. In Explorations and Surveys to Ascertain the Most Practicable and Economical Route for a Railroad from the Mississippi River to the Pacific Ocean. U.S. 33rd Congr., 2nd Sess., Sen. Exec. Doc. 78, Vol. 7.

PARKER, M., F.J. WOOD, JR., B.H. SMITH, and R.G. ELDER. 1985. Erosional downcutting in lower order riparian ecosystems: have historical changes been caused by removal of beaver? pp. 35-38. In R.R. Johnson, C.D. Ziebell, D.R. Patton, P.F. Ffolliott, and R.H. Hamre (tech. coords.). Riparian Ecosystems and Their Management: Reconciling Conflicting Uses. First N. Am. Riparian Conf., 16-18 Apr. 1986, Tucson, AZ. USDA For. Serv., Gen. Tech. Rept. RM-120. 523pp.

PARSONS, S. and S. HUDSON. 1985. Channel Cross Section Surveys and Data Analysis. USDI Bureau of Land Management Tech. Ref. TR04341-1, 48pp.

PATTON, P.C. and S.A. SCHUMM. 1981. Ephemeral-stream processes: implications for study of Quaternary valley fills. Quat. Res. 15: 24-43.

PAXSON, J.K. 1981. Temporal and spatial relationships in the development of Southwestern riparian gallery forests. M.S. thesis. Arizona State University, Tempe, AZ 85281. 56pp.

PROPST, D.L., K.R. BESTGEN, and C.W. PAINTER. 1985a. Ichthyofaunal survey of the Gila-San Francisco basin, New Mexico, a status report, 1982-1983. Final Rept. N. Mex. Proj. E3, N. Mex. Game Fish Endang. Spec. Prog., Santa Fe.

PROPST, D.L., P.C. MARSH, and W.L. MINCKLEY. 1985b. Arizona Survey for Spikedace (*Meda fulgida*) and Loach Minnow (*Tiaroga cobitis*): Fort Apache and San Carlos Apache Indian Reservations and Eagle Creek, May 1985. Rept. U.S. Fish Wildl. Serv., Albuquerque, NM. N. Mex. Game Fish Dept., Santa Fe, and Ariz. St. Univ., Tempe.

PUTMAN, F., K. MITCHELL, and G. BUSHNER. 1987. Water Resources of the Upper San Pedro Basin, Arizona (Draft Report). Arizona Department of Water Resources, Hydrology Division, Phoenix, Arizona, 149pp.

RINNE, J.N. 1975. Changes in minnow populations in a small desert stream, resulting from naturally and artificially induced factors. Southwest. Nat. 20: 185-195.

—, J.E. JOHNSON, B.L. JENSEN, A.W. RUGER, and R. SORENSON. 1986. The role of hatcheries in the management and recovery of threatened and endangered fishes. pp. 271-285. In R.H. Stroud (ed.). Fish Culture in Fisheries Management. Fish Cult., Fish Manag. Sects., Am. Fish. Soc., Bethesda, MD.

RITTER, D.F. 1978. Process Geomorphology. Wm. C. Brown Publishers, Dubuque, Iowa, 603pp.

RODHE, F.C. 1980. *Meda fulgida* Girard, spikedace. p. 206. In D.S. Lee et al. (eds.). Atlas of North American Freshwater Fishes. N. Car. St. Mus. Nat. Hist., Raleigh.

ROESKE, R.H. and W.L. WERRELL, 1973. Hydrologic Conditions in the San Pedro River Valley, Arizona, 1971. Arizona Water Commission Bulletin 4. Phoenix, Arizona. 76p.

ROSENKRANCE, L.K. 1986. Safford District, AZ: Closure of San Pedro River to public use. Fed. Regist. 51: 8714.

ROVEY, C.K. 1967. Hydrologic Analysis: Potential Impacts of Well Pumping on the Upper San Pedro River, Arizona. Letter report, 7 pgs.

RULE, R. 1885. Southern region. pp. 10-15. In J.H. Taggart (ed.). Annual Report Arizona Fish Commission, 1883-1884, to Frederick A. Tritle, Governor of the Territory of Arizona. St. Capitol, Phoenix.

SCHOENHERR, A.A. 1974. Life History of the Topminnow *Poeciliopsis occidentalis* (Baird and Girard) in Arizona, and an Analysis of its Interaction with the Mosquitofish *Gambusia affinis* (Baird and Girard). Unpubl. Ph.D. Dissertat., Ariz. St. Univ., Tempe.

—. 1977. Density dependent and density independent regulation of reproduction in the Gila topminnow, *Poeciliopsis o. occidentalis* (Baird and Girard). Ecology 58: 438-444.

—. 1981. The role of competition in the replacement of native species by introduced fishes. pp. 173-203, In R.J. Naiman and D.L. Soltz (eds.). Fishes in North American Deserts. John Wiley and Sons, Inc., New York.

SCHREIBER, D.J. 1978. Food Interrelationships of Native Fishes in Aravaipa Creek. Unpubl. M.S. Thesis, Ariz. St. Univ., Tempe.

— and W.L. MINCKLEY. 1982. Food interrelationships of native fishes in a Sonoran Desert stream. Grt. Basin Nat. 41 (1981): 409-426

SCHUMM, S.A. and R.F. HADLEY. 1957. Arroyos and the semi-arid cycle of erosion. Am. J. Sci. 255: 161-174.

SEETHALER, K.H. 1978. Life History and Ecology of the Colorado Squawfish (*Ptychocheilus lucius*) in the Upper Colorado River Basin. Unpubl. M.S. Thesis, Utah St. Univ., Logan.

SEIBERT, D.J. 1980. Movements of Fishes in Aravaipa Creek, Arizona. Unpubl. M.S. Thesis, Ariz. St. Univ., Tempe.

SMITH, E.L. and G.L. BENDER. 1974d. Established Natural Areas in Arizona. A Guidebook for Scientists and Educators. Plan. Div., Ariz. Off. Econ. Plan. Devel., Phoenix.

SMITH, G.R. 1966. Distribution and evolution of the North American catostomid fishes of the subgenus *Pantosteus*, genus *Catostomus*. Univ. Mich. Mus. Zool. Misc. Publ. 129: 1-132.

—. Effects of habitat size on species richness and adult body sizes of desert fishes. pp. 125-171. In R.J. Naiman and D.L Soltz (eds.). Fishes in North American Deserts. John Wiley and Sons, Inc., New York.

SMITH, H.M. 1900. Report on inquiry respecting food-fishes and the fishing grounds. pp. 159-164. In Report of the Commissioner of Fish and Fisheries for the year ending June 30, 1899. U.S. Govt. Print. Off., Washington, DC.

SOLTZ, D.L. and R.J. NAIMAN. 1978. The natural history of native fishes in the Death Valley system. Los Angeles Co. Nat. Hist. Mus. Sci. Ser. 30: 1-76.

STRONG, P.I. 1979. Beaver-cottonwood interactions and beaver ecology in Big Ben National Park. M.S. thesis. Oklahoma State University. p. 79.

SUMNER, J.S. and P.F. HALVORSON, 1983. Geophysical Exploration Surveys for Ground Water in the San Pedro Basin, Arizona. Univ. of Ariz. Research Project Tech. Completion Report A-108-ARIZ. 28pp.

SWENSON, E.A. and C.L. MULLINS. 1985. Revegetating riparian trees in Southwestern floodplains. First North American Riparian Conference, Riparian Ecosystems and Their Management: Reconciling Conflicting Uses. Tucson, AZ. April 16-18. 1985. pp. 135-138.

SYKES, G. 1937. The Colorado Delta. Publ. Carnegie Inst. Washington 460: i-viii, 1-193.

TAGGART, J.H. 1885. Annual Report Arizona Fish Commission, 1883-1884, to Frederick A. Tritle, Governor of the Territory of Arizona. St. Capitol, Phoenix.

TAYLOR, D.W. 1982. Eastern Sierra riparian vegetation: ecological effects of stream diversions. Mono Basin Research Group, Contribution No. 6. Inyo National Forest, 789 N. Main, Bishop, CA 93514. 56pp.

TROMBLE, J.M. 1977. Water requirements for mesquite (*Prosopis juliflora*). USDA, Agricultural Research. Western Region, Las Cruces, NM 88001. pp. 171-179.

TYLER, D.S. 1881. A Concise History of the Mormon Battalion in the Mexican War. The Rio Grande Press, Chicago (1964 reprint).

TYUS, H.M. 1985. Homing behavior noted for Colorado squawfish. Copeia 1985: 213-215.

—. 1987. Distribution, reproduction, and habitat use of the razorback sucker in the Green River, Utah, 1975-86. Trans. Am. Fish. Soc., in press.

—, B.D. BURDICK, R.A. VALDEZ, C.M. HAYNES, T.A. LYTLE, and C.R. BERRY. 1982a. Fishes of the upper Colorado River basin: distribution, abundance, and status. pp. 12-70. In W.H. Miller et al. (eds.). Proc. Symp. Ann. Meet. Am. Fish. Soc., Bethesda, MD.

TYUS, H.M., C.W. McADA, and B.D. BURDICK. 1982b. Green River fishery investigations, 1979-1981. pp. 1-100. In Colorado River Fishery Project, Part II. Field Investigations. Final Rept. Mem. Understand. 9-07-40-L-1016, U.S. Bur. Reclam., Upper Colo. Reg., Salt Lake City, UT, U.S. Fish. Wildl. Serv., Denver, CO..

U.R.S. COMPANY, W.R. BOOTH, and ASSOCIATES. 1976. Water Quality Management plan for the upper Gila and San Pedro River basins. Rept. Ariz. Dept. Health Serv., Phoenix. U.R.S. Co., W.R. Booth, and Assoc., Phoenix.

USBLM. 1986. Water resources assessment and management strategy for the San Pedro River —San Simon Resource area, Arizona. Rev. Proj. Proposal, Div. Res. Serv. Cent., Bur. Land Mgmt., Denver, CO.

—. 1987. Wilderness management plan: Aravaipa Canyon Wilderness (draft). Bur. Land Mgmt., Safford, AZ Distri., Safford.

USDI. 1985a. Endangered and threatened wildlife and plants; proposal to determine the loach minnow to be a threatened species and to determine its critical habitat. Fed. Regist. 50.

USDI. 1985b. Endangered and threatened wildlife and plants; proposal to determine the spikedace to be a threatened species and to determine its critical habitat. Fed. Regist. 50.

USDI. 1986c. Endangered and threatened wildlife and plants; determination of endangered status for the desert pupfish. Fed. Regist. 51:

USFWS. 1984c. Recovery plan for Gila and Yaqui topminnow (Poeciliopsis occidentalis Baird and Girard). U.S. Fish Wildl. Serv., Off. Endang. Spec., Albuquerque, NM.

USEPA. 1973. Water quality criteria. Nat. Acad. Sci., Govt. Print. Off., Washington, DC.

—. 1976. Quality criteria for water. U.S. Govt. Print. Off., Washington, DC.

UNIVERSITY OF ARIZONA, WATER RESOURCES RESEARCH CENTER. 1978. Surface water quality monitoring: San Pedro River basin, Arizona, October 1977. Rept. Ariz. Dept. Health Serv., Phoenix. Univ. Ariz. Wat. Resour. Res. Cent., Tucson.

VAN HAVEREN, B.P. and W.L. JACKSON. 1986. Concepts in stream riparian rehabilitation. In: R.E. McCabe, ed. Transactions of the Fifty-First North American Wildlife and Natural Resources Conference. Wildlife Management Institute, Washington, D.C. 280-289.

VANICEK, C.D. 1967. Ecological Studies of Native Green River Fishes Below Flaming Gorge Dam, 1964-66. Unpubl. Ph.D. Dissertat., Utah St. Univ., Logan.

— and R.H. KRAMER. 1969. Life history of the Colorado squawfish, *Ptychocheilus lucius*, and the Colorado chub, *Gila robusta*, in the Green River in Dinosaur National Monument, 1964-1966. Trans. Am. Fish. Soc. 98: 193-208.

VANICEK, D.D., R.H. KRAMER, and D.R. FRANKLIN. 1970. Distribution of Green River Fishes in Utah and Colorado following closure of Flaming Gorge Dam. Southwest. Nat. 14: 297-315.

WILSON, E.D., R.T. MOORE, and R.T. O'HAIRE. 1960. Geologic map of Pima and Santa Cruz Counties, Arizona. Ariz. Bur. Mines, Tucson.

WINN, H.E. and R.R. MILLER. 1954. Native postlarval fishes of the lower Colorado River basin, with a key to their identification. Calif. Fish Game 40: 273-285.

APPENDIX I

HYDROLOGY DATA

CROSS SECTION 1

Enter gradient of reach (feet/foot).
.002

Enter the Mannings "N" value for this stage.
.02

The rating table contains the discharge and hydraulic perimeters at 15 stages between limits set by the user. What are the minimum and maximum stages of the rating?
Min, max .1, 13

Stage	Discharge	Velocity	Cross section Area	Wetted Perimeter	Hydraulic Radius	Top Width
.100	.264	.520	.507	8.181	.062	8.142
1.021	65.480	2.704	24.218	32.995	.734	32.528
1.943	240.465	4.290	56.047	38.199	1.467	37.342
2.864	488.062	5.173	94.344	48.566	1.943	47.478
3.786	744.452	5.099	145.990	76.790	1.901	75.529
4.707	1205.919	5.054	238.586	127.172	1.876	125.527
5.629	2088.811	5.481	381.074	179.859	2.119	177.711
6.550	3720.844	6.792	547.820	187.452	2.922	185.049
7.471	5726.032	7.929	722.196	195.937	3.686	193.314
8.393	6989.625	7.485	933.783	276.180	3.381	273.378
9.314	9646.606	7.913	1219.084	331.727	3.675	328.741
10.236	13709.063	8.959	1530.251	345.664	4.427	342.359
11.157	18502.273	10.004	1849.466	354.028	5.224	350.305
12.079	23900.881	10.986	2175.571	361.886	6.012	357.519
13.000	29844.035	11.898	2508.294	370.186	6.776	365.152

CROSS SECTION 2

Enter gradient of reach (feet/foot).
.002

Enter the Mannings "N" value for this stage.
.02

The rating table contains the discharge and hydraulic perimeters at 15 stages between limits set by the user. What are the minimum and maximum stages of the rating?
Min, max .1,10

Stage	Discharge	Velocity	Cross section Area	Wetted Perimeter	Hydraulic Radius	Top Width
.100	.135	.451	.300	6.006	.050	6.000
.807	30.403	1.551	19.604	61.478	.319	61.338
1.514	201.571	3.094	65.147	72.502	.899	71.999
2.221	518.439	4.416	117.391	76.612	1.532	75.76
2.929	949.075	5.508	172.296	80.722	2.134	79.52
3.636	1484.476	6.458	229.861	84.832	2.710	83.286
4.343	2127.759	7.338	289.948	88.343	3.282	86.425
5.050	2719.483	7.691	353.597	100.415	3.521	98.081
5.757	2227.892	4.907	454.050	253.032	1.794	142.359
6.464	3127.062	4.508	693.629	438.904	1.580	275.745
7.171	5071.407	4.768	1063.653	618.820	1.719	208.299
7.879	8336.818	5.419	1538.530	738.792	2.082	733.896
8.586	13387.604	6.472	2068.665	761.078	2.718	755.734
9.293	19593.146	7.524	2604.023	764.212	3.407	758.410
10.000	26710.828	8.503	3141.273	767.347	4.094	761.086

CROSS SECTION 3

Enter gradient of reach (feet/foot).
.002

Enter the Mannings "N" value for this stage.
.02

The rating table contains the discharge and hydraulic perimeters at 15 stages between limits set by the user. What are the minimum and maximum stages of the rating?
Min, max .1,9

Stage	Discharge	Velocity	Cross section Area	Wetted Perimeter	Hydraulic Radius	Top Width
.100	.323	.451	.717	14.335	.050	14.333
.736	46.575	2.262	20.590	36.658	.562	26.498
1.371	133.179	2.848	46.755	58.907	.794	16.891
2.007	336.346	3.393	99.124	96.055	1.032	47.452
2.643	683.029	4.126	165.526	119.608	1.384	64.60
3.279	1238.771	5.050	245.319	130.948	1.873	129.787
3.914	1951.306	5.903	330.576	139.620	2.368	138.304
4.550	2860.460	6.821	419.340	142.567	2.941	140.953
5.186	3907.363	7.665	509.788	145.514	3.503	143.602
5.821	5085.419	8.449	601.919	148.462	4.054	146.251
6.457	6389.664	9.184	695.735	151.409	4.595	148.899
7.093	7816.254	9.879	791.234	154.356	5.126	151.548
7.729	8865.970	9.967	889.550	171.236	5.195	4.656
8.364	9601.968	9.444	1016.746	212.202	4.791	206.371
9.000	11196.093	9.677	1156.993	232.802	4.970	209.844

CROSS SECTION 4

Enter gradient of reach (feet/foot).
.002

Enter the Mannings "N" value for this stage.
.02

The rating table contains the discharge and hydraulic perimeters at 15 stages between limits set by the user. What are the minimum and maximum stages of the rating?
Min, max .1,15

Stage	Discharge	Velocity	Cross section Area	Wetted Perimeter	Hydraulic Radius	Top Width
.100	.444	.672	.661	7.265	.091	7.222
1.164	38.865	2.330	16.679	28.400	.587	27.908
2.229	221.339	4.046	54.708	40.719	1.344	39.803
3.293	549.040	5.448	100.774	47.998	2.100	46.765
4.357	1015.885	6.586	154.250	55.278	2.790	53.726
5.421	1309.142	5.869	223.071	95.035	2.347	60.167
6.486	2121.179	6.162	344.225	136.301	2.525	65.405
7.550	3404.044	6.645	512.244	181.116	2.828	165.867
8.614	4554.008	6.222	731.895	285.620	2.562	62.039
9.679	7222.249	6.461	1117.750	412.203	2.712	407.830
10.743	10840.944	6.908	1569.284	523.494	2.998	487.484
11.807	15641.697	6.856	2281.506	769.815	2.964	494.093
12.871	25482.711	8.164	3121.323	810.470	3.851	804.020
13.936	38064.484	9.567	3978.740	814.410	4.885	807.233
15.000	52588.703	10.866	4839.576	818.350	5.914	810.446

CROSS SECTION 5

Enter gradient of reach (feet/foot).
.002

Enter the Mannings "N" value for this stage.
.02

The rating table contains the discharge and hydraulic perimeters at 15 stages between limits set by the user. What are the minimum and maximum stages of the rating?
Min, max .1,18

Stage	Discharge	Velocity	Cross section Area	Wetted Perimeter	Hydraulic Radius	Top Width
.100	1.580	.806	1.960	22.236	.088	.000
1.379	3.57.324	4.462	80.082	69.754	1.148	68.957
2.657	1207.646	7.072	170.763	74.542	2.291	72.891
3.936	2405.487	9.021	266.658	80.799	3.300	78.384
5.214	3503.295	9.154	382.706	113.442	3.374	110.856
6.493	5608.681	10.422	538.140	131.303	4.098	128.493
7.771	8005.219	11.130	719.228	159.014	4.523	155.901
9.050	11334.565	12.164	931.814	180.320	5.168	177.011
10.329	14206.327	11.943	1189.462	236.582	5.028	232.898
11.607	20015.041	13.366	1497.432	251.571	5.952	247.494
12.886	26962.658	14.811	1820.487	262.213	6.943	257.708
14.164	34957.863	16.220	2155.216	270.856	7.957	265.890
15.443	43851.332	17.538	2500.406	279.500	8.946	274.072
16.721	53632.172	18.778	2856.057	288.143	9.912	282.254
18.000	64537.191	20.034	3221.391	294.933	10.922	288.489

CROSS SECTION 6

Enter gradient of reach (feet/foot).
.002

Enter the Mannings "N" value for this stage.
.02

The rating table contains the discharge and hydraulic perimeters at 15 stages between limits set by the user. What are the minimum and maximum stages of the rating?
Min, max .1,15

Stage	Discharge	Velocity	Cross section Area	Wetted Perimeter	Hydraulic Radius	Top Width
.100	.035	.548	.065	1.307	.049	1.292
1.164	40.396	2.307	17.507	41.005	.427	39.716
2.229	305.603	4.108	74.395	73.358	1.014	14.349
3.293	956.772	5.691	168.120	101.663	1.654	31.039
4.357	1920.126	6.457	297.363	148.781	1.999	50.507
5.421	3762.594	8.142	462.100	163.281	2.830	159.047
6.486	6055.607	9.397	644.419	183.659	3.509	180.134
7.550	8906.116	10.570	842.562	201.279	4.186	197.472
8.614	12479.929	11.768	1060.530	215.684	4.917	211.629
9.679	12920.740	9.682	1334.531	363.678	3.670	359.215
10.743	17157.566	9.570	1792.915	497.214	3.606	492.015
11.807	24980.148	10.518	2374.968	571.583	4.155	565.952
12.871	36145.578	12.123	2981.571	579.906	5.141	573.974
13.936	48997.008	13.625	3596.190	587.057	6.126	580.353
15.000	63424.766	15.041	4216.656	593.418	7.106	585.625

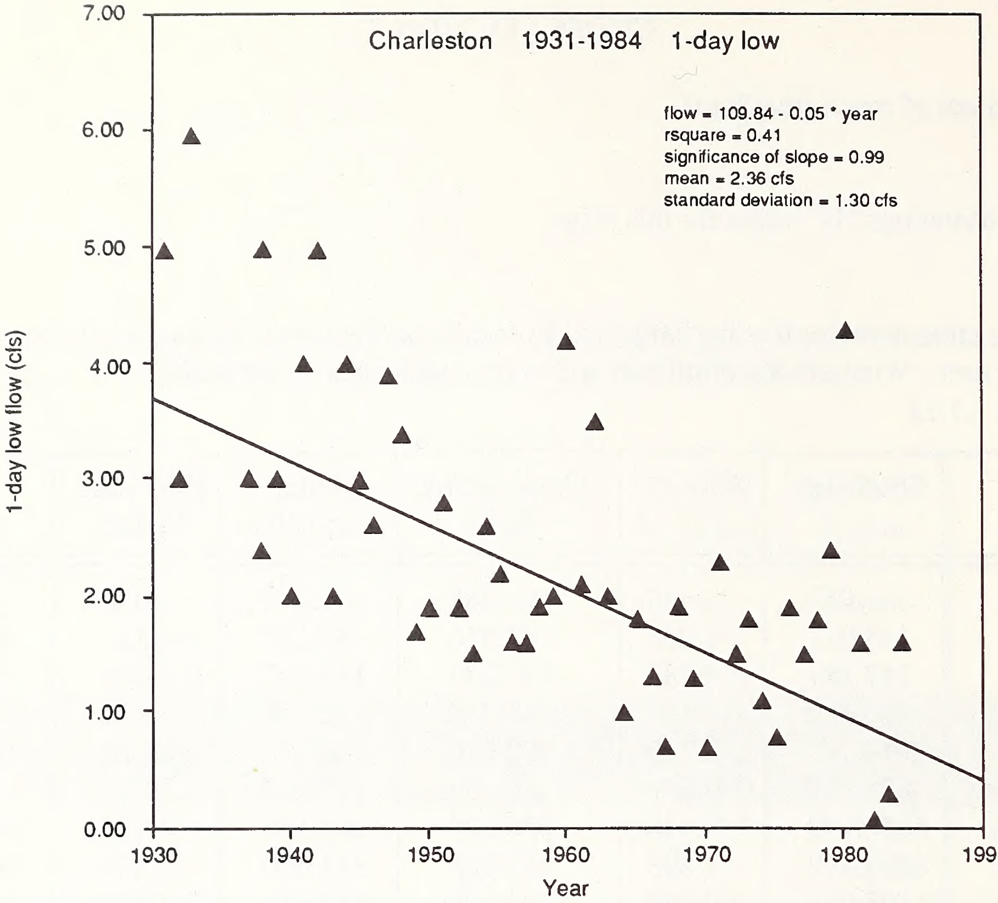
CROSS SECTION 7

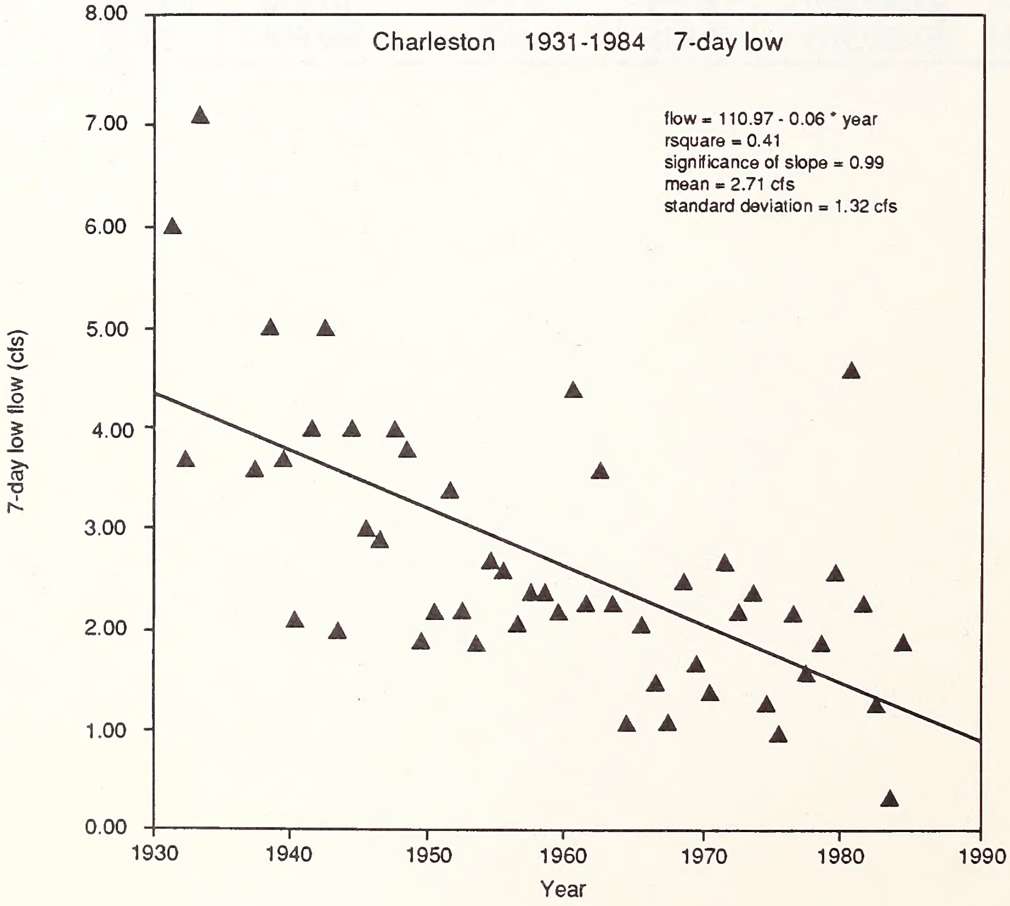
Enter gradient of reach (feet/foot).
.002

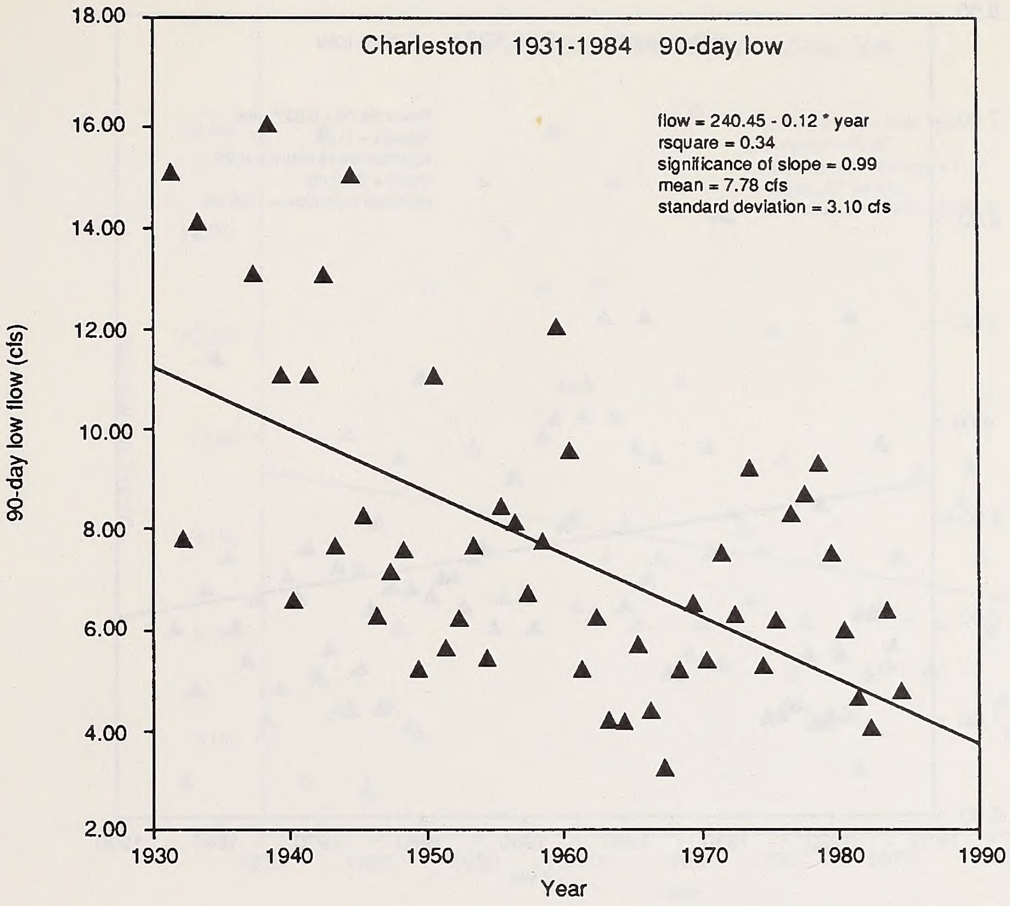
Enter the Mannings "N" value for this stage.
.02

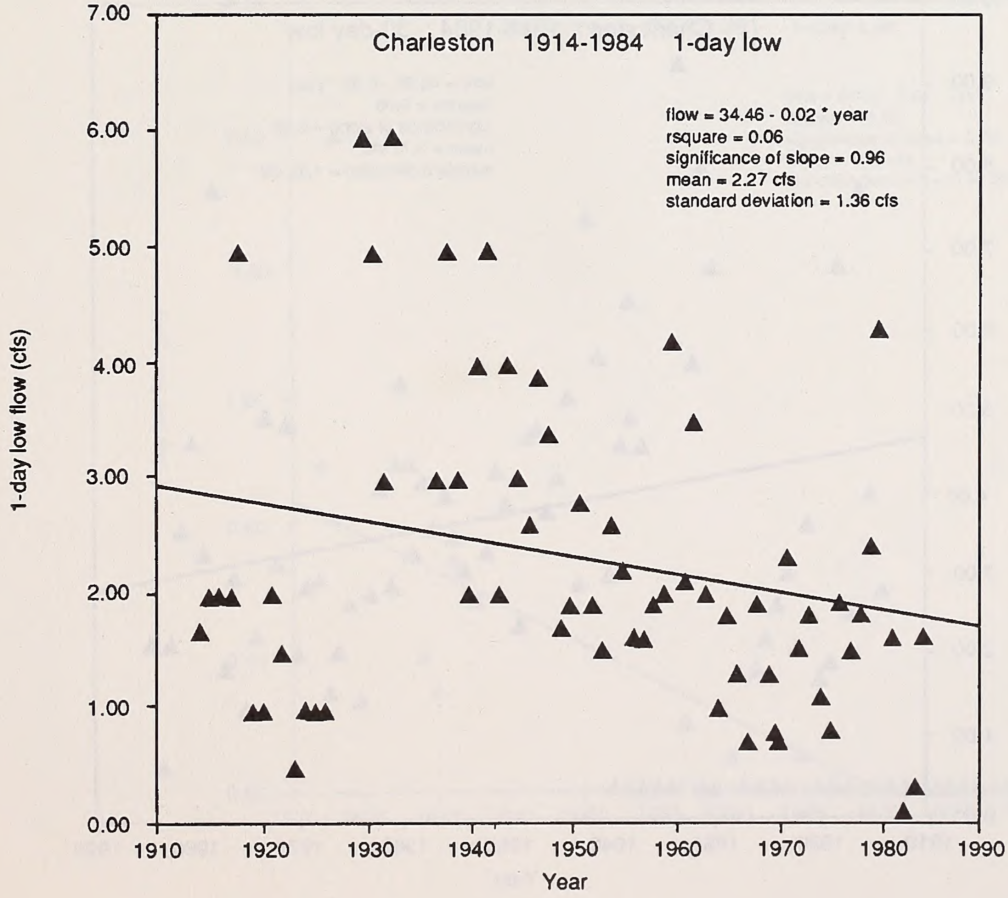
The rating table contains the discharge and hydraulic perimeters at 15 stages between limits set by the user. What are the minimum and maximum stages of the rating?
Min, max .1,12

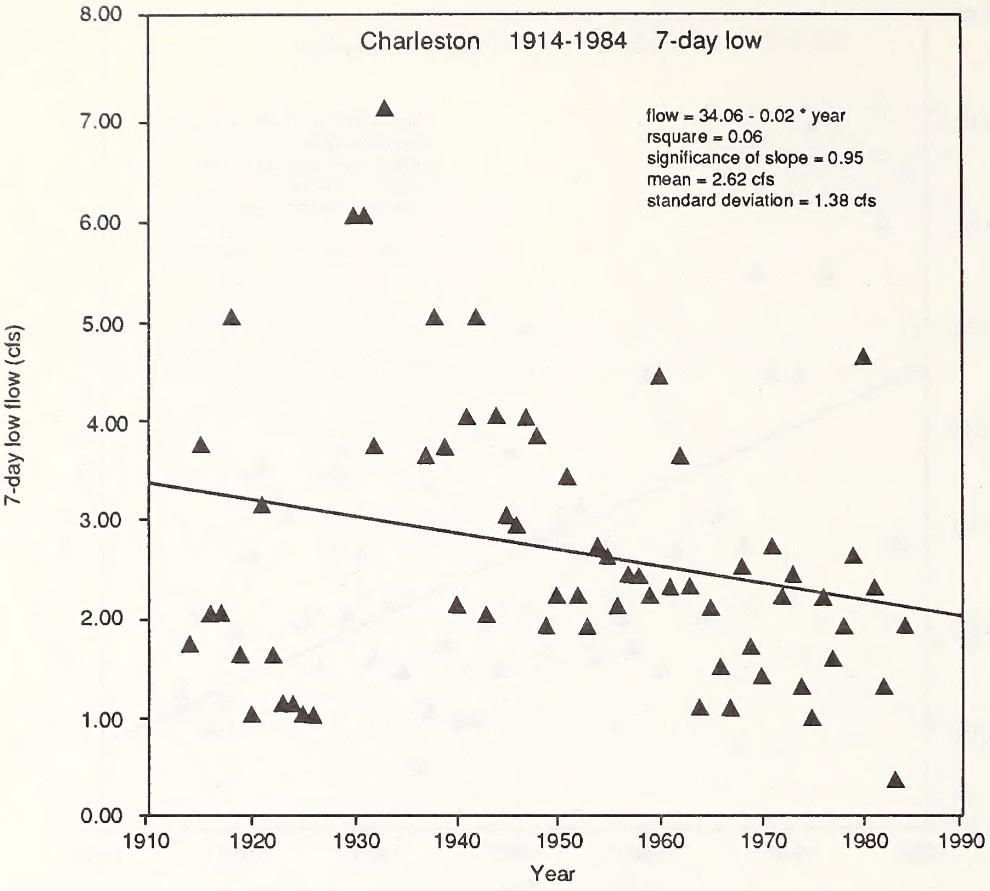
Stage	Discharge	Velocity	Cross section Area	Wetted Perimeter	Hydraulic Radius	Top Width
.100	.055	.626	.088	1.777	.050	1.762
.950	145.021	3.065	47.316	88.137	.537	87.933
1.800	747.187	5.288	141.292	116.127	1.217	115.603
2.650	1766.182	7.307	241.712	122.314	1.976	121.472
3.500	2913.549	8.256	352.910	148.700	2.373	147.664
4.350	4532.061	9.274	488.659	172.924	2.826	171.747
5.200	5758.730	8.848	650.825	247.147	2.633	245.751
6.050	8207.192	9.293	883.165	311.600	2.834	309.353
6.900	11108.987	9.363	1186.469	413.917	2.866	410.736
7.750	16964.828	11.033	1537.583	419.331	3.667	415.266
8.600	21587.039	11.346	1902.677	497.631	3.823	492.361
9.450	25786.584	10.888	2368.300	658.849	3.595	652.023
10.300	35629.543	12.053	2956.158	706.136	4.186	697.853
11.150	48249.250	13.593	3549.455	707.870	5.014	698.140
12.000	62330.969	15.045	4142.996	709.604	5.838	698.427

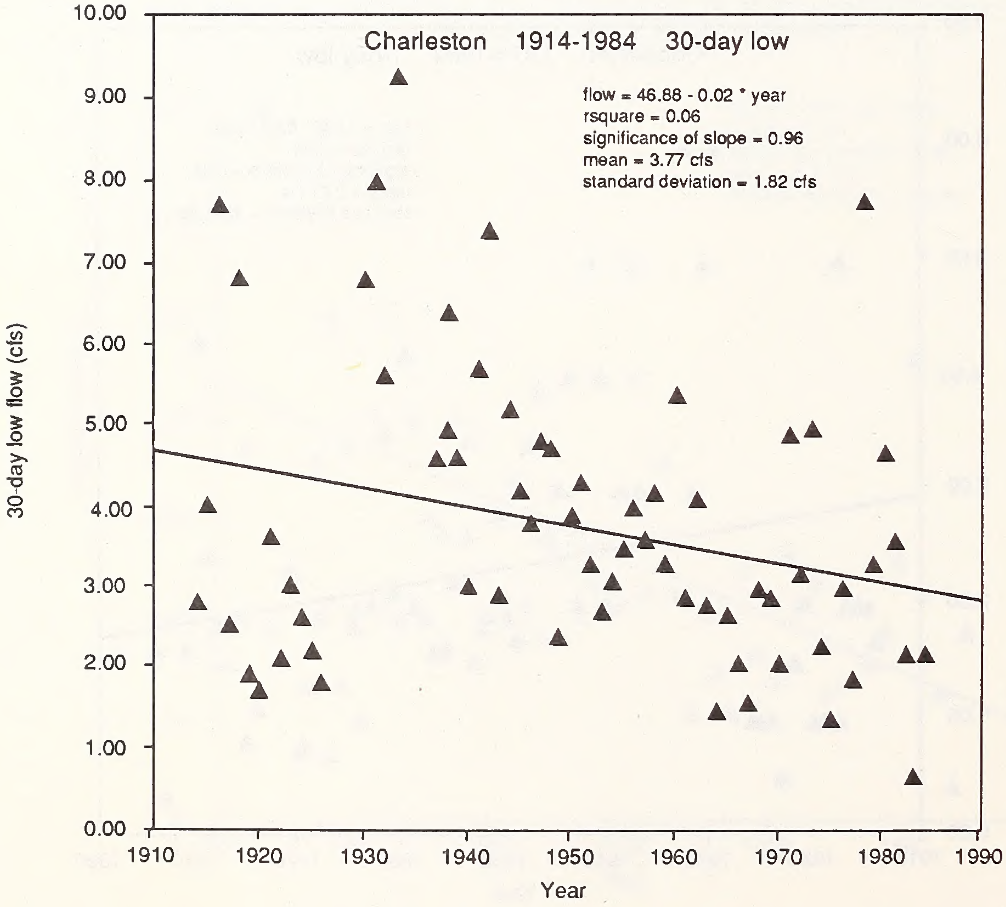

Charleston 1931-1984 1-day low
flow = 109.84 - 0.05 * year
rsquare = 0.41
significance of slope = 0.99
mean = 2.36 cfs
standard deviation = 1.30 cfs
1-day low flow (cfs)
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
1930
1940
1950
1960
1970
1980
1990
Year

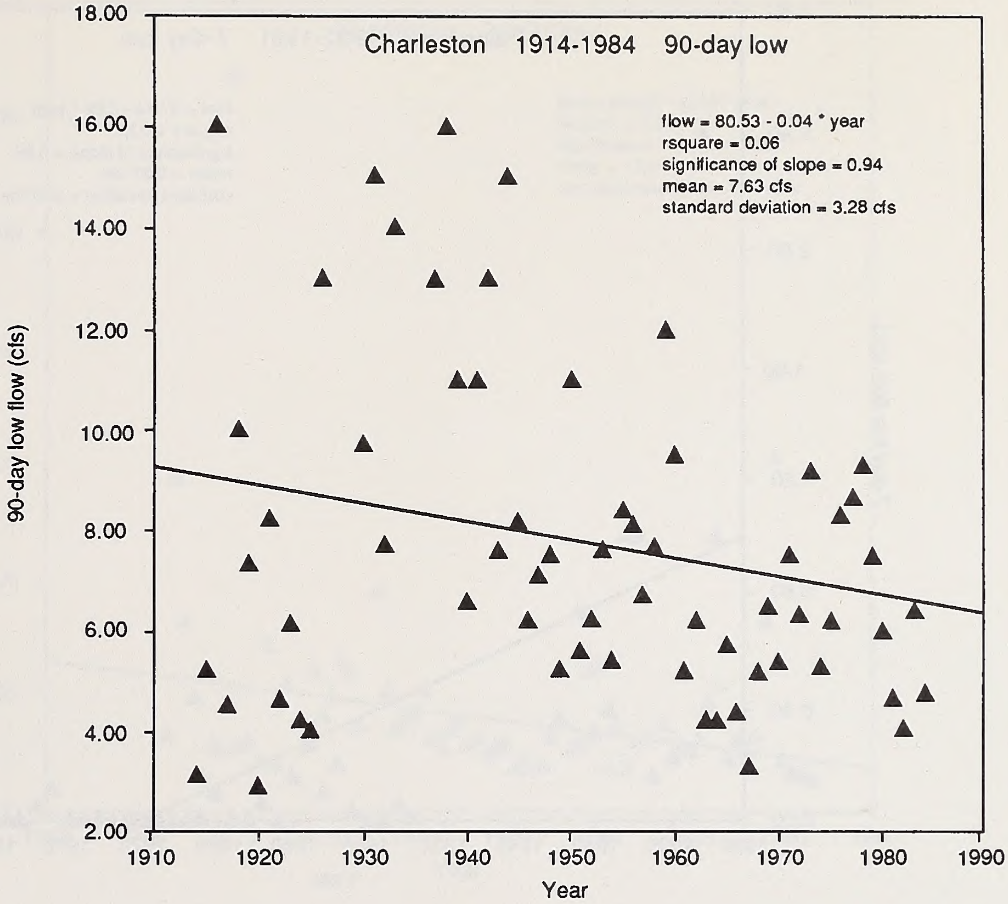

Charleston 1931-1984 7-day low
flow = 110.97 - 0.06 * year
rsquare = 0.41
significance of slope = 0.99
mean = 2.71 cfs
standard deviation = 1.32 cfs
7-day low flow (cfs)
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
1930
1940
1950
1960
1970
1980
1990
Year

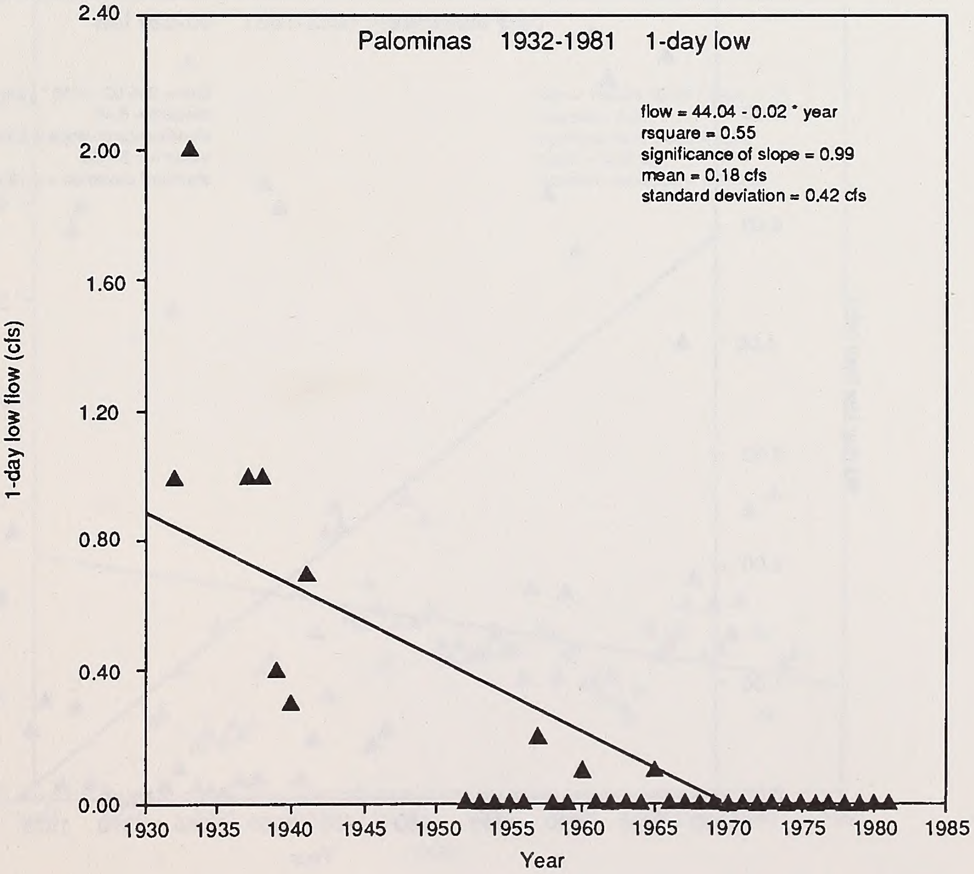

Charleston 1931-1984 90-day low
flow = 240.45 - 0.12 * year
rsquare = 0.34
significance of slope = 0.99
mean = 7.78 cfs
standard deviation = 3.10 cfs
90-day low flow (cfs)
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
1930
1940
1950
1960
1970
1980
1990
Year

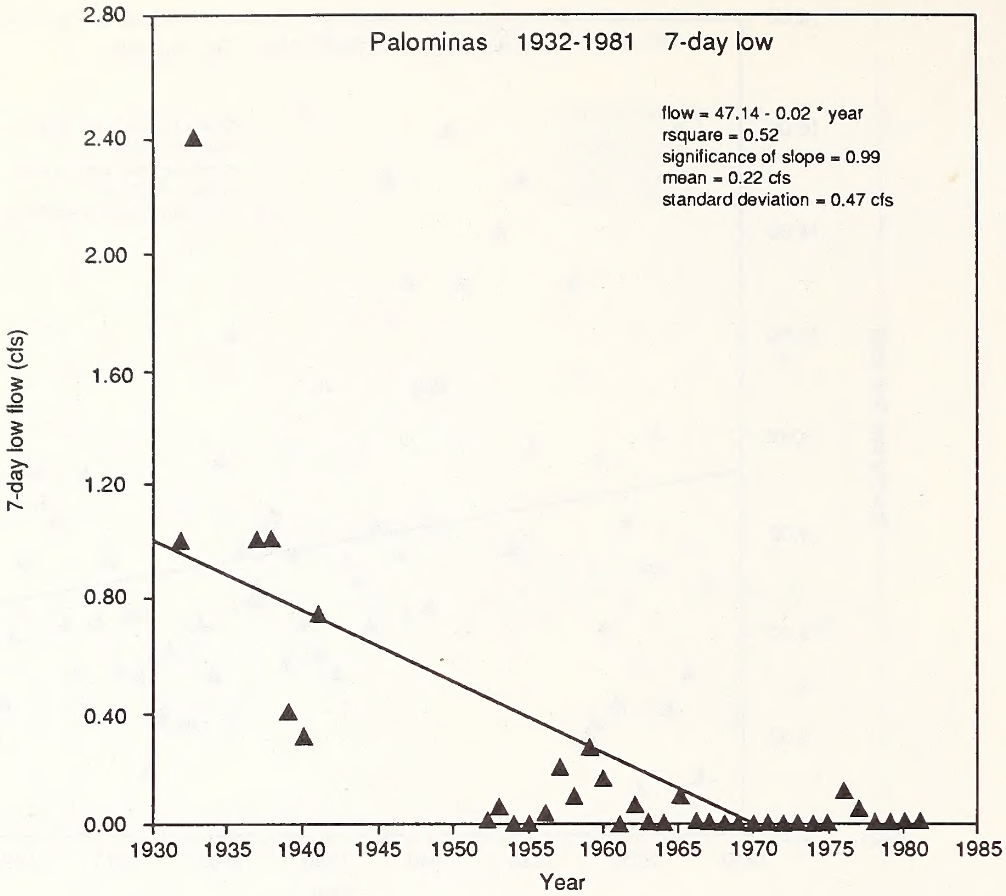

Charleston 1914-1984 1-day low
flow = 34.46 - 0.02 * year
rsquare = 0.06
significance of slope = 0.96
mean = 2.27 cfs
standard deviation = 1.36 cfs
1-day low flow (cfs)
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
1910
1920
1930
1940
1950
1960
1970
1980
1990
Year

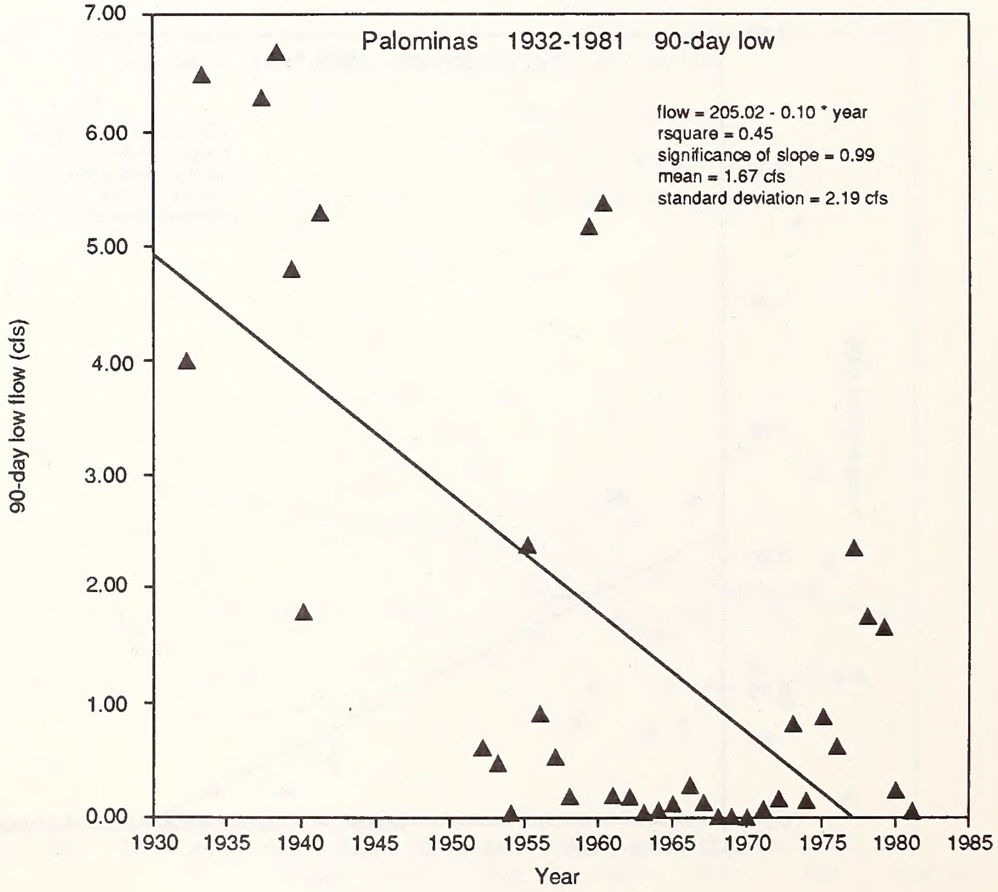

Charleston 1914-1984 7-day low
flow = 34.06 - 0.02 * year
rsquare = 0.06
significance of slope = 0.95
mean = 2.62 cfs
standard deviation = 1.38 cfs
7-day low flow (cfs)
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
1910
1920
1930
1940
1950
1960
1970
1980
1990
Year

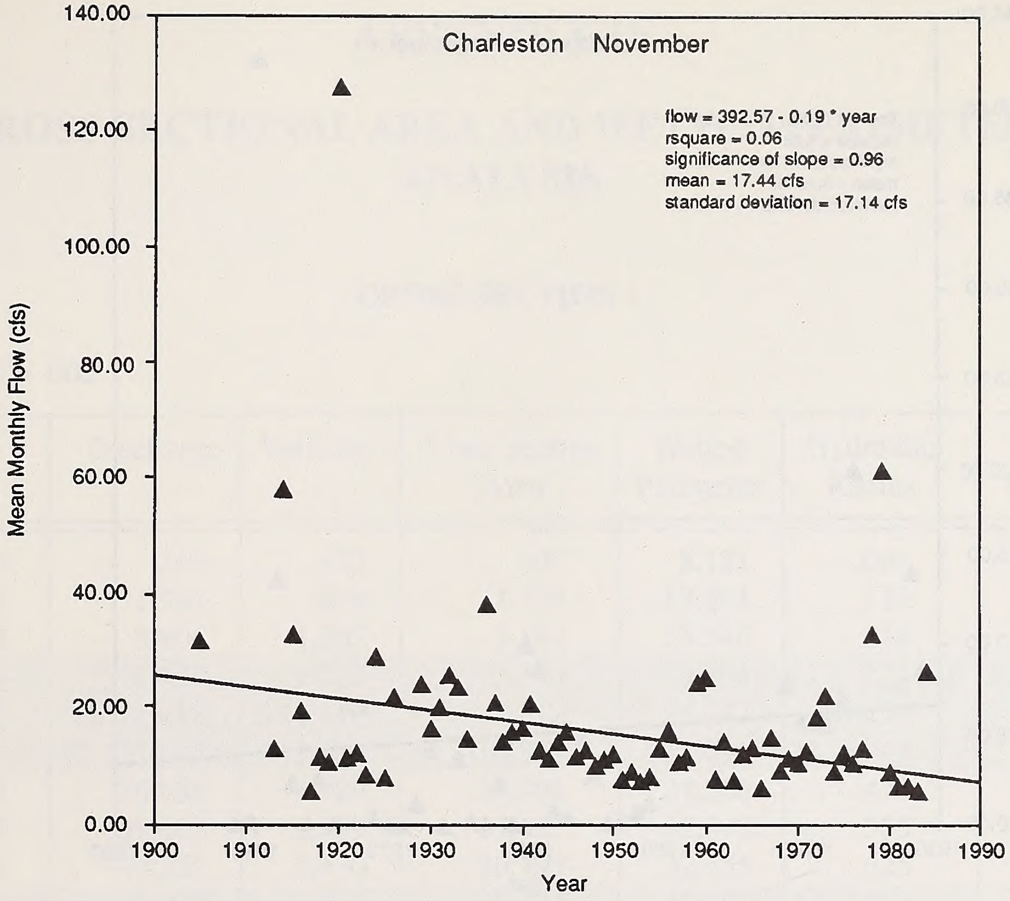

Charleston 1914-1984 30-day low
flow = 46.88 - 0.02 * year
rsquare = 0.06
significance of slope = 0.96
mean = 3.77 cfs
standard deviation = 1.82 cfs
30-day low flow (cfs)
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
1910
1920
1930
1940
1950
1960
1970
1980
1990
Year

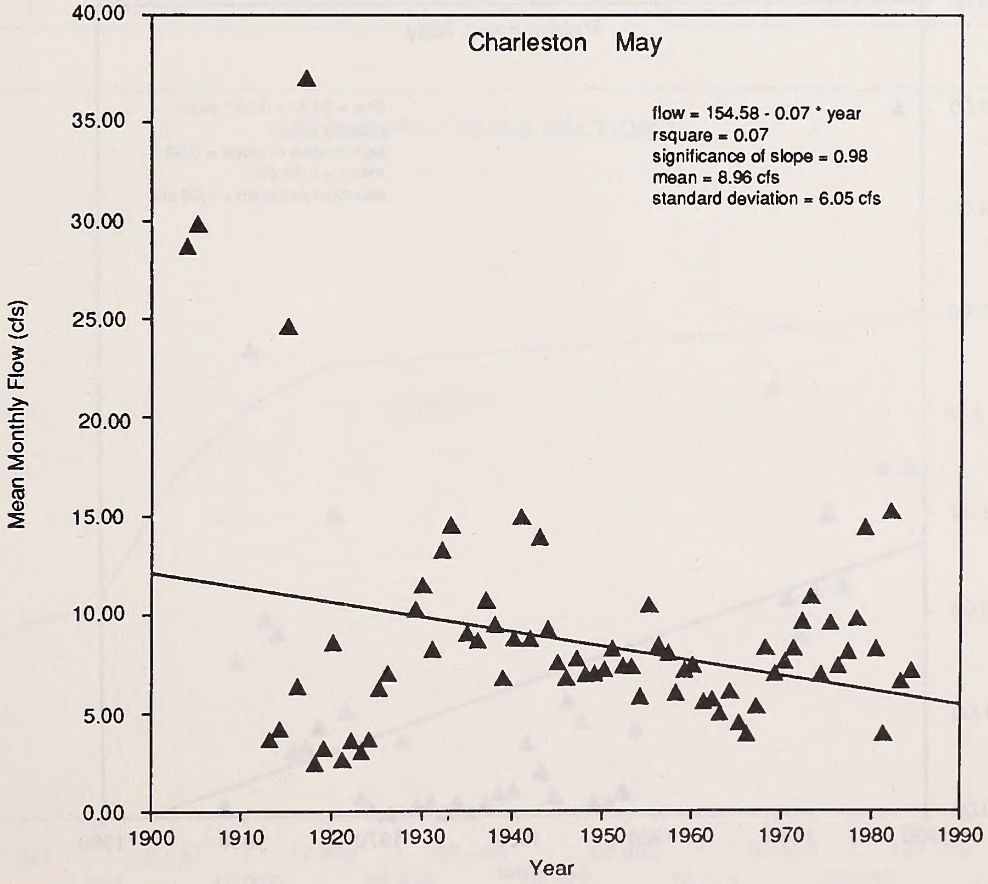

Charleston 1914-1984 90-day low
flow = 80.53 - 0.04 * year
rsquare = 0.06
significance of slope = 0.94
mean = 7.63 cfs
standard deviation = 3.28 cfs
90-day low flow (cfs)
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
1910
1920
1930
1940
1950
1960
1970
1980
1990
Year

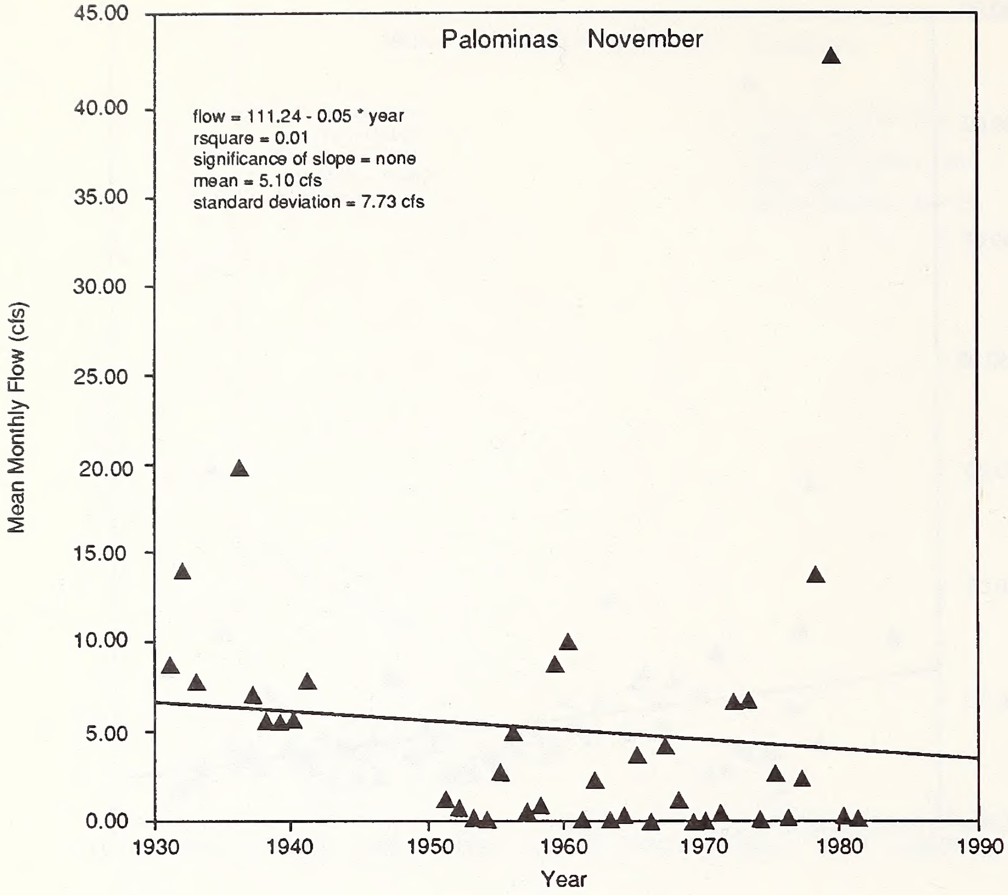

Palominas 1932-1981 1-day low
flow = 44.04 - 0.02 * year
rsquare = 0.55
significance of slope = 0.99
mean = 0.18 cfs
standard deviation = 0.42 cfs
1-day low flow (cfs)
2.40
2.00
1.60
1.20
0.80
0.40
0.00
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
Year

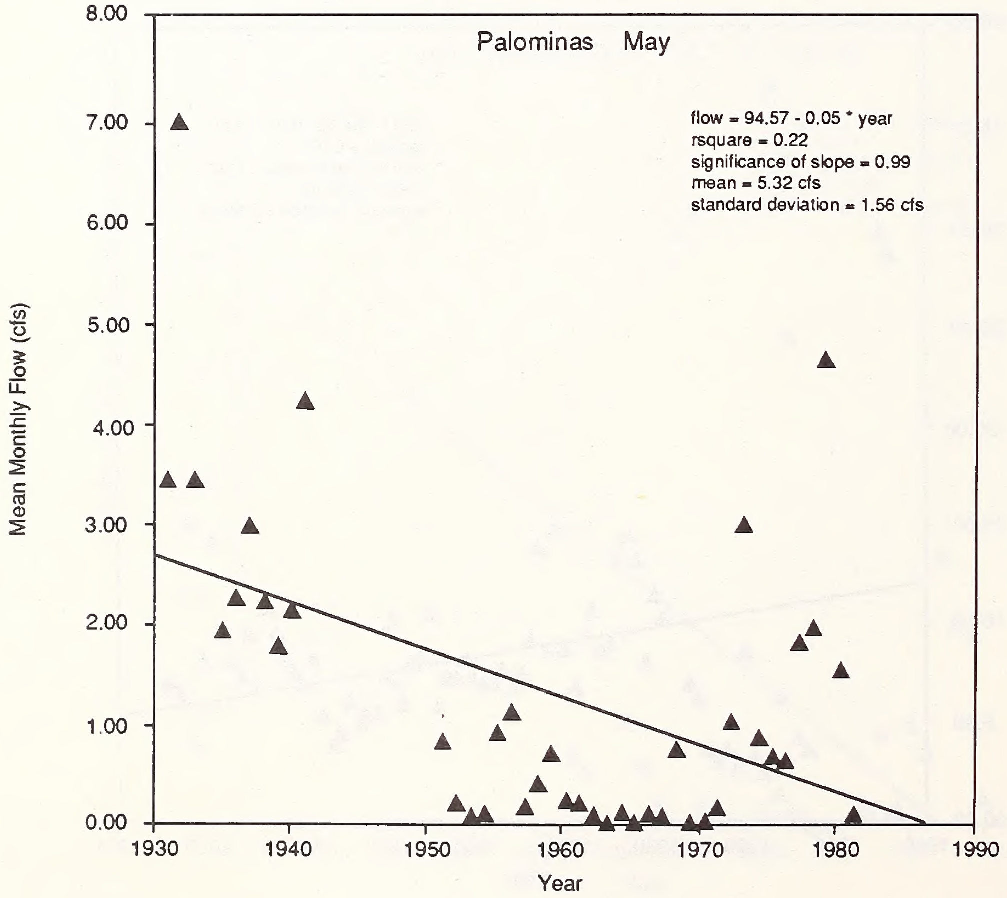

Palominas 1932-1981 7-day low
flow = 47.14 - 0.02 * year
rsquare = 0.52
significance of slope = 0.99
mean = 0.22 cfs
standard deviation = 0.47 cfs
7-day low flow (cfs)
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
Year


Palominas 1932-1981 90-day low
flow = 205.02 - 0.10 * year
rsquare = 0.45
significance of slope = 0.99
mean = 1.67 cfs
standard deviation = 2.19 cfs
90-day low flow (cfs)
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
Year


Charleston November
flow = 392.57 - 0.19 * year
rsquare = 0.06
significance of slope = 0.96
mean = 17.44 cfs
standard deviation = 17.14 cfs
Mean Monthly Flow (cfs)
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
Year


Charleston May
flow = 154.58 - 0.07 * year
rsquare = 0.07
significance of slope = 0.98
mean = 8.96 cfs
standard deviation = 6.05 cfs
Mean Monthly Flow (cfs)
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
Year


Paliminas November
flow = 111.24 - 0.05 * year
rsquare = 0.01
significance of slope = none
mean = 5.10 cfs
standard deviation = 7.73 cfs
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Mean Monthly Flow (cfs)
1930
1940
1950
1960
1970
1980
1990
Year


Palominas May
flow = 94.57 - 0.05 * year
rsquare = 0.22
significance of slope = 0.99
mean = 5.32 cfs
standard deviation = 1.56 cfs
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Mean Monthly Flow (cfs)
1930
1940
1950
1960
1970
1980
1990
Year

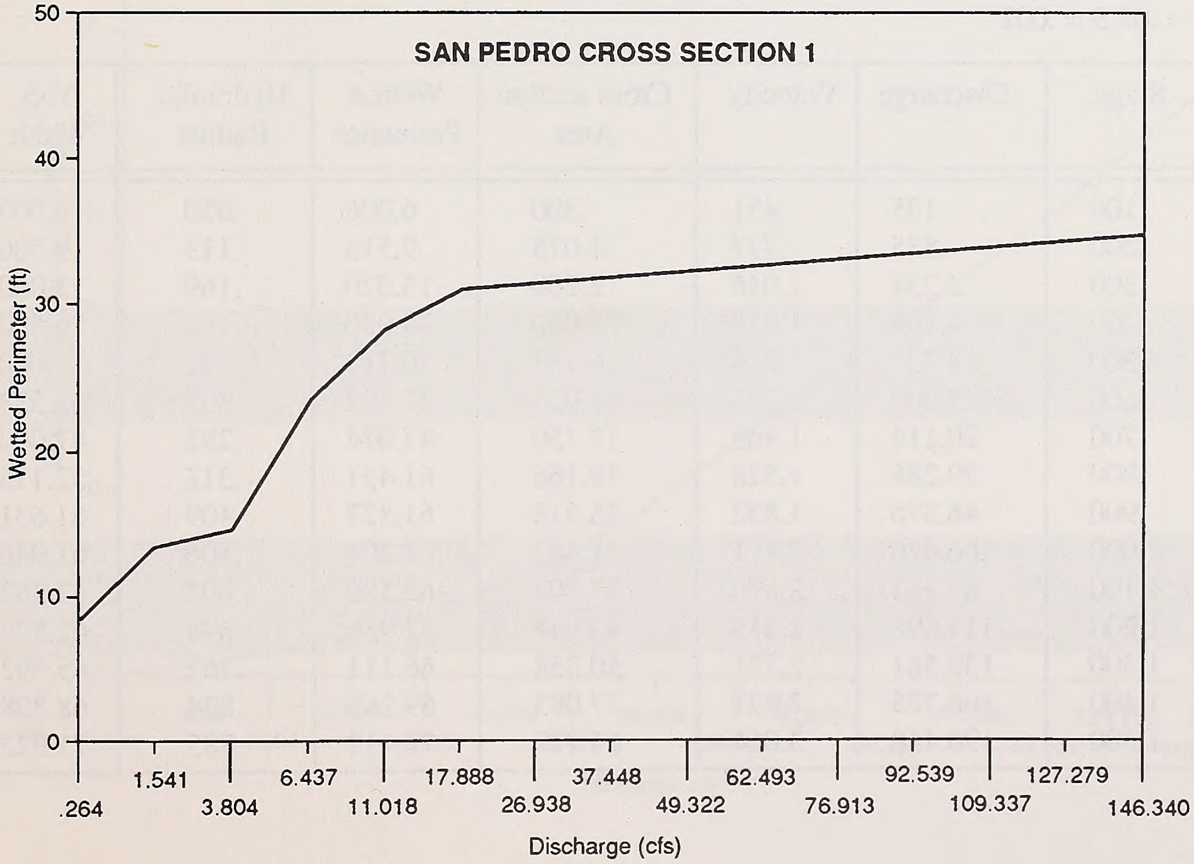
APPENDIX II

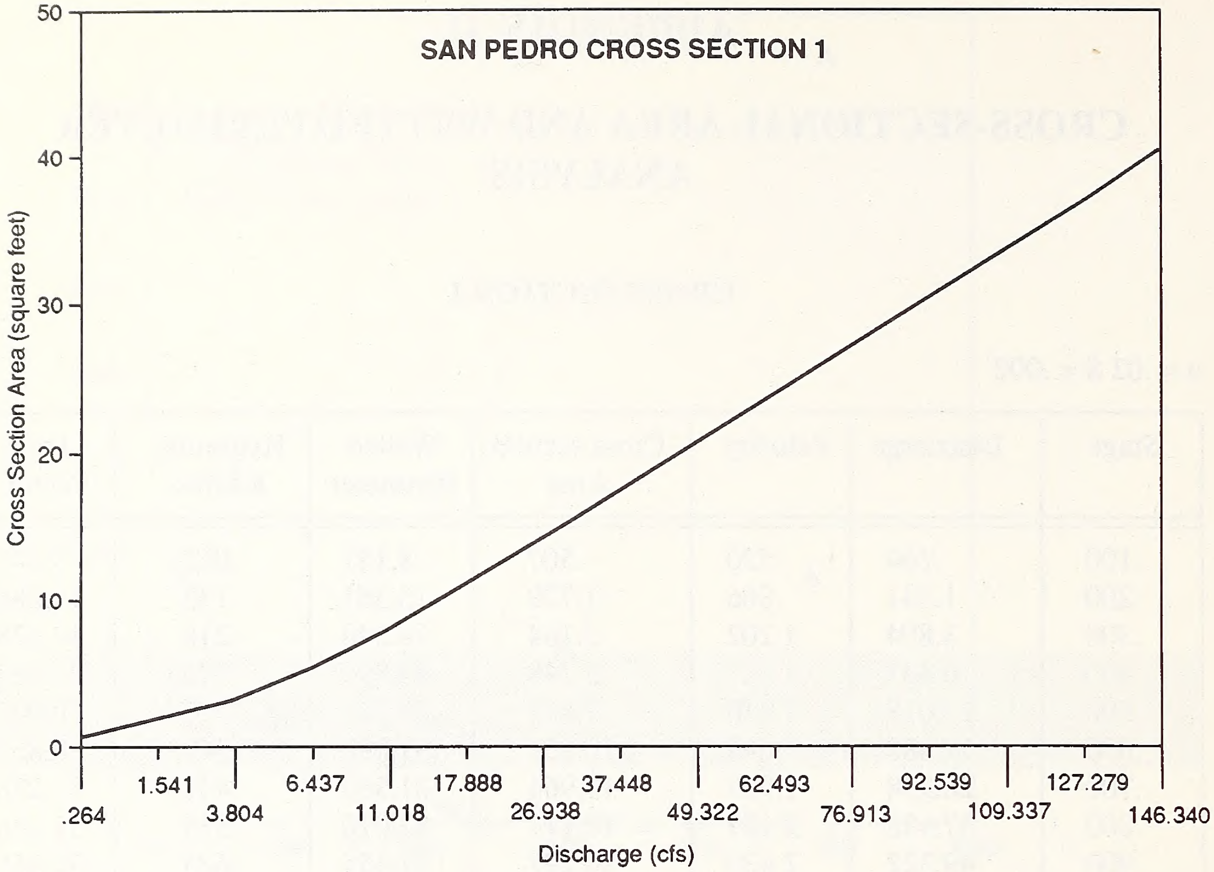
CROSS-SECTIONAL AREA AND WETTED PERIMETER ANALYSIS

CROSS SECTION 1

n = .02 S = .002

Stage	Discharge	Velocity	Cross section Area	Wetted Perimeter	Hydraulic Radius	Top Width
.100	.264	.520	.507	8.181	.062	8.142
.200	1.541	.866	1.779	13.361	.133	13.286
.300	3.804	1.202	3.164	14.540	.218	14.428
.400	6.437	1.227	5.248	23.394	.224	23.238
.500	11.018	1.410	7.812	28.247	.277	28.047
.600	17.888	1.648	10.857	31.096	.349	30.857
.700	26.938	1.929	13.964	31.566	.442	31.278
.800	37.488	2.189	17.111	32.010	.535	31.666
.900	49.322	2.430	20.297	32.455	.625	32.055
1.000	62.493	2.657	23.522	32.900	.715	32.444
1.100	76.913	2.871	26.786	33.344	.803	32.833
1.200	92.539	3.076	30.089	33.789	.890	33.222
1.300	109.337	3.271	33.430	34.234	.977	33.611
1.400	127.279	3.458	36.811	34.679	1.061	34.000
1.500	146.340	3.638	40.230	35.123	1.145	34.389

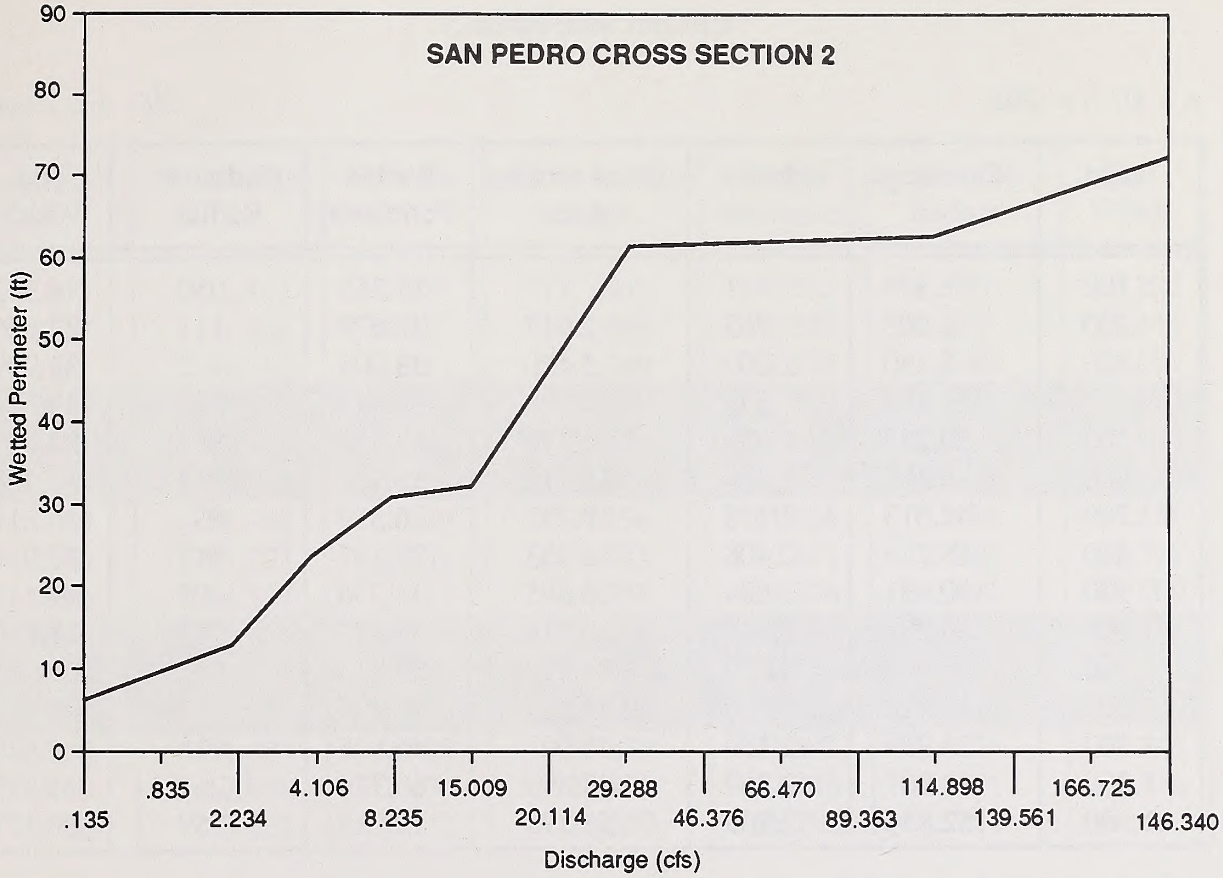


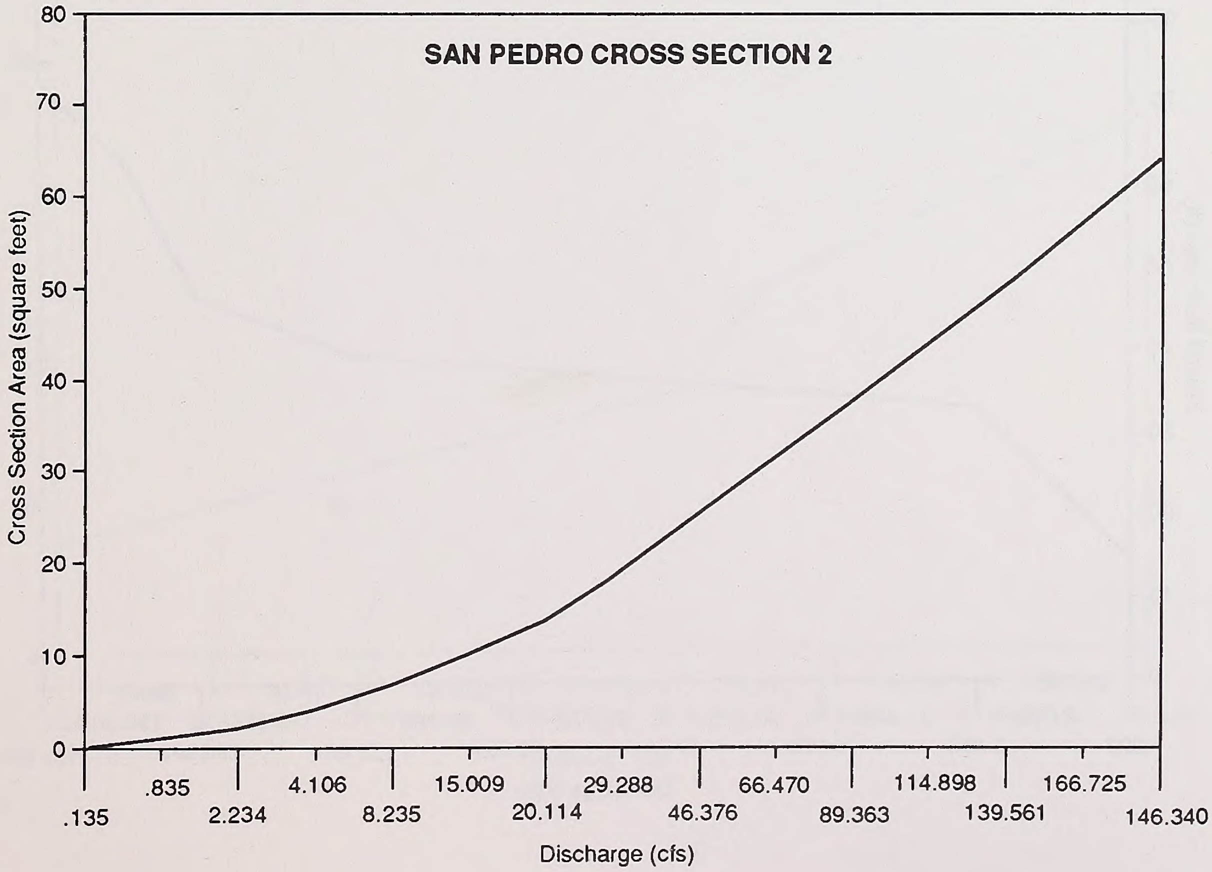


CROSS SECTION 2

n = .02 S = .002

Stage	Discharge	Velocity	Cross section Area	Wetted Perimeter	Hydraulic Radius	Top Width
.100	.135	.451	.300	6.006	.050	6.000
.200	.835	.777	1.075	9.513	.113	9.500
.300	2.234	1.016	2.200	13.020	.169	13.000
.400	4.106	1.014	4.050	24.030	.169	16.500
.500	8.235	1.214	6.783	30.713	.221	.000
.600	15.009	1.511	9.933	32.392	.307	32.333
.700	20.114	1.463	13.750	47.074	.292	47.000
.800	29.288	1.528	19.166	61.451	.312	52.115
.900	46.376	1.832	25.313	61.827	.409	61.631
1.000	66.470	2.111	31.492	62.204	.506	61.946
1.100	89.363	2.370	37.702	62.580	.602	62.262
1.200	114.898	2.615	43.944	62.956	.698	62.577
1.300	139.561	2.771	50.358	66.111	.762	65.692
1.400	166.725	2.921	57.083	69.265	.824	68.808
1.500	196.448	3.064	64.119	72.419	.885	71.923

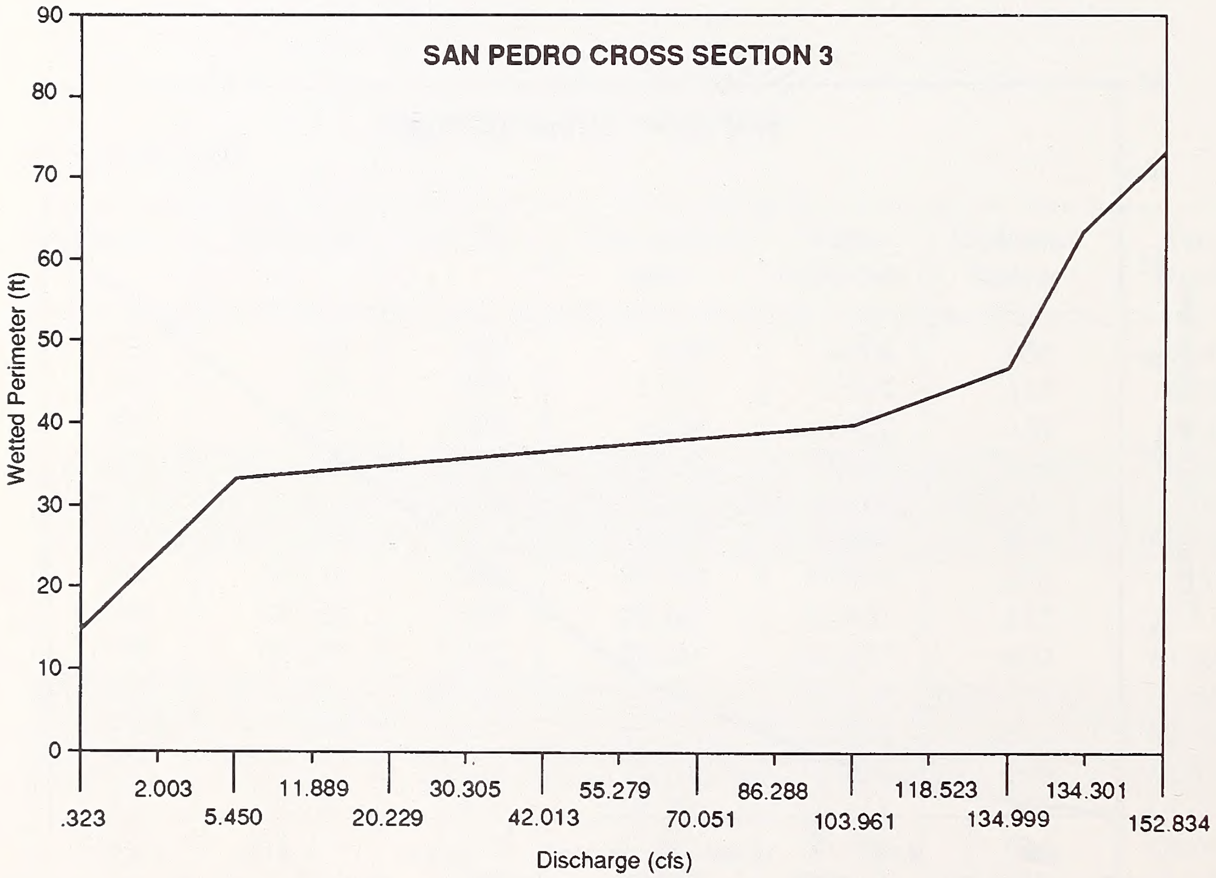

SAN PEDRO CROSS SECTION 2
Wetted Perimeter (ft)
90
80
70
60
50
40
30
20
10
0
.135
.835
2.234
4.106
8.235
15.009
20.114
29.288
46.376
66.470
89.363
114.898
139.561
166.725
146.340
Discharge (cfs)


SAN PEDRO CROSS SECTION 2
Cross Section Area (square feet)
80
70
60
50
40
30
20
10
0
.135
.835
2.234
4.106
8.235
15.009
20.114
29.288
46.376
66.470
89.363
114.898
139.561
166.725
146.340
Discharge (cfs)

CROSS SECTION 3

n = .02 S = .002

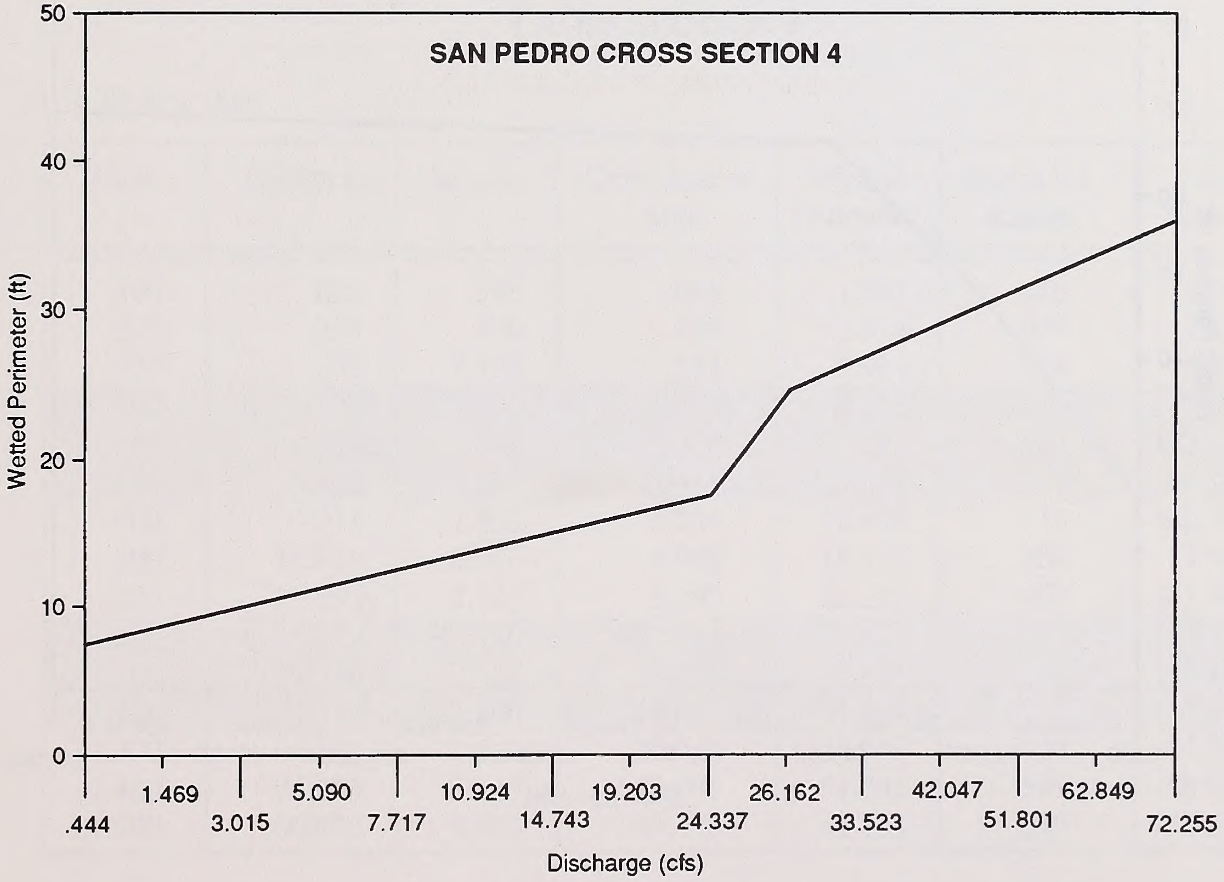
Stage	Discharge	Velocity	Cross section Area	Wetted Perimeter	Hydraulic Radius	Top Width
.100	.323	.451	.717	14.355	.050	14.333
.200	2.003	.765	2.617	23.670	.111	23.666
.300	5.450	1.000	5.450	33.005	.165	32.999
.400	11.889	1.353	8.790	33.843	.260	33.802
.500	20.229	1.657	12.210	34.682	.352	34.605
.600	30.305	1.929	15.711	35.520	.442	35.408
.700	42.013	2.178	19.292	36.359	.531	36.211
.800	55.279	2.408	22.953	37.197	.617	37.014
.900	70.051	2.624	26.695	38.036	.702	37.817
1.000	86.288	2.828	30.516	38.874	.785	38.620
1.100	103.961	3.020	34.419	39.713	.867	.000
1.200	118.523	3.076	38.537	43.275	.891	2.714
1.300	134.999	3.139	43.007	46.838	.918	5.429
1.400	134.301	2.769	48.495	63.734	.761	21.475
1.500	152.834	2.765	55.278	72.829	.759	29.523



CROSS SECTION 4

n = .02 S = .002

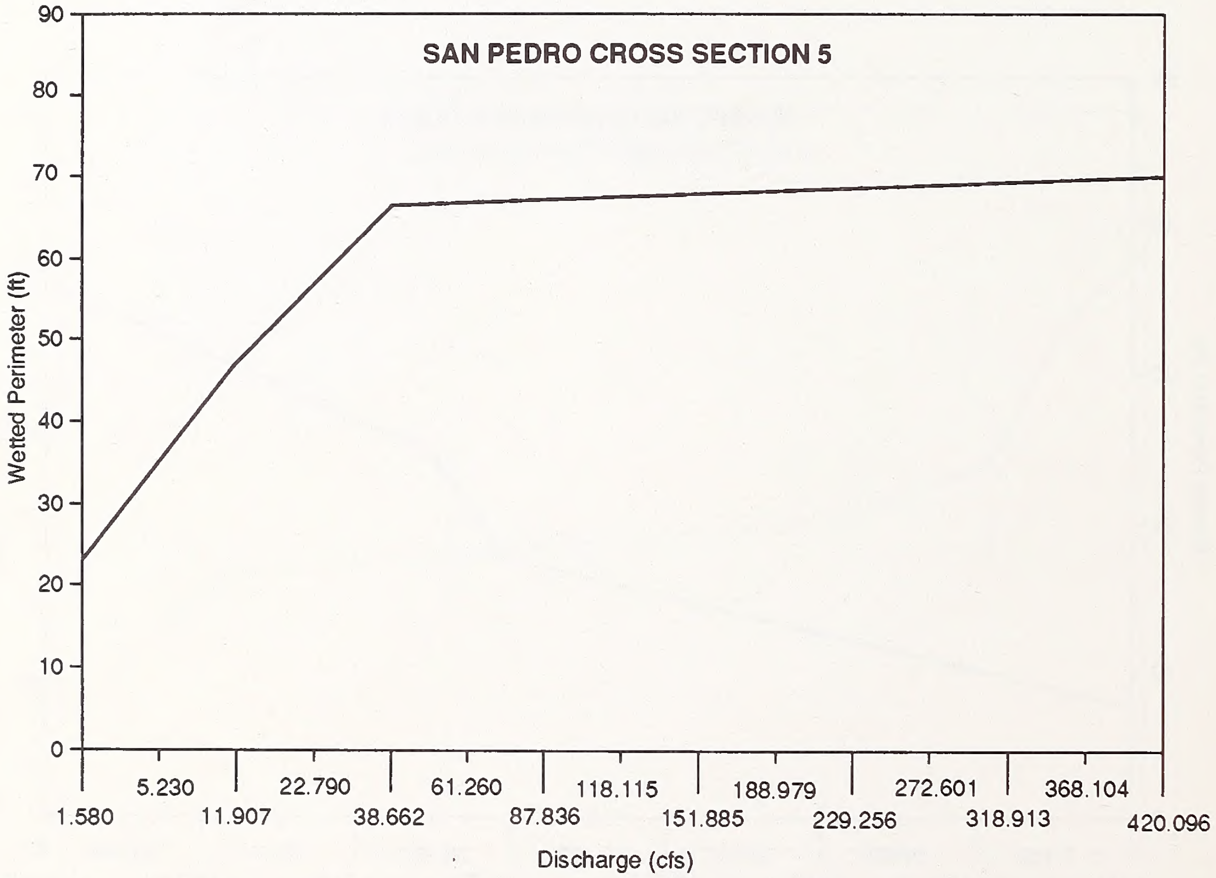
Stage	Discharge	Velocity	Cross section Area	Wetted Perimeter	Hydraulic Radius	Top Width
.100	.444	.672	.661	7.265	.091	7.222
.200	1.469	1.017	1.444	8.530	.169	8.444
.300	3.015	1.283	2.350	9.795	.240	9.667
.400	5.090	1.507	3.378	11.060	.305	10.889
.500	7.717	1.704	4.528	12.325	.367	12.111
.600	10.924	1.883	5.800	13.591	.427	13.333
.700	14.743	2.049	7.194	14.856	.484	14.556
.800	19.203	2.204	8.711	16.121	.540	15.778
.900	24.337	2.351	10.350	17.386	.595	17.000
1.000	26.162	2.109	12.406	24.536	.506	24.111
1.100	33.523	2.245	14.932	26.888	.555	26.422
1.200	42.047	2.377	17.690	29.239	.605	28.733
1.300	51.801	2.505	20.679	31.591	.655	31.044
1.400	62.849	2.630	23.899	33.943	.704	33.356
1.500	75.255	2.752	27.350	36.295	.754	35.667

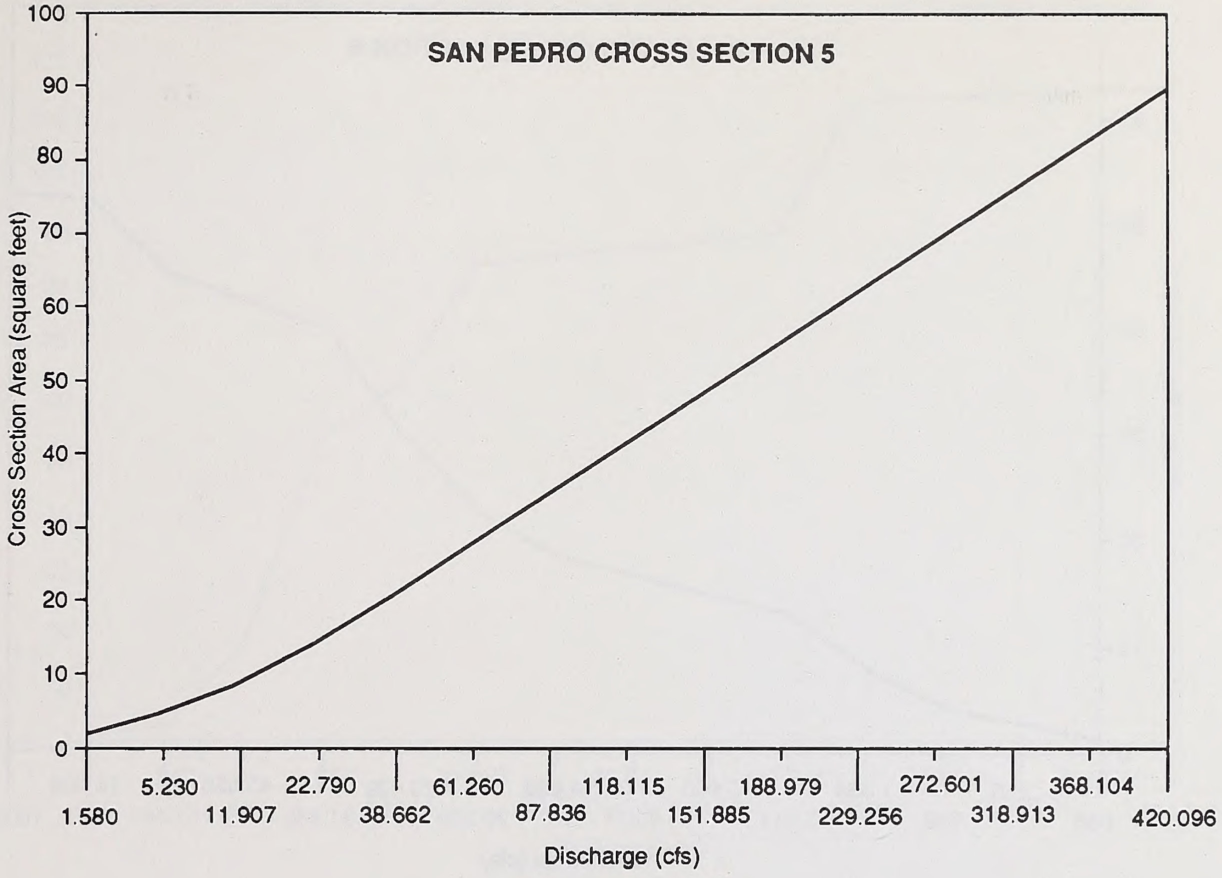


CROSS SECTION 5

n = .02 S = .003

Stage	Discharge	Velocity	Cross section Area	Wetted Perimeter	Hydraulic Radius	Top Width
.100	1.580	.806	1.960	22.236	.088	.000
.200	.230	.088	4.809	34.810	.138	7.331
.300	11.907	1.336	8.913	47.385	.188	14.662
.400	22.790	1.619	14.076	56.092	.251	18.083
.500	38.662	1.869	20.686	66.464	.311	66.254
.600	61.260	2.242	27.327	66.838	.409	66.562
.700	87.836	2.584	33.998	67.213	.506	66.869
.800	118.115	2.902	40.701	67.587	.602	67.177
.900	151.885	3.202	47.434	67.962	.698	67.485
1.000	188.979	3.487	54.197	68.336	.793	67.792
1.100	229.256	3.759	60.992	68.711	.888	68.100
1.200	272.601	4.020	67.818	69.085	.982	68.408
1.300	318.913	4.271	74.674	69.460	1.075	68.715
1.400	368.104	4.513	81.561	69.834	1.168	69.023
1.500	420.096	4.748	88.478	70.209	1.260	69.331

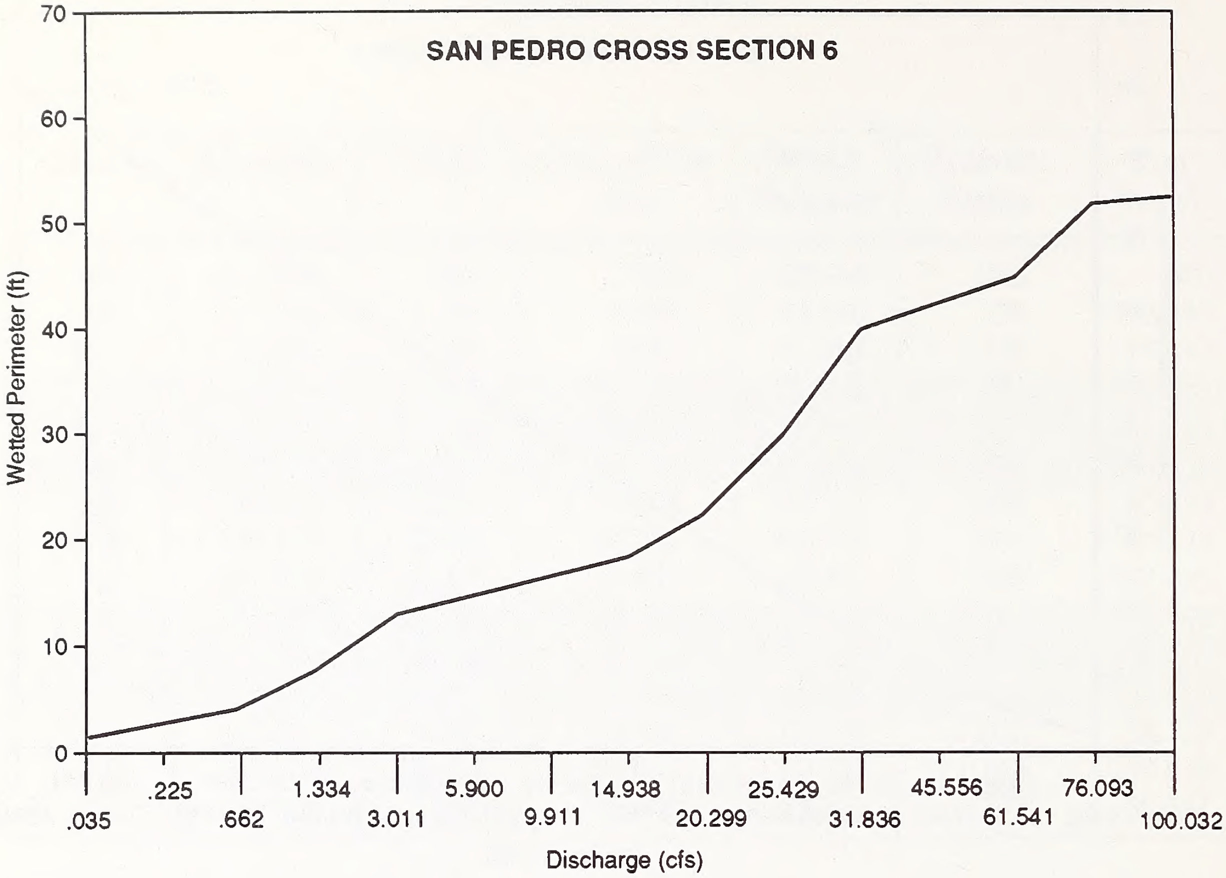




CROSS SECTION 6

n = .02 S = .003

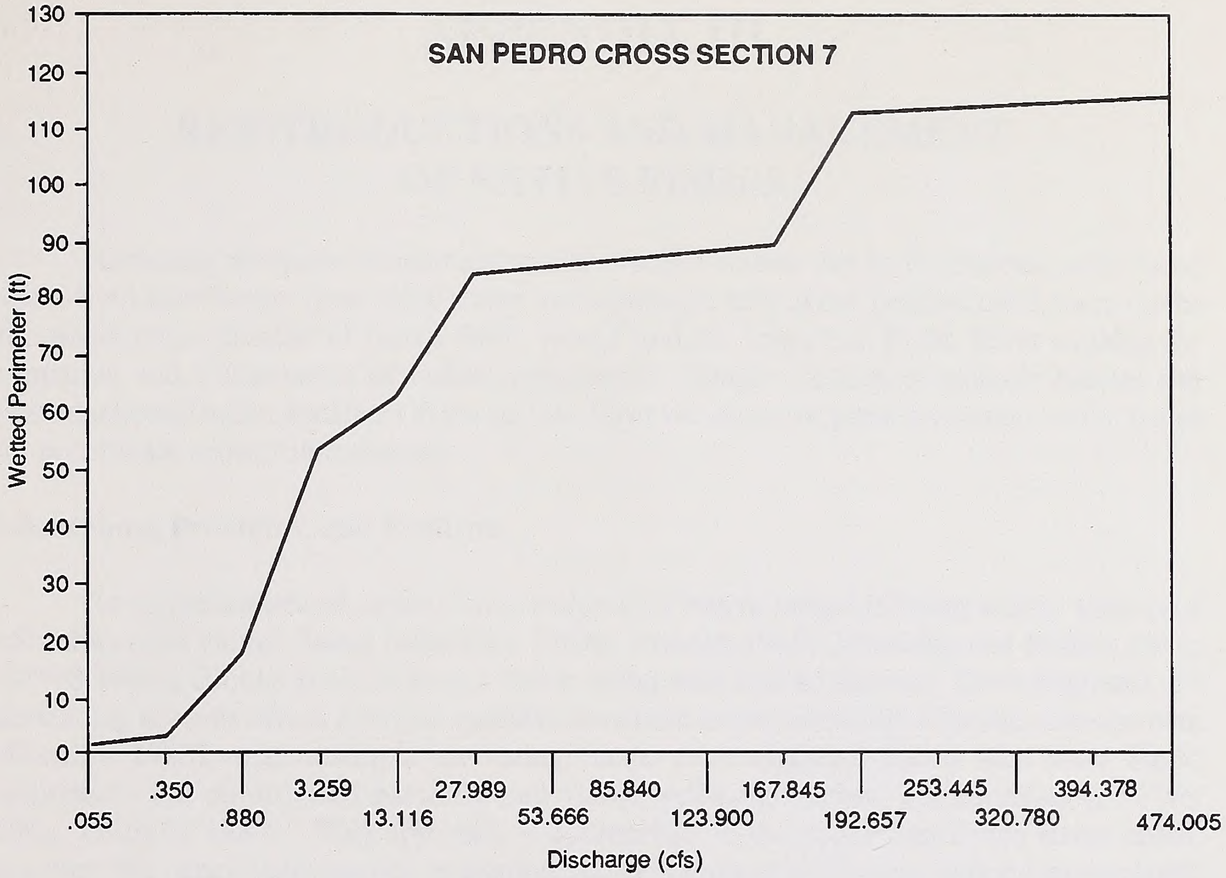
Stage	Discharge	Velocity	Cross section Area	Wetted Perimeter	Hydraulic Radius	Top Width
.100	.035	.548	.065	1.307	.049	1.292
.200	.225	.870	.258	2.614	.099	2.583
.300	.662	1.140	.581	3.921	.148	3.875
.400	1.334	1.160	1.150	7.555	.152	7.499
.500	3.011	1.306	2.306	12.691	.182	12.624
.600	5.900	1.606	3.675	14.827	.248	14.749
.700	9.911	1.895	5.231	16.465	.318	16.374
.800	14.938	2.150	6.949	18.103	.384	17.998
.900	20.299	2.243	9.049	22.112	.409	21.998
1.000	25.429	2.190	11.613	29.425	.395	29.283
1.100	31.836	2.131	14.937	39.411	.379	39.197
1.200	45.556	2.400	18.978	41.890	.453	41.611
1.300	61.541	2.646	23.260	44.369	.524	44.026
1.400	76.093	2.717	28.008	51.345	.545	50.940
1.500	100.032	3.020	33.123	51.811	.639	51.355

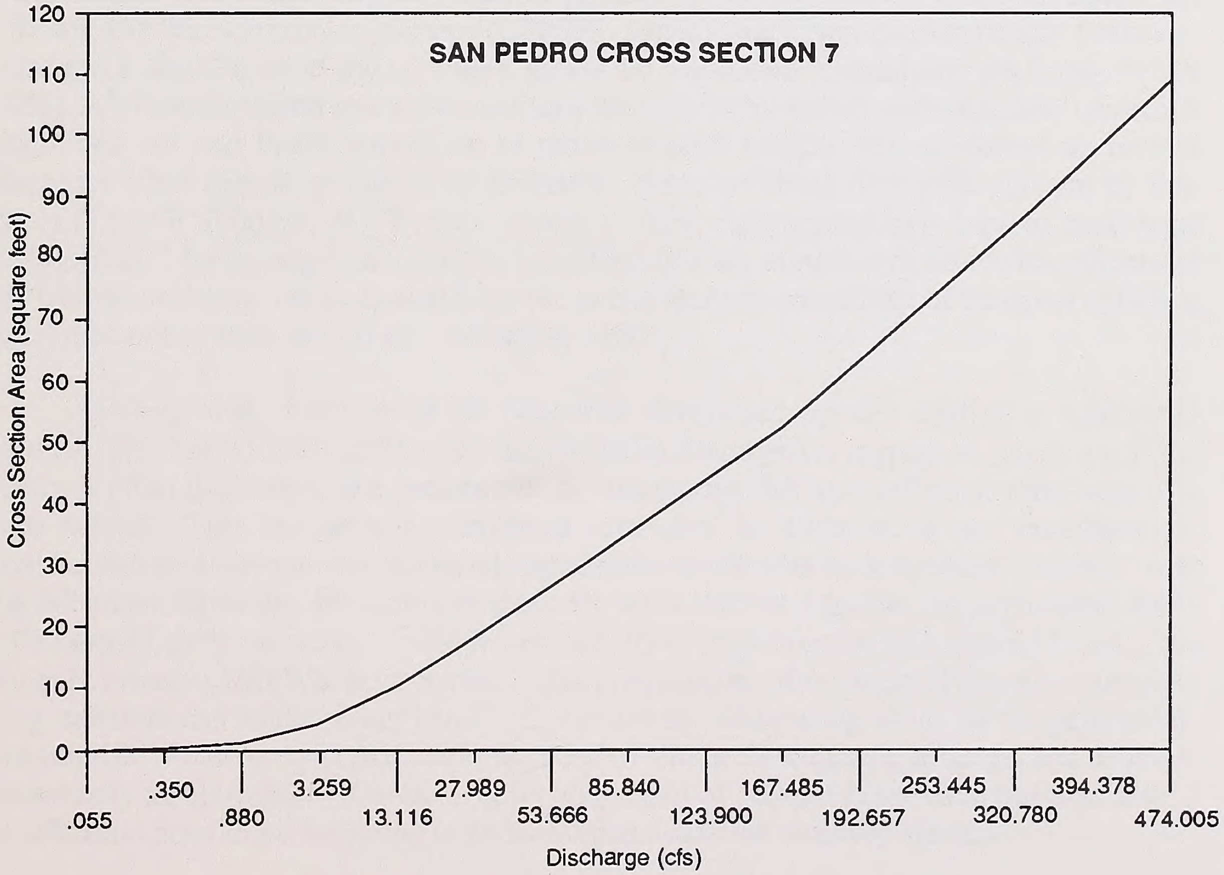


CROSS SECTION 7

n = .02 S = .0039

Stage	Discharge	Velocity	Cross section Area	Wetted Perimeter	Hydraulic Radius	Top Width
.100	.055	.626	.088	1.777	.050	1.762
.200	.350	.994	.352	3.555	.099	3.524
.300	.880	.754	1.168	17.835	.065	17.786
.400	3.259	.821	3.968	53.281	.074	8.214
.500	13.116	1.347	9.736	62.228	.156	62.142
.600	27.989	1.621	17.271	83.678	.206	83.570
.700	53.666	2.088	25.700	85.123	.302	84.998
.800	85.840	2.506	34.258	86.329	.397	86.172
.900	123.900	2.886	42.934	87.535	.490	87.346
1.000	167.485	3.238	51.728	88.740	.583	88.520
1.100	192.657	3.121	61.738	111.941	.552	111.693
1.200	253.445	3.475	72.935	112.539	.648	112.252
1.300	320.780	3.810	84.189	113.137	.744	112.810
1.400	394.378	4.130	95.498	113.735	.840	113.369
1.500	474.005	4.436	106.862	114.333	.935	113.927


SAN PEDRO CROSS SECTION 7
Wetted Perimeter (ft)
130
120
110
100
90
80
70
60
50
40
30
20
10
0
.055
.350
.880
3.259
13.116
27.989
53.666
85.840
123.900
167.845
192.657
253.445
320.780
394.378
474.005
Discharge (cfs)


SAN PEDRO CROSS SECTION 7
Cross Section Area (square feet)
120
110
100
90
80
70
60
50
40
30
20
10
0
.055
.350
.880
3.259
13.116
27.989
53.666
85.840
123.900
167.485
192.657
253.445
320.780
394.378
474.005
Discharge (cfs)

APPENDIX III

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." There is concern 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.

One might 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 the term "biologically endangered" is used 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 extinctions. 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 ma 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 natural riverine habitats, those on the floodplain, and even excavation of semi-natural, oxbow-like reaches, will contribute 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 Berde 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 aspect 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.

Recommendations

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 if 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 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 Fairbanks.

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 be 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 flood-plain. 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 razor back 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 flannel-mouth 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 flannel-mouth 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 probable 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 warrant, 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.

50272 - 101

REPORT DOCUMENTATION PAGE

1. Report No. BLM/YA/PT-88/004+7200

2.

3. Recipient's Accession No.

4. Title and Subtitle
Assessment of Water Conditions and Management Opportunities in Support of Riparian Values: BLM San Pedro River Properties, Arizona. Project Completion Report.

5. Report Date May 1988

6.

7. Author(s) William Jackson, Tony Martinez, Paul Cuplin, W.L. Minkley, Bo Shelby, Paul Summers, Dan McGothlin, Bruce Van Havern

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
U.S. Department of the Interior
Bureau of Land Management - Service Center
P.O. Box 25047
Denver, CO 80225-0047

10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.
(C)
(G)

12. Sponsoring Organization Name and Address
U.S. Department of the Interior
Bureau of Land Management - Arizona State Office
P.O. Box 16563
Phoenix, AZ 85011

13. Type of Report & Period Covered

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

The Bureau of Land Management's Safford District recently acquired 44,000 acres of land along the San Pedro River in southeastern Arizona, so that valuable riparian ecosystems, wildlife, cultural, historic, educational and recreational resources may be protected and managed for the American public. Legislation has been introduced in Congress to designate this land the San Pedro Riparian National Conservation Area.

Critical to the management of the San Pedro properties is the management of the water resource. Instream flow water rights must be obtained and the ground-water resource effectively managed if the riparian and other resource values of the area are to be conserved, protected and enhanced. BLM has sought instream flow protection for this area through the State of Arizona, but has not yet qualified this claim.

17. Document Analysis a. Description

* Water rights	Ground Water
* Hydrology	Surface Waters
Vegetation	
Fishes	

b. Identifiers/Open-Ended Terms

*San Pedro Riparian National Conservation Area	
*Instream flow	
*Riparian ecosystems	
San Pedro River, AZ	Aquatic habitats

c. COSATI Field/Group

18. Availability Statement
Release Unlimited

19. Security Class (This Report) Unclassified

20. Security Class (This Page) Unclassified

21. No. of Pages 196

22. Price

(See ANSI-Z39.18)

See Instructions on Reverse

OPTIONAL FORM 272 (4-77)
(Formerly NTIS-35)
Department of Commerce

☆ U.S. GOVERNMENT PRINTING OFFICE: 1988—573-003/80,816 REGION NO. 8