Ecological Implications of Verde River Flows

February 2008

Verde River Basin Partnership
Arizona Water Institute
The Nature Conservancy
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Prepared in cooperation with the
Arizona Water Institute, The Nature Conservancy, and Verde River Basin Partnership.

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Dedicated to Laurie Wirt (1958-2006)

The Verde River Ecological Flows report is dedicated to the memory of Laurie Wirt. Laurie worked as a hydrologist for the U.S. Geological Survey. Laurie believed that good science should guide decision-making about water resources, and she was tireless in her pursuit of scientific data to document the nature of the hydrologic connection between the Big Chino aquifer and the upper Verde River. Laurie always had time for interested citizens as well as fellow scientists. Laurie brought warmth and happiness, as well as increased hydrologic fluency, to a whole range of people. Laurie died pursuing one of her passions – white water kayaking. She is deeply missed and frequently remembered.

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Executive Summary

The Verde River is an essential element of life in central Arizona for both its natural and human communities. Apparent conflicts have developed, however, between human communities in different parts of the watershed, and between human demands for water and those of the plants and animals that use the river. Such issues are not unique to the Verde, and experience in watersheds around the world has shown that water conflicts can be reduced or resolved through better understanding. To the extent that land and water managers understand the physical processes involved and the character of various water demands, they can work for solutions that better meet the needs of the Verde's ecosystem and the human communities within it.

This study is an effort to describe the needs of the plant and animal communities that depend on water in the Verde River. It is intended to fill a gap in the discussions of Verde water management. By highlighting the basic needs of the Verde River Ecosystem, it shows areas of overlap with human demands and can be used to refine the sense of trade-offs in management decisions.

The Verde River Ecological Flows study was a collaborative effort, sponsored by the Arizona Water Institute, The Nature Conservancy, and the Verde River Basin Partnership, and involving experts from fifteen agencies, universities, and other organizations.

Summary of Results

This study identifies where the scientific information is clear as to the types and scope of change that would result from changes in surface and groundwater conditions on the Verde River, and where additional scientific studies are needed to resolve particular issues. There is clear scientific evidence that the plants and animals in and along the banks of the Verde River depend on river flows, and would be affected if these flows diminish. Reduced base flow would alter aquatic habitat, reducing or removing populations of some fish and other animals and plants dependent on open water conditions for at least part of their life cycles. In addition, if base flow were to decrease and stream reaches changed from perennial to intermittent, the water table in the stream aquifer would show increased seasonal and year-to-year fluctuations, and the average annual depth from the land surface to saturated soils would increase.

Riparian forest response to stream flow regime and depth-to-groundwater fluctuations have been extensively studied in southwestern rivers. Based on these studies, experts predicted: 1) declines in cottonwood and willow abundance; 2) decreases in structural diversity; and 3) increases in non-native species such as tamarisk. Such vegetation changes would likely cause shifts in the bird community, with reductions or loss of some species.

Thresholds for some species have not been adequately quantified for the Verde River through scientific study. To capture the state of our knowledge and facilitate the needed research, subject experts reviewed the available science and developed hypotheses on the ecological responses of species to changing river and groundwater levels. When refined with adequate data, these hypotheses will provide advance warning of potential species loss from the river system in time to prevent it.

The effects of reduced base flow would differ according to the local hydrologic and geomorphic conditions. Base flow in the upper Verde River is smaller than in the Verde Valley, so the same volume of water removed from the river would remove a greater proportion of streamflow in the upper reach than in the Verde Valley. Thus, ecological impact may be larger in the upper reach. However, water use and land use are complex in the Verde Valley. Workshop participants identified several studies that would address this information gap.

A Research Agenda for the Future

A major goal of the Verde River Ecological Flows workshop was to identify critical gaps in our knowledge, and to develop a prioritized research agenda to fill those gaps. The experts stressed that data collection needs to be integrated among the physical and biological science disciplines.

Priority research goals include better characterization of the river and its floodplain with representative cross-sections and longitudinal profiles, developing information on the flood stage that can be expected with various flow levels, and documenting depth to groundwater at representative study sites. Biological research priorities include measuring vegetation attributes at the same representative sites, and quantifying fish habitat availability as it relates to stream flow. Results from such integrated data collection should provide the essential platform for quantifying the responses of plants and animals to changes in river flow.

Chapter 1
Introduction

By Jeanmarie A. Haney

The Verde River Ecological Flows study is a collaboration of the Arizona Water Institute, The Nature Conservancy, and the Verde River Basin Partnership. The study's purpose is to develop conceptual models of the Verde River ecosystem that link hydrologic variation to ecological response, in the hope that these models would guide future data collection and ultimately lead to better-informed water management.

The first phase of the study, documented herein, included a synthesis of available literature and a two-day experts' workshop. The workshop tapped the knowledge and experience of an interdisciplinary group of experts in the fields of ecology, biology, hydrology, and geomorphology. The goals of the workshop were to develop conceptual models, document streamflow-ecology relationships, and develop a prioritized agenda for further research. This report describes the physical setting, riparian ecosystem, and wildlife resources of the Verde River; documents results and outcomes from the workshop; and identifies linkages between hydrologic variation and ecological response.

Workshop participants recognized that although much is known, many questions remain. Thus, development of a prioritized research agenda was an important outcome from the workshop. Future phases of the study will begin implementing the research agenda.

Need and Purpose

The Verde River is a critical component of life in central Arizona and beyond, for both the natural and human communities (Figure 1-1). There is concern about how the growing human water needs of the area are going to be met while also preserving the important ecological values of the Verde River. Pro-active long-term water management, armed with credible information on the water needs of the ecosystem, can address and minimize consequences to the ecosystem from various growth and management scenarios before impacts happen.

Federal legislation enacted in November of 2005 - the Northern Arizona Land Exchange and Verde River Basin Partnership Act of 2005 (Public Law 109-110) - authorizes federal funding via the Secretaries of Agriculture and Interior for water resource planning and scientific studies in the Verde River Basin. Title II of that act directs the U.S. Geological Survey to prepare a water budget analysis for the Verde Valley, including "*an analysis of the potential long-term consequences of various water use scenarios on groundwater levels and Verde River flows.*" To be comprehensive, such an analysis must include consequences to the ecosystem resulting from human-induced changes in flow regimes and groundwater levels in various reaches of the river. The intent of the Verde River Ecological Flows study is to develop the science to describe those consequences. Decision making informed by sound science supports the missions of the three collaborating partners of this study.

Environmental Flows - A Way to Address Ecosystem Water Needs

To understand consequences to the ecosystem of various water use scenarios, it is necessary to understand the hydrology-biology relationships that form the basis for the water needs of the ecosystem. Ecosystem water needs encompass more than consumptive use by riparian vegetation, and include both streamflow regime (magnitude, frequency, duration, and timing of flows) and groundwater conditions (depth to groundwater and annual groundwater level fluctuations).

At locations around the globe, water managers and planners are addressing the water

Figure 1-1. Regional hydrologic context of the Verde River.

needs of river ecosystems proactively by reserving some portion of river flows for ecosystem support, known as environmental flows. Environmental flows are being analyzed and implemented to address both human and ecosystem needs for water, in efforts to minimize future ecological damage. An environmental flow regime maintains, and may even improve, ecosystem health in rivers that have been impacted by human water needs (Dyson et al. 2003).

The Nature Conservancy has been working with international experts to develop a collaborative, interdisciplinary, and adaptive framework for developing environmental flows (Richter et al. 2003; Richter et al. 2006). Because there are always conflicting needs for water, it is critical that an environmental flow recommendation have a sound science basis.

Our purpose with this study was to begin developing that science basis. The decisions of how to apply the knowledge gained - whether to work toward environmental flows on the Verde River - will be part of on-going water management discussions in the Verde River watershed. We do not make policy recommendations herein, but concentrate on the science of delineating the water needs of the Verde River ecosystem.

An early step in developing the science frequently involves experts' workshops to develop consensus on existing knowledge, ecosystem water needs, and research goals (Richter et al. 2006). In Arizona, this approach was used to analyze ecosystem water needs on the Bill Williams River, with the results used to guide operations of Alamo Dam (Shafroth and Beauchamp 2006; http://billwilliamsriver.org/Streamflow/). A similar approach was taken here, modified for an unregulated river.

The Verde River Ecological Flows workshop was facilitated by staff from the Conservancy's Global Freshwater Team. The workshop provided a forum for synergy among experts, who worked together to define what is well-known and extensively documented, what is understood but little documented, and what is poorly understood. Based on these findings, workshop participants developed a prioritized research agenda, designed to gather the data to further refine and quantify flow-ecology response models.

Flow-Ecology Response Functions

Plants and animals that depend on aquatic and riparian ecosystems have developed life cycles that are keyed to the natural pattern of streamflows, including intra-annual and inter-annual flow variations (Figure 1-2, Appendix 3). Groundwater levels in floodplain alluvial aquifers are also highly responsive to streamflow regimes. Flow-ecology response functions document these relationships by illustrating how a selected biological variable would be expected to change in response to alteration of a specific hydrologic variable. Developing flow-ecology response functions correlates ecological risk, which cannot be managed directly, to streamflow

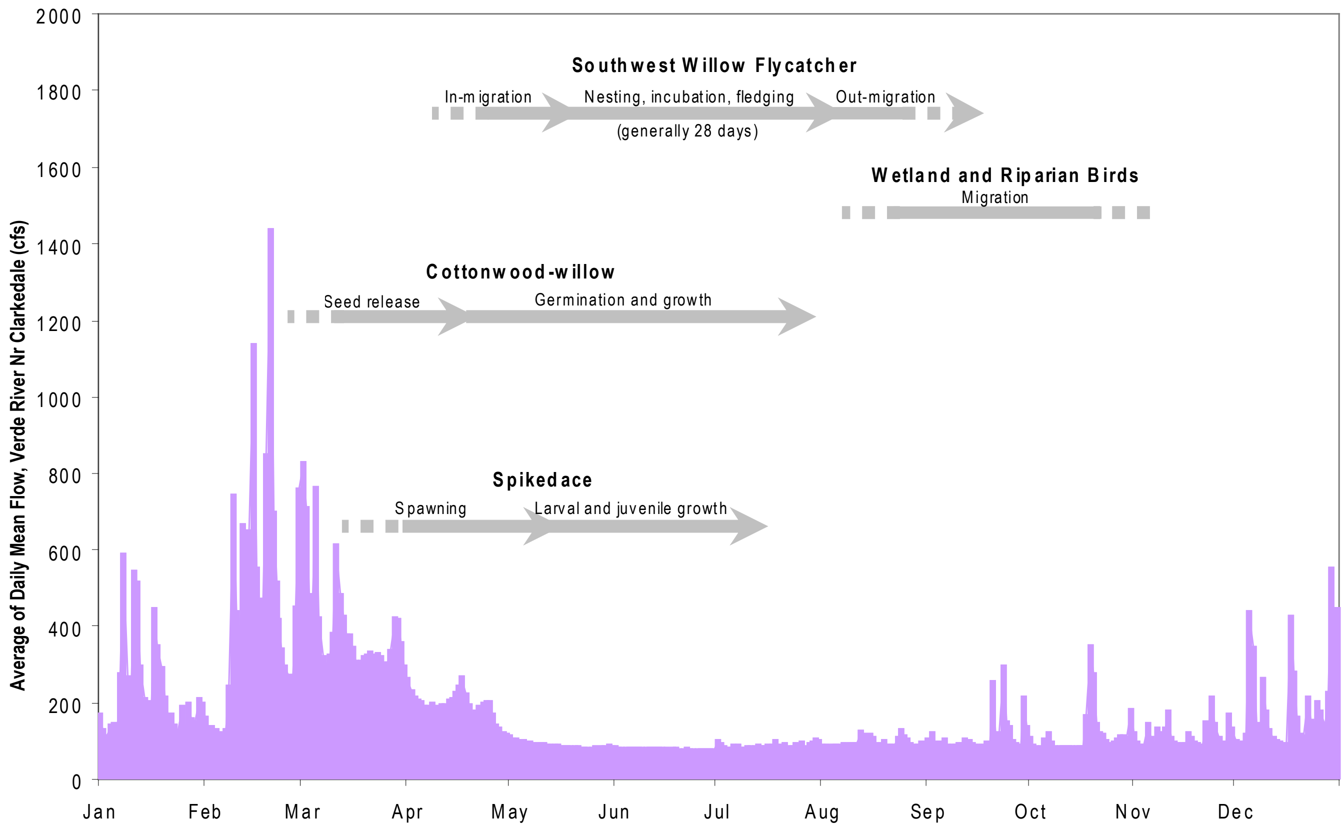

Figure 1-2. An initial conceptual ecological model for the Verde River. Riparian and aquatic plants and animals have life cycles that have evolved with the natural flow regime of the river. These relationships may be described and quantified through flow-ecology response functions.

conditions, which can be managed through water-use policies. Thus, results from an ecological flows study can help water managers integrate human and ecosystem water needs in a spatially comprehensive manner.

An example of a flow-ecology response function is shown on Figure 1-3. There are many biological and hydrological variables that could be selected for developing flow-ecology response functions; experts in the workshop were tasked with selecting the key relationships for the Verde River. Flow-ecology response relationships can first be described in conceptual terms, and relationships can be further quantified as data become available. For certain elements of the Verde ecosystem, such as cottonwood trees, considerable data exist linking recruitment, sapling survival, and growth to streamflows and groundwater levels. Other elements, such as fish, have more complex responses and thus are more difficult to quantify. However, for even the most complex organisms, certain aspects of the life cycle are known and can be documented with respect to flows.

The long-term goal of this flow-ecology study is to understand the ecological needs of plants and animals that depend on the Verde River so that human communities can sustainably share the water resources of this beautiful landscape.

Report Organization

Chapters 2 through 5 provide background information on Verde River hydrology, geomorphology, riparian ecology, and wildlife resources. These chapters were assembled by an academic team funded by a grant from the Arizona Water Institute and led by Dr. Abe Springer. They summarize background material and were provided to workshop participants prior to the workshop. Chapter 6 provides a report on workshop activities and outcomes. Chapter 7 provides a synthesis of what is known about flow-ecology responses and ecosystem water needs on the Verde River, what this knowledge indicates about probable impacts of

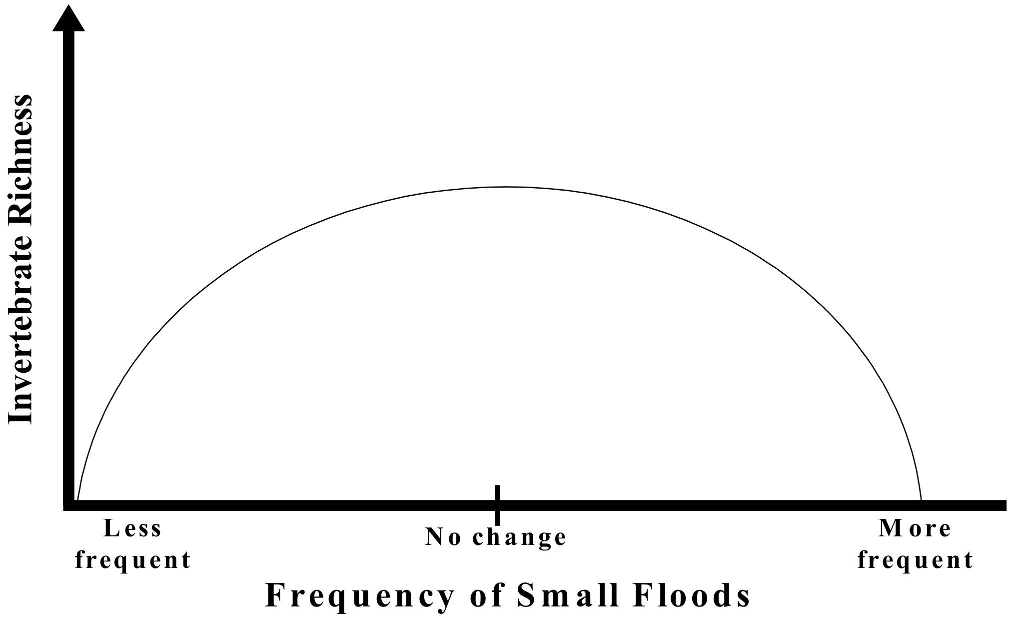

Figure 1-3. Conceptual flow-ecology response curve. Until data is assembled or collected to test this relationship, this curve represents a hypothesis. This hypothesis is supported by scientific understanding that suggests that decreasing frequency of substrate-disturbing floods leads to a shift to long-lived, large-bodied species; declines in richness would be expected as fine sediments accumulate. With increasing frequency of substrate-disturbing floods, a shift to "weedy" species would be expected, along with loss of species with poor recolonization ability.

flow reductions, and what additional information is needed to increase our knowledge of flow-ecology relationships.

A draft version of this report was reviewed by workshop participants. Comments were received from the majority of workshop participants and those comments were incorporated in the final report to the extent possible. A summary of comments received and revisions made is provided in Appendix 4.

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Chapter 2. Background: Hydrology of the Upper and Middle Verde River

By Abe E. Springer and Jeanmarie A. Haney

Site Description

The Verde River is a tributary to the Salt River in the Colorado River Basin. The entire watershed of the Verde River is contained in the State of Arizona and is predominantly in Yavapai County. It has a vast headwaters region of largely ephemeral washes in the Prescott-Chino Valley area and in the Big Chino Wash drainage (Figure 2-1). It begins perennial flow from a group of springs near the confluence with Granite Creek, approximately 2 miles downstream from the town of Paulden. This study is concerned primarily with the Verde River mainstem from its headwaters to below Camp Verde. This part of the river is within the Transition Zone physiographic province, between the Colorado Plateau and the Basin and Range physiographic provinces. Its major tributaries are Chino Wash, Williamson Valley Wash, Walnut Creek, Granite Creek, Hell Canyon, Sycamore Creek, Oak Creek, Beaver Creek, and West Clear Creek. There are three USGS stream gages on this reach of the Verde River mainstem (Figure 2-1). There are two physiographically and culturally distinct reaches bounded by USGS stream gages: 1) the upper Verde River, a relatively remote and undeveloped canyon reach that extends from near Paulden to the USGS gage just below Sycamore Canyon; and 2) the middle Verde River in the Verde Valley - a much more accessible alluvial reach that extends from the gage just below Sycamore Canyon to the gage near Camp Verde and borders communities, farms, and ranches. These two river reaches correspond to the upper Verde River watershed and the middle Verde River watershed.

Steamflow in the upper 26 miles of the Verde River is sustained by surface runoff and groundwater discharge from the upper Verde River springs (Figure 2-2); spring discharge is comprised chiefly of water from the Big Chino (80%) and Little Chino (14%) aquifers (Wirt et al. 2005). Additional groundwater enters the main stem near Perkinsville and Mormon Pocket from consolidated rock aquifers on the southern Colorado Plateau. Streamflow in the middle Verde River is sustained by surface runoff, base flow from the upper Verde River, groundwater discharge from the basin fill aquifer in the Verde Valley, and contributions from the major tributaries in the middle Verde River watershed (e.g. Sycamore, Oak, Beaver, and West Clear creeks). Base flow in these tributaries is comprised largely of groundwater

Table 2-1. Verde River Basin land management.

Land Manager	Total Watershed Acres	Total Watershed Proportion	Big & Little Chino Proportion	Verde Valley Proportion	Lower Verde Proportion
Forest Service	2,715,983	64%	23%	88%	90%
Private	995,703	23%	52%	8%	5%
State Trust	385,920	9%	21%	3%	1%
Tribal	91,208	2%	4%	<1%	3%
Military	26,011	1%	<1%	2%	0%
Local or State Parks	22,859	1%	<1%	<1%	2%
AZ Game and Fish	1,190	<1%	0%	<1%	0%
National Parks	1,168	<1%	0%	<1%	0%
Bureau of Land Management	401	<1%			
Other	326	<1%	<1%	<1%	0%
WATERSHED TOTAL	**4,240,770**	**100%**	**37%**	**38%**	**25%**

Table 2-2. Summary statistics of annual and winter base flow at selected gaging stations in the upper and middle Verde River watersheds, central Arizona (from Blasch et al. 2006) [mi^2, square miles; ft^3/s, cubic feet per second; acre-feet/mi^2, acre-feet per square mile; ft^3/s/mi, cubic feet per second per mile; NC, not calculated].

Streamflow gaging station (station number)	Period of record analyzed[1]	Drainage area (mi^2)	Average annual base flow (ft^3/s)	Average winter base flow (ft^3/s)	Base flow per square mile of drainage area[2] (acre-ft/mi^2)	Median winter base flow (ft^3/s)	Standard deviation of winter base flow (ft^3/s)	Average summer base flow (ft^3/s)	Summer evapotrans-piration (ft^3/s/mi)
Verde River gaging stations									
Verde River near Paulden (09503700)	1964–2003	2,507	24.4	25.1	7.3	24.9	1.9	23.3	0.23
Verde River near Clarkdale (09504000)	1966–2003	3,503	79	83.5	17.3	82.6	5.8	76.6	0.17
Verde River near Camp Verde (09506000)	1934–1945, 1989–2003	5,009	NC	214 199	28.8[3]	203	16	NC	NC
Tributary gaging stations									
Del Rio Springs (09502900)	1997–2003	NC	1.75	2.05	NC	2.1	0.2	1.5	NC
Williamson Valley Wash (09502800)	1965–1985 and 2001–2003	255	NC	3.7	10.6	2.5	2.5	0	NC
Granite Creek at Prescott (09502960)	1994–2003	30	NC	0.6	13.3	0.4	0.5	NC	NC
Granite Creek near Prescott (095033000)	1933–1947 and 1995–2003	36.3	NC	1.1	22.0	0.9	0.9	NC	NC
Oak Creek near Sedona (09504420)	1981–2003	233	31.7	36.4	113.0	35.7	4.2	28.7	0.48
Oak Creek near Cornville (09504500)	1940–2003	355	NC	41.8	82.8	NC	NC	NC	NC
Wet Beaver Creek (09505200)	1961–1982 and 1991–2003	111	7.4	8.4	54.8	7.8	1.7	7.0	0.2
West Clear Creek (09505800)	1964–2003	241	18.2	19.9	59.8	18.6	3.8	15.5	0.15

[1]Only complete years of data were analyzed.
[2]Based on winter base-flow analysis.
[3]Based on 1989-2003 record.

discharge from the C and Redwall-Muav aquifers at the Mogollon Escarpment and Coconino Plateau. The flow of the Verde River increases significantly as it passes through this portion of the watershed.

Surface land management varies between portions of the watershed, and may have significant effects on water resources (Table 2-1). The U.S. Forest Service manages a large majority of the land, but the proportion varies between sub-basins. More than half of the upper Verde River watershed, comprising the Big Chino and Little Chino sub-basins, is in private ownership, with an additional 21% managed as Arizona State Trust lands. Thus, about 73% of the upper watershed could potentially be developed for urban or suburban uses. In contrast, the middle Verde River watershed has only 11% in private or state lands, and the lower Verde sub-basin has only 6%.

Climate

The following climate summary is from Blasch et al. (2006). "The climate of the study area is primarily arid to semiarid and includes wide

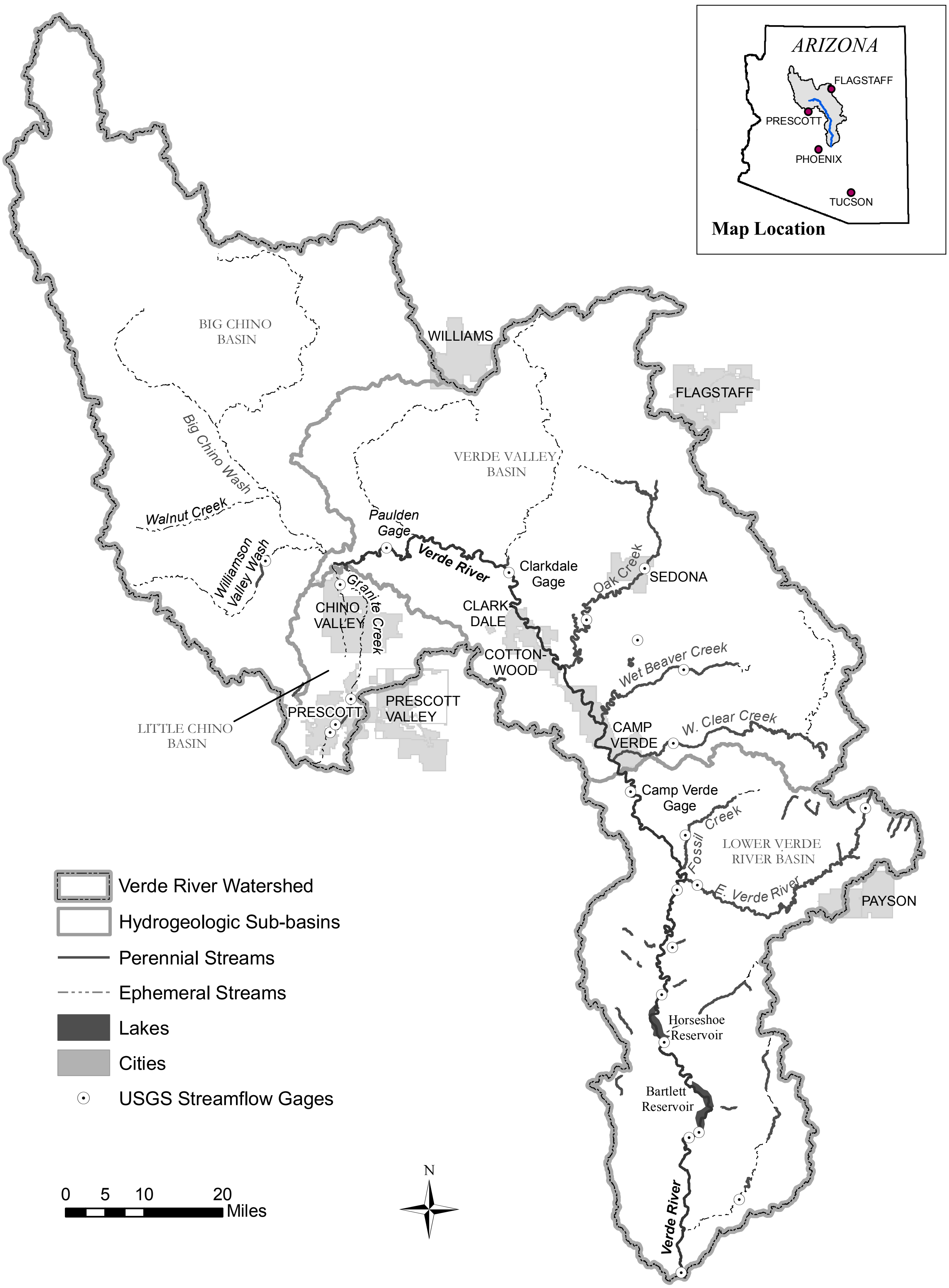

Figure 2-1. Verde River Watershed. This study focuses on the Upper Verde River (above Clarkdale gage) and the Verde Valley (Clarkdale gage to Camp Verde gage).

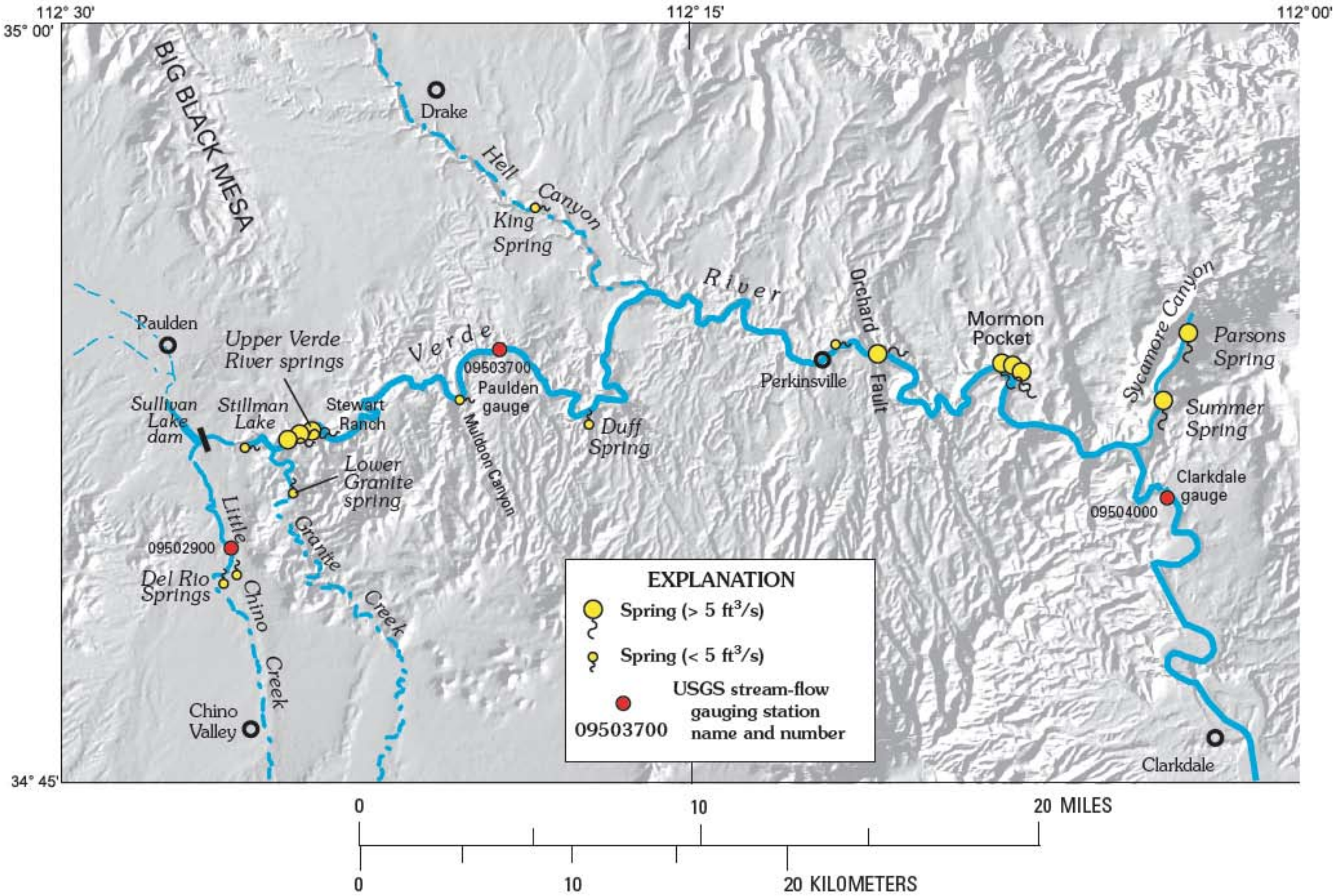

Figure 2-2. Locations of known springs along the upper Verde River from Sullivan Lake to Sycamore Creek. From Wirt et al. 2005, Figure A2.

ranges in temperature and precipitation. Climate conditions are strongly correlated with altitude; moderate summers and severe winters occur at higher altitudes, and extreme summer heat and mild winters occur at lower altitudes. Microclimates also are common in the study area, as the slope and exposure of the mountains and deep canyons control the amount of solar radiation that reaches the land surface. The study area, like much of the Southwest, is also subject to extended dry periods or droughts. Collection of hydrologic data for this study corresponded with the transition from a wet period to the onset of a drought. Average annual precipitation ranges from about 10 in. in the basins to about 40 in. in the mountains and in the higher altitudes of the Coconino Plateau. In general, precipitation is distributed bimodally, between summer monsoons and winter frontal storms. Mean annual temperatures range from about 43°F to 63°F and are inversely correlative with altitude." Blasch et al. (2006) estimated with the PRISM model that the average annual rainfall for the area is approximately 18 inches/yr.

Precipitation (and streamflow) have a long-term cyclicity based on the El Nino Southern Oscillation and Pacific Decadal Oscillations. There have been 30 to 40 year periods with precipitation generally above or below the long-term average (Figure 2-3) - rainfall was below average from approximately 1942 to 1977, high from 1977 to 1993, and low thereafter; whereas, snowfall has been below average from 1951 to the present in spite of a large snowfall at the end of 1967.

Stream Gages

Stream gages on the main stem of the Verde River are near Paulden, Clarkdale, and Camp Verde (Figure 2-1 and Table 2-2); the gages have records of 42, 46, and 27 years, respectively. Unfortunately, the short-term record at the gages does not provide information on pre-development streamflow conditions. In recent years, Salt River Project

Table 2-3. Average annual base flow in the Verde River and summary of water use in the Upper and Middle Verde Watersheds (data summarized from Blasch et al. 2006). Values given in acre feet (AF).

Average Annual Base flow at USGS gages:		
Paulden	17,681 AF	
Clarkdale	57,247 AF	
Camp Verde	150,000 AF	
Groundwater Use:	**Withdrawal**	**Consumptive Use**
Big Chino	14,526 AF	9,015 AF
Little Chino	13,412 AF	7,546 AF
Verde Valley	16,283 AF	13,492 AF
Surface Water Use:	**Withdrawal**	**Consumptive Use**
Verde Valley	33,883 AF	16,942 AF

(1999), working with others, such as the U.S. Bureau of Reclamation, has installed low-flow gaging stations on the Verde River at Campbell Ranch (Arizona Game and Fish Department property) near Paulden; at Black Bridge in Camp Verde, upstream from the confluence with Beaver Creek; and at the Verde Falls, below Beasley Flat.

Unless otherwise noted, data in this paragraph are summarized from Blasch et al. (2006). Average annual base flow (1964-2003) at the Paulden gage is 24.4 cfs (17,681 acre-feet per year [AF/yr]). Average annual base flow (1966-2003) at the Clarkdale gage is 79 cfs (57,247 AF/yr). The Camp Verde gage is downstream from Camp Verde and from all irrigation diversions in the Verde Valley. Winter (December, January, and February) base flow at the Camp Verde gage averaged 199 cfs during the period from 1989 – 2003 (144,203 AF/yr).

Median monthly flow and mean daily flow for each of the three gages are shown on Figures 2-4 and 2-5. Perennial base flow of the Verde River begins at Stillman Lake, which is located just upstream from the confluence with Granite Creek (Figure 2-1). Base flow increases at various locations where springs discharge into the Verde River (Orchard Spring, Mormon Pocket), where perennial tributaries join the river (Sycamore Creek, Oak Creek, Beaver Creek, and West Clear Creek), and a reach in the Verde Valley area (between Cottonwood and Camp Verde), where the source has yet to be defined. The magnitude of increase in base flow with distance downstream is shown on Figure 2-6. Streamflow at the Paulden and Clarkdale gages is relatively unaffected by human alteration and exhibits a mostly natural hydrograph, although some minor base flow reduction does occur due to consumptive use in the headwater aquifers and at Perkinsville. Streamflow at the Camp Verde gage, however, has been extensively altered, especially in the lower flow regimes, due to irrigation diversions throughout the Verde Valley.

Streamflow reflects both surface-water runoff and groundwater base flow sources. Although there are occasional high runoff events during the summer monsoon season, the average annual high flow is a result of winter snowmelt and typically occurs in late winter. At all three of the main stem Verde River gages, there is perennial flow supported by groundwater discharge during extended periods without runoff. The cyclicity of precipitation is also reflected in streamflow (Figure 2-7).

Modifications to the River

Human activities such as groundwater pumping, surface-water diversions, flood control, and development in the floodplain cause alterations to a river's natural flow regime. Groundwater pumping captures water that would otherwise discharge to a stream or to evapotranspiration (Filippone and Leake 2005), thus reducing the magnitude of base flow. Surface-water diversions also reduce the magnitude of base flow and increases the duration of extreme low flows. In some cases, diversion causes dewatered reaches below the diversion structure. Flood control structures and development in the floodplain may cause higher peak flows due to constriction of the floodplain and increased runoff due to increased impervious cover.

Human uses have already altered parts of the Verde River. Perennial flow in the Verde historically began at Del Rio Springs, about 5 miles upstream from the present beginning of continuous flow near the mouth of Granite Creek (Figure 2-2). Loss of that flow is attributed to agricultural diversions and groundwater pumping in the Little Chino Valley (Wirt, 2005, p. A11).

Groundwater Pumping

Groundwater pumping occurs from basin-fill aquifers underlying the Little and Big Chino Valleys and from aquifers underlying the Verde Valley. Natural groundwater discharge from these aquifers contributes to base flow in the Verde River.

There has been extensive growth in water use in the Verde River watershed since Euro-American settlement. This growth has accelerated since 1980. In 2003, estimated groundwater withdrawals were 14,526 acre-feet in the Big Chino Valley; 13,412 AF in the Little Chino Valley; and 16,283 AF in the Verde Valley; estimated surface-water withdrawal in the Verde Valley in 2003 was 33,883 (Blasch et al. 2006: Appendix 9). Water withdrawals and consumptive use are summarized in Table 2-3. Population is expected to double or triple by 2050 in most areas of the watershed (H3J Consulting 2007) with associated increase in water demand.

Wirt (2005) concluded that 80 to 86 percent of water discharging at the headwaters of the Verde River, i.e. the upper Verde Springs, comes from the Big Chino basin-fill aquifer; about 14% comes from the Little Chino basin-fill aquifer; and between 0 and 6 percent comes from the Paleozoic carbonate rocks north of the Verde River. Nelson (2002) estimated that the pre-development groundwater contribution from the Little Chino Sub-basin to the Verde River was about 7,400 acre-feet per year. Subsequently, Blasch et al. (2006) estimated the average groundwater contribution from the Little Chino Sub-basin to the Verde River during the period 1990 through 2003 to be approximately 3,780 acre-feet per year. We interpret the reduction in discharge, approximately 3,620 acre-feet per year (5 cfs), to reflect pumpage by irrigation wells, municipal wells, and small domestic wells through much of the twentieth century and currently continuing. Groundwater flow paths and groundwater-surface water relationships in the Verde Valley are just starting to be studied in any detail.

Table 2-4. Summary of diversion ditches in the Verde River Watershed by source (after Alam 1997).

Water Source	Sum discharge (cfs) at Head	Sum Ditch Length (miles)	Number of Ditches
Verde River	209	48	11
Oak Creek	60	30	20
Beaver Creek	10	10	9
West Clear Creek	5	3	2
TOTAL	283	91	42

Surface-water Diversions in the Verde Valley

Data pertaining to diversion ditches are from Alam (1997) and from analysis of a ditch GIS layer obtained from ADWR and attributed by Salt River Project with data from Alam (1997). There are 42 diversion ditches in the Verde Valley, for a total of approximately 91 ditch miles, although most of the diversion occurs on 9 of the 42 ditches. There are 11 ditches that head on the Verde River main stem, for a total of 48 ditch miles, diverting at their heads an estimated total of 209 ft^3/sec. Return flows from ditch diversion occur throughout the reach serviced by the ditch, as both surface and subsurface water. Table 2-4 summarizes, by water source (i.e. mainstem and tributary ditches), the total discharge at ditch heads, the length of ditches, and the number of ditches.

Changes in flow regime

Trends in base flow at stream gages near Paulden (Figure 2-7a) and Clarkdale (Figure 2-7b) appear to be responsive to climate conditions. Base flow at both of these gages increased from the late-1970s to the late-1990s, but began decreasing in the late-1990s through present, a time of low precipitation (Figure 2-3). Although a correlation of base flow with rainfall seems apparent, data are not sufficient to clearly distinguish between storage change and climate in interpreting changes in base flow at Paulden. However, the parallelism between the Paulden and Clarkdale base flow departures combined with the greater magnitude of Clarkdale departures strongly supports a dominantly climatic influence—especially because virtually all groundwater pumping upstream from the Clarkdale gage is also upstream from the Paulden gage. But there has also been a steady decline in water use for irrigation in the Big Chino subbasin from the 1960s through the 1990's (Yavapai County WAC 2003). Wirt and Hjalmarson (2000) suggested that the gradual increase in base flow reflected decreased pumping of groundwater in the Big Chino subbasin.

Although there are short-term fluctuations in base flow on the Verde River near Camp Verde, in general, base flow has been declining since about 1994 (Figure 2-7c). Streamflow at the gage near Camp Verde is highly influenced by diversions and pumping in the Verde Valley, especially during the growing season. To better understand the ecological implications of decreased streamflow due to ditch diversion, discharge measurements were taken on March 18 and March 20, 2007, at a location about 3 miles downstream from the Cottonwood Ditch diversion. On March 18, the Cottonwood Ditch was shut down for maintenance; on March 20, the Cottonwood Ditch was operating. Measured instantaneous streamflow was 85 cfs and 31 cfs, respectively (J. Haney, unpublished data). This represents a considerable reduction in streamflow; however, extensive conclusions cannot be drawn from one measurement at one location. Downstream diversions, return flows, and groundwater and tributary inflows attenuate the affect of diversion into the Cottonwood Ditch. Irrigation ditches in the Verde Valley likely increase the residence time of water in the valley and may provide habitat opportunities. Hydrological implications of surface-water diversions and the irrigation ditch systems in the Verde Valley are complex; hence, ecological implications are complex and additional study is needed.

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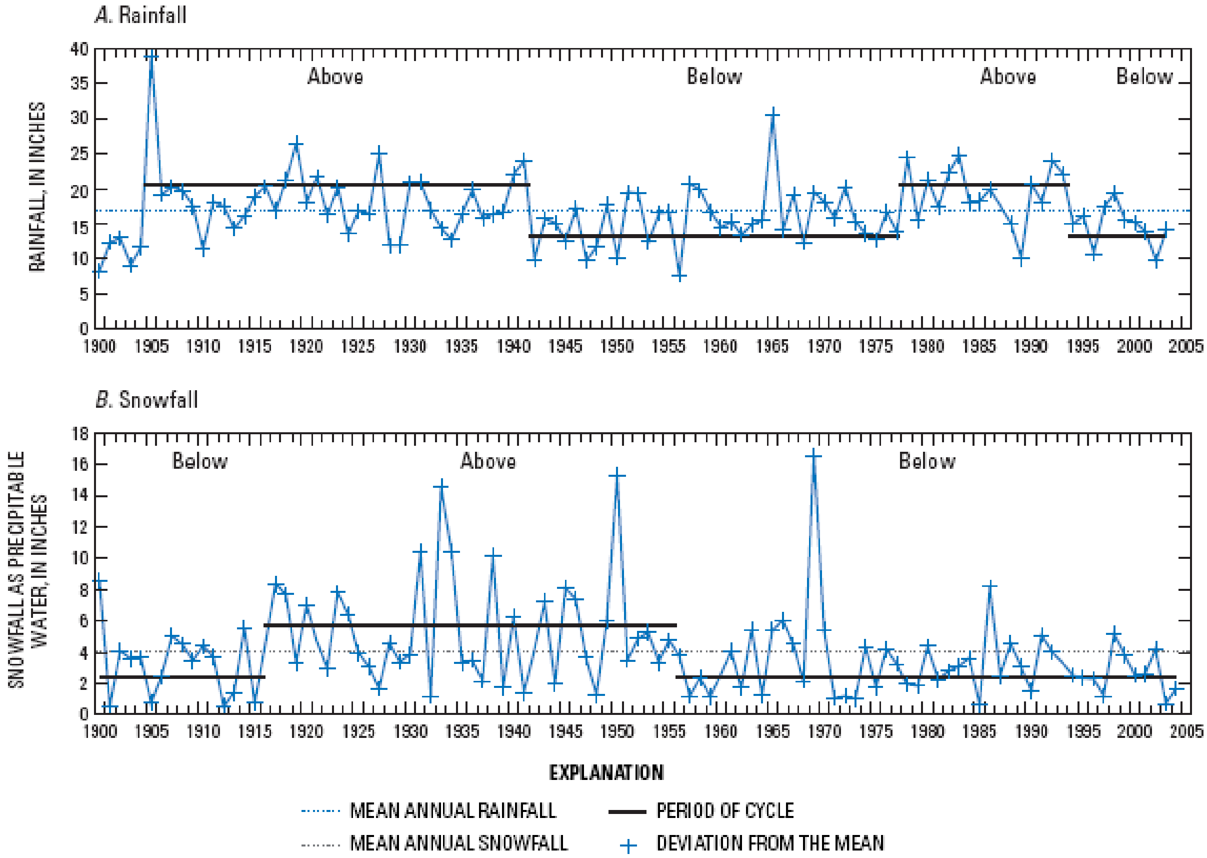


Figure 2-3. Comparison of annual deviations for rainfall at selected gages and snowfall from selected gages in the upper and middle Verde River watersheds. (Blasch et al. 2006)

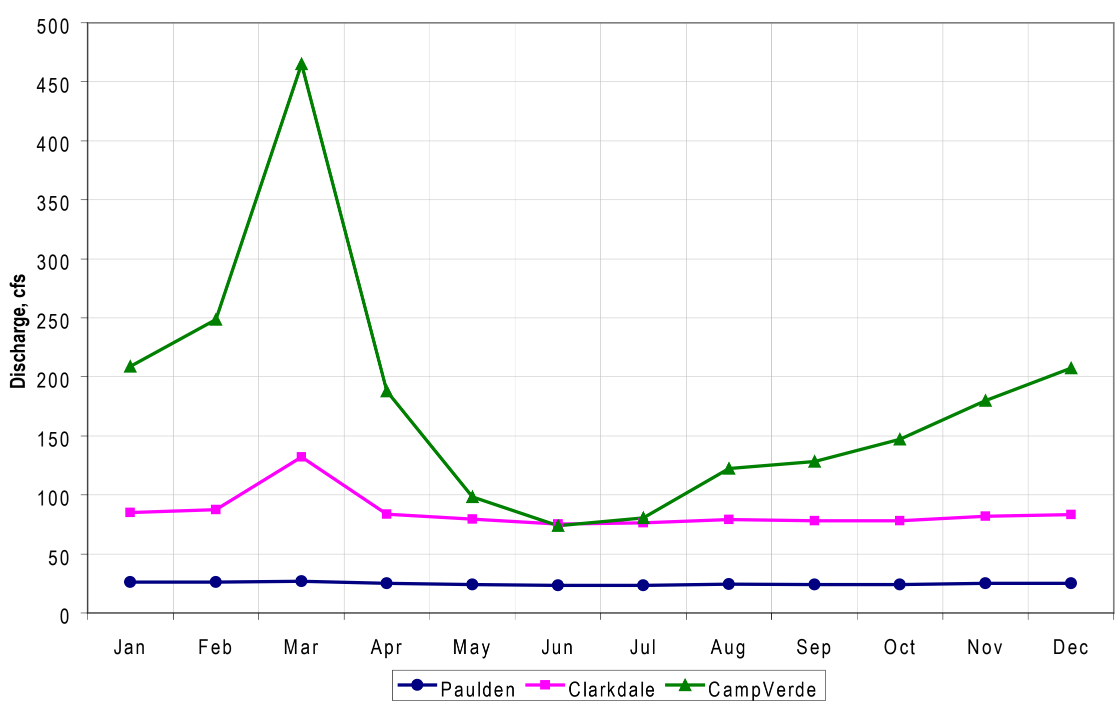


Figure 2-4. Monthly median flow at the three gages in the study area.

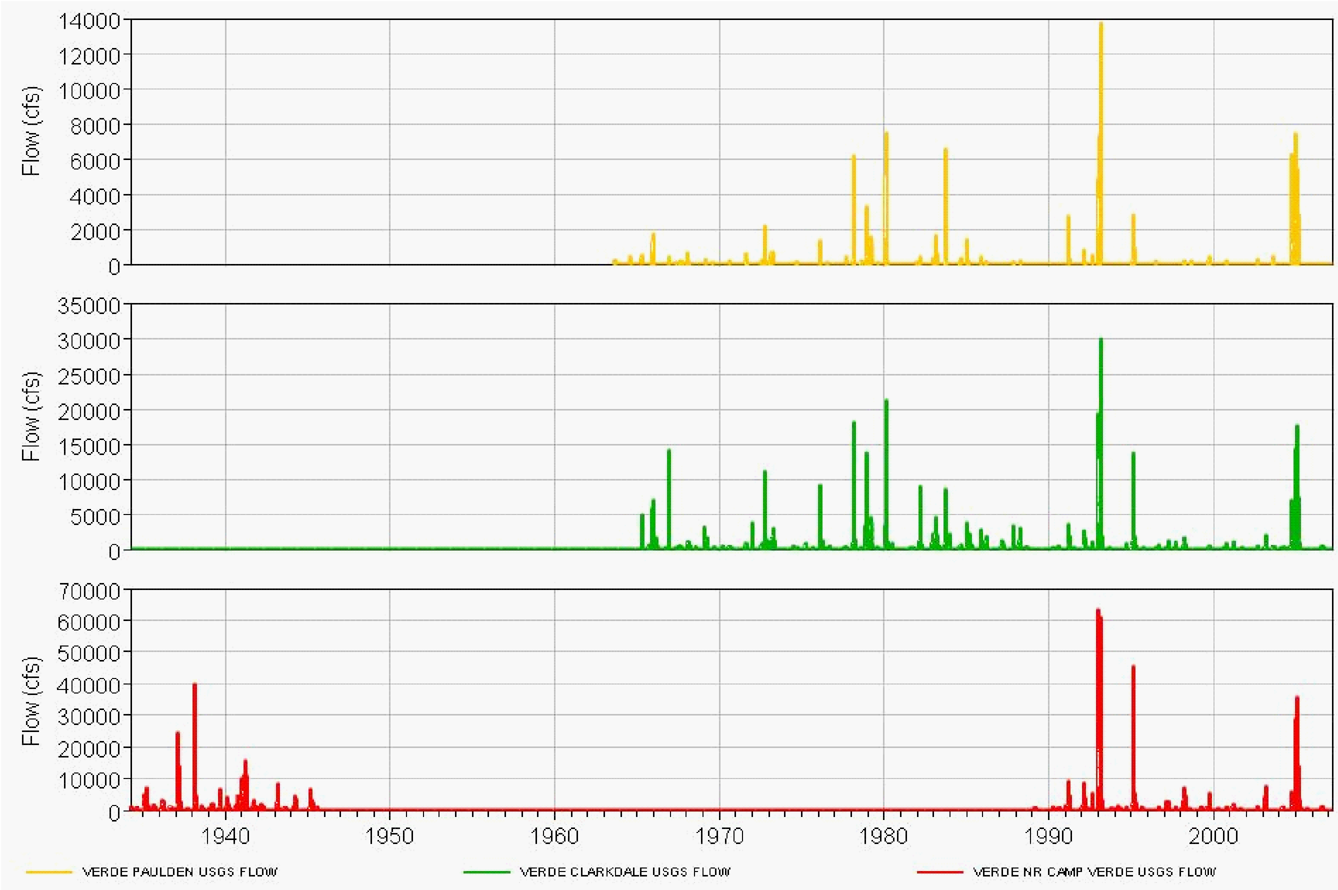


Figure 2-5. Mean daily streamflow for the Verde River near Paulden (top), Clarkdale (middle), and Camp Verde (bottom). Note the different vertical axis scales as you move downstream. (Clarkdale gage period of record also includes 6/18/15-10/31/16 and 5/22/17-7/25/21; however, those data are not displayed herein.)

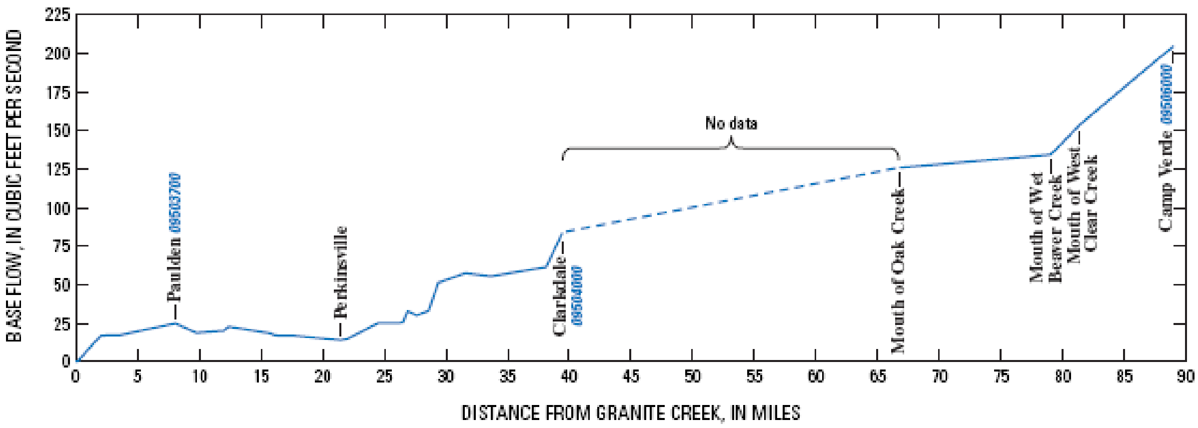


Figure 2-6. Base flow in the Verde River from the mouth of Granite Creek to the gaging station near Camp Verde (Blasch et al. 2006).

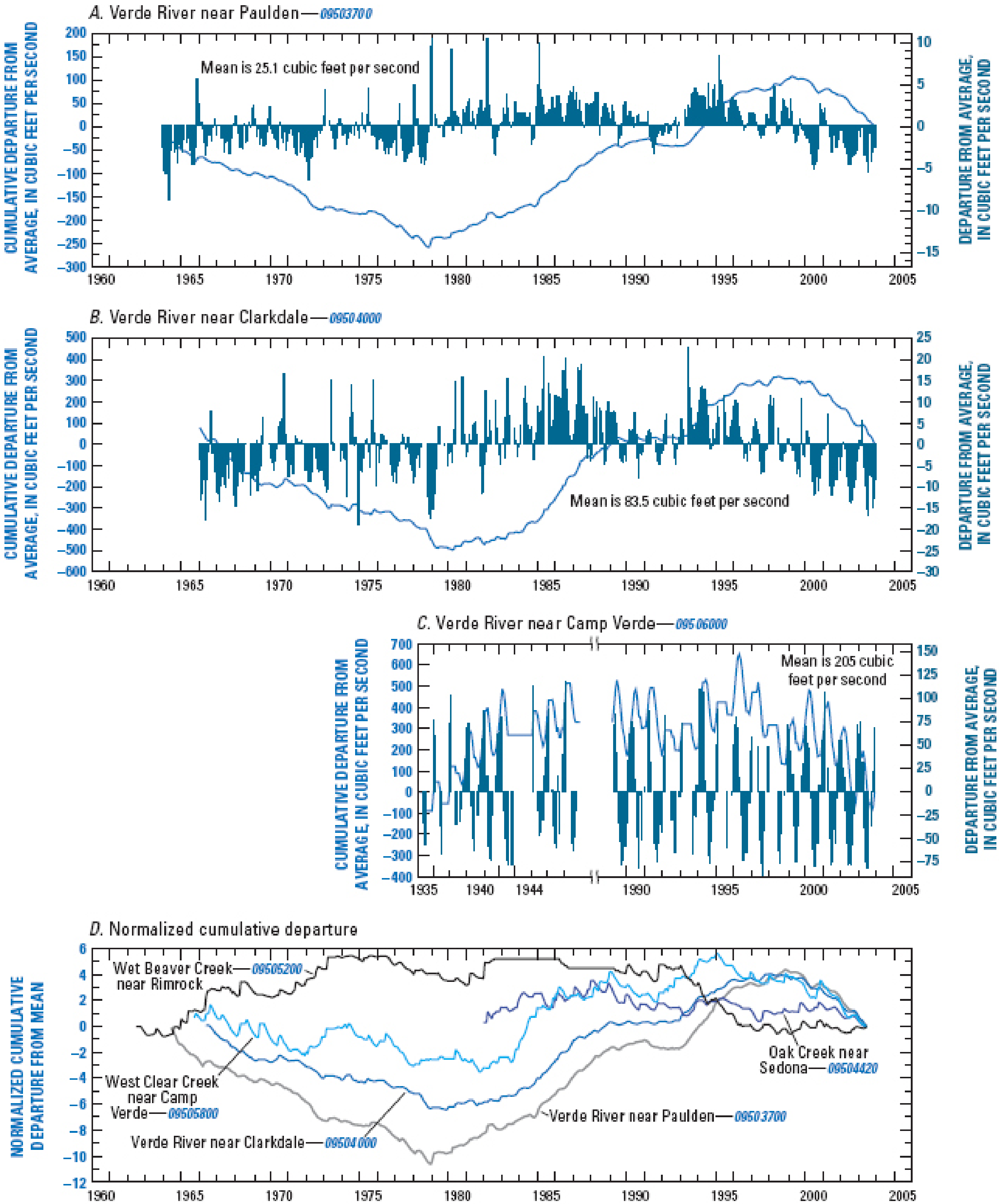


Figure 2-7. Cumulative departure from average winter base flow (reprinted from Blasch et al. 2006). A, Verde River near Paulden; B, Verde River near Clarkdale; C, Verde River near Camp Verde; D, Normalized cumulative departure for selected USGS gaging stations.

Chapter 3. Background: Fluvial Geomorphology and Flood History of the Verde River

By Philip A. Pearthree, Ph.D.

Introduction

The Verde River is a large and dynamic fluvial system that drains much of central and northern Arizona (Figure 3-1). The Verde River is special because it retains perennial flow along nearly all of its length. It is also unusual because unlike many large rivers in the West, most of the watershed is unregulated (no significant dams) and thus retains

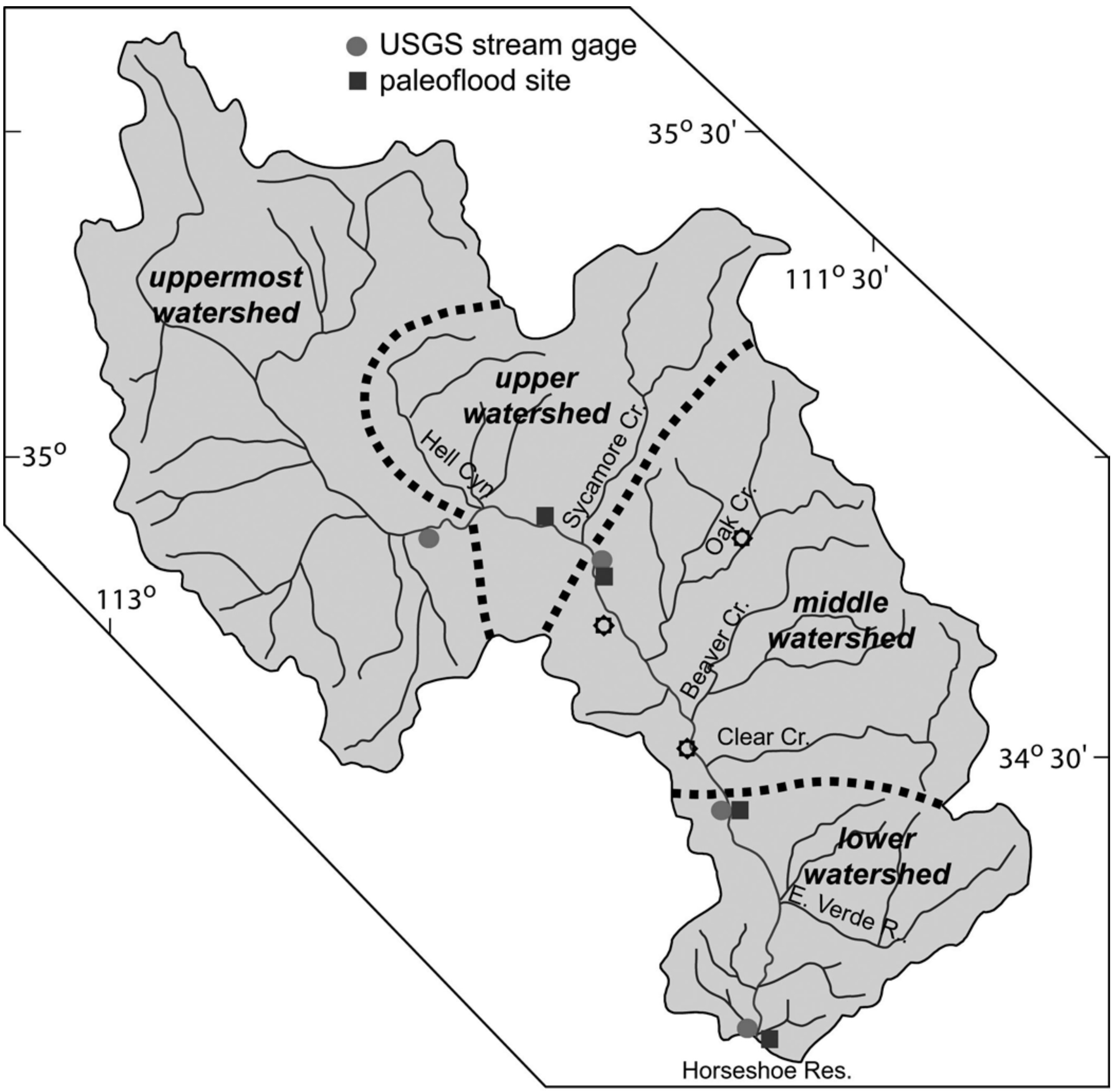


Figure 3-1. Watershed and locations of stream gages and paleoflood study sites.

a natural flood regime. Direct human impacts on the geomorphic system such as gravel mining, urban encroachment and engineered bank protection generally have been modest. The purpose of this chapter is to provide an overview of the primary geomorphic elements of the river system, summarize the flood history, and briefly explore the relationship between floods and the geomorphology of the river system.

The watershed of the Verde River includes much of the rugged transition zone between the Basin and Range and Colorado Plateau physiographic provinces in north-central Arizona. The northern portion of the watershed drains the southwestern margin of the Colorado Plateau, where gently-dipping Paleozoic sedimentary rocks about 5,500 to 7,500 ft above sea level are locally capped by volcanic mountains that rise to 10,000-12,640 ft above sea level. The rest of the watershed lies in the Central Highlands, which consist of high bedrock mountain blocks and variably dissected sedimentary basins (Richard et al. 2000). Much of the Verde watershed drains the Mogollon Rim escarpment along the margin of the Colorado Plateau, and several tributaries to the Verde River have incised deeply into the southern margin of the escarpment.

The Verde River flows through alternating narrow bedrock canyons and broader, dissected alluvial basins along much of its course. The upper reach of the Verde River consists of narrow, deep, steep-sided canyons (Figure 3-2a) incised into an old bedrock erosion surface, with a short alluvial reach near Perkinsville. In the canyon reaches, river deposits are very limited in lateral extent and consist of channel deposits, narrow, discontinuous terraces along the channel, and stacks of flood deposits in niches and tributary mouths. Young river deposits are more extensive along the alluvial reach in Verde Valley, but even in this area the river is deeply entrenched into the basin deposits that provide lateral topographic constraints on the river (Figure 3-2b). Marginal floodplain / low terrace deposits are more extensive in the alluvial reaches. In addition, there are more and better-preserved remnants of older river levels preserved as higher river terraces in alluvial reaches. Smaller tributary washes typically deposit their sediment in alluvial fans along the margin of the floodplain, and these fans alter or control the course of the river channel locally.

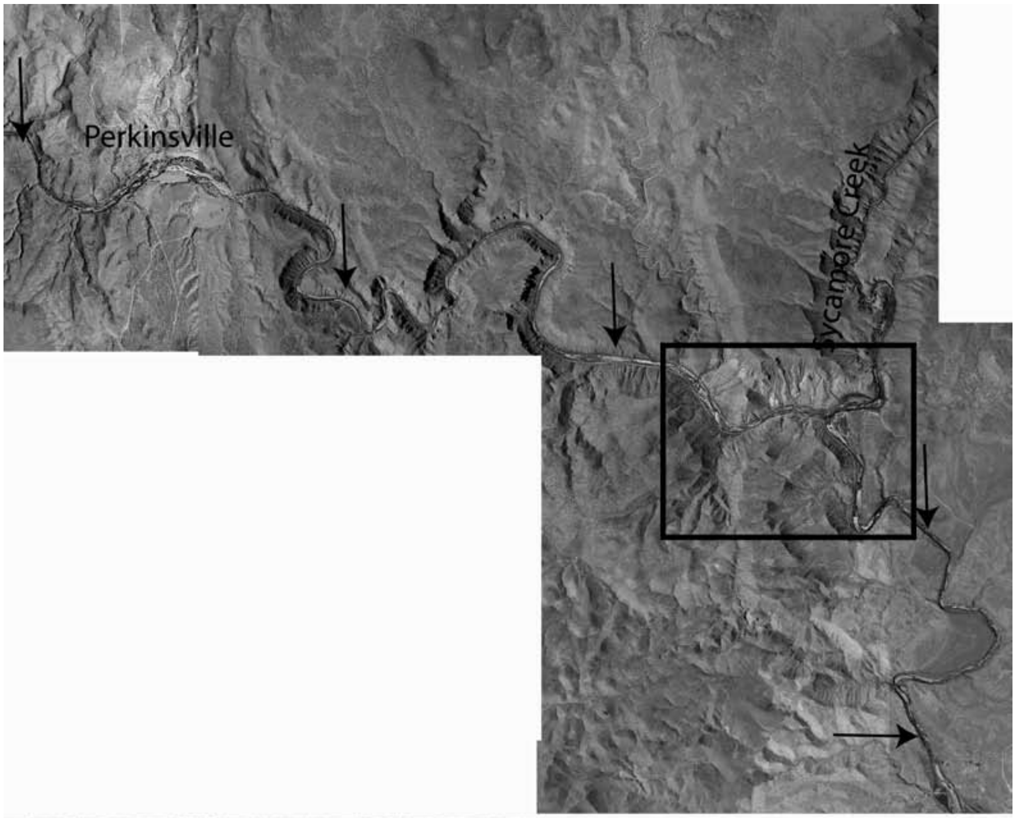
Fluvial Geomorphology

The Verde River fluvial system may be divided into 4 geomorphic components that are found to a greater or lesser degree along both alluvial and canyon reaches (Figure 3-3). The smallest but most persistent element is the low-flow channel. This low-flow channel winds through the flood channel, a much larger channel that is shaped by flood flows. The character of the flood channel is strongly dependent on the time since the last large flood, particularly in terms of the amount of vegetation growing in the channel. Slightly higher terraces that are subject to partial or total inundation during large floods bound the flood channel in many places. These flood terraces or floodplain areas typically are moderately to densely vegetated, and vegetation in these areas is not substantially affected by the occurrence of floods except in the case of lateral bank erosion. The final geomorphic component consists of bedrock, eroded basin deposits, older alluvial deposits, and young tributary deposits that form the lateral boundaries of the fluvial geomorphic system.

<u>Low-flow Channel</u>

The low-flow channel conveys the base flow of the river (excluding floods), and is formed by relatively frequent flow events. Alternating pools and riffles (rapids) are ubiquitous in low-flow channels with bed load coarser than sand (Leopold et al. 1964), and this is certainly the case along the Verde River in both canyon and bedrock reaches. Pools are relatively wide and deep, and flow velocities are quite low (Figure 3-4a). Riffles are narrower, shallower, and steeper, and flow velocities are much higher (Figure 3-4b). Bed material in pools may include some cobbles and boulders left by floods, but typically it consists of silt, sand and fine gravel. Riffles form in areas of gravel bar deposition during larger flow events (Knighton 1984), so gravel is always an important component of the bed material in riffles. Particle size in riffles typically ranges from pebbles to cobbles and in some cases small boulders.

3-2a



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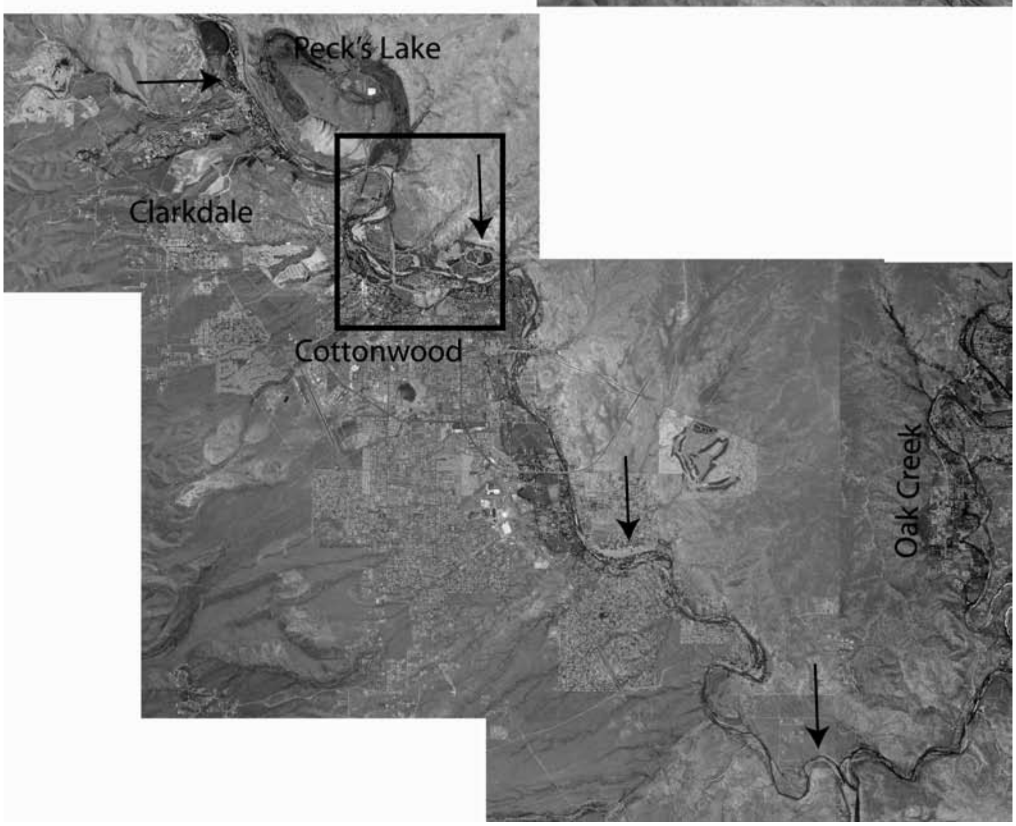

Figure 3-2. Examples of canyon (upper) and alluvial (lower) reaches of the Verde River. Arrows highlight the course of the river. The river system is quite narrow in the canyon reach, and is locally much wider in the alluvial reach. Even in alluvial reaches the river is incised into older deposits that provide lateral constraints on the river. Black boxes show the areas where examples of historical channel changes are detailed in Figures 3-9 and 3-10.

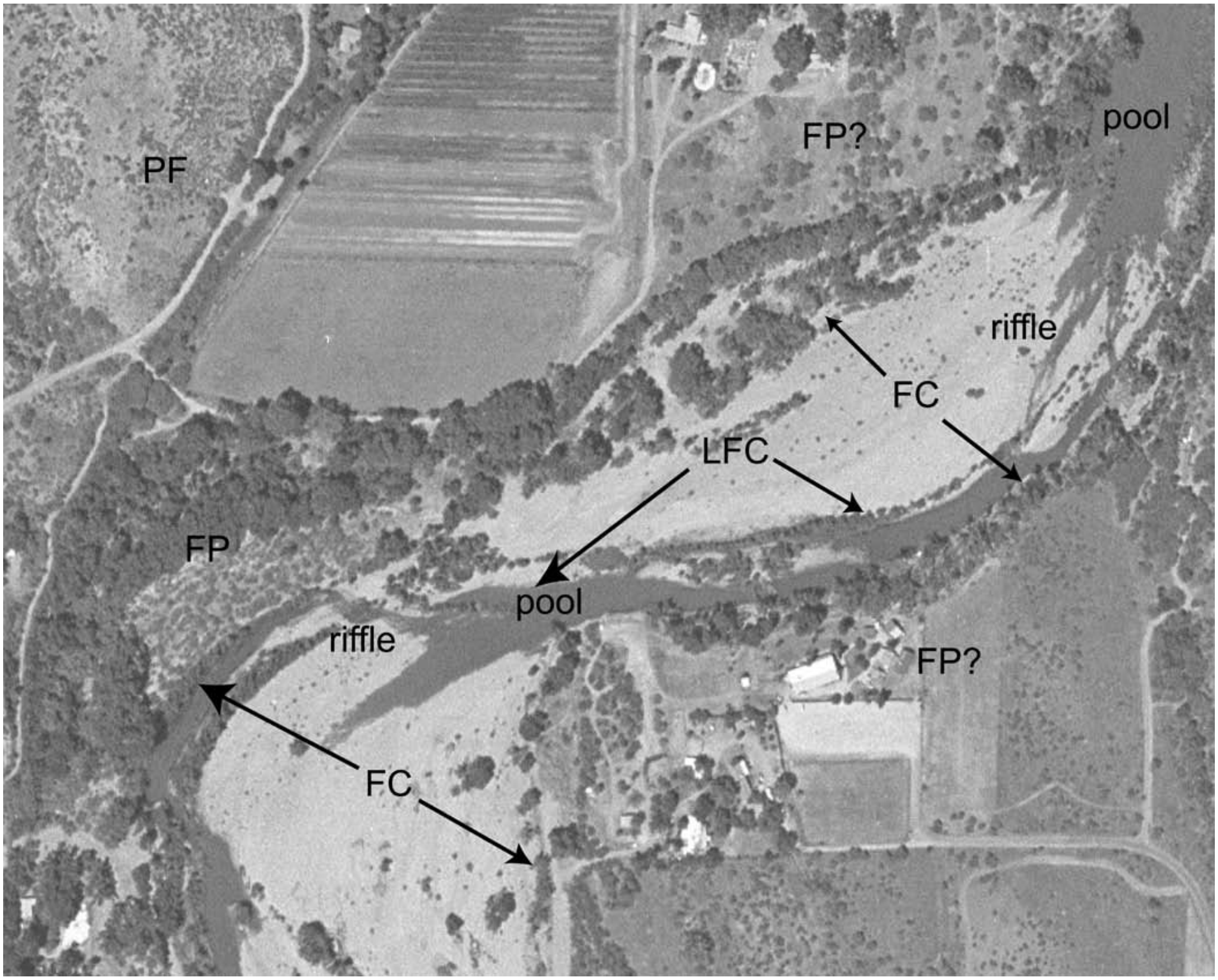

Figure 3-3. An example of riffles and pools of the low flow channel (LFC), within the much larger flood channel (FC) covered with fresh sediment and little vegetation. At relatively low flow rates, it is fairly common for the low-flow channel to split into multiple small channels in riffles. Definite (FP) and possible (FP?) areas of floodplain inundation in large floods are labeled. Eroded Pleistocene river terraces flank the river on the west. This particular reach is near Dead Horse Ranch State Park in Verde Valley, and the photo was taken in July 2005.

Gravel bar deposition along a river commonly alternates from side to side, so riffles typically alternate from one side of the flood channel to another (Figure 3-5). Changes in water-surface slope associated with riffles and pools result in a stepped water-surface profile, with flatter, less steep pool reaches and steeper riffle reaches. With increasing flow rates, the water-surface profile becomes smoother and pools and riffles become less apparent (Leopold et al. 1964).

To illustrate the general physical characteristics of the low-flow channel, minimum and maximum channel width estimates were made in riffles and pools for a canyon reach and an alluvial reach using orthophotos taken in July 2005. In the canyon reach, maximum pool widths were less than 35 m with an average of 24 m (Figure 3-6). In the alluvial reach, pool widths were less than 65 m with an average of 37 m. Minimum channel widths in riffles varied from about 5 to 15 m in both reaches, with an average width of about 10 m. Spacing between riffles is typically roughly 300 m, but there is substantial variability up to 600 m; field investigation might reveal more riffles that were not obvious on the orthophotos. The widest parts of pools typically are not far above riffles, which

3-4a

3-4b

Figure 3-4. Pools (upper) and riffles (lower) are characteristic of the low-flow channel. Pools are wider and deeper and typically have very low velocity flow. Bed material may include some cobbles and boulders, but typically is finer grained. Riffles are shallow and narrow and have higher velocity flow. Riffles generally have pebble-cobble-boulder beds. Photos are slightly downstream from the Salt River Project low flow gage at Campbell Ranch, about 5.5 miles upstream from the Paulden gage courtesy of J. Haney.

Figure 3-5. Gravel bars of alternating orientation deposited in the flood channel form the architecture of the system through which the low-flow channel flows. Low-flow riffles typically exist at the upper ends of large gravel bars, and pools typically are formed below the downstream ends of the large gravel bars. Blue arrows show several large gravel bars and their general orientation. The confluence with Oak Creek is in the upper right part of this figure.

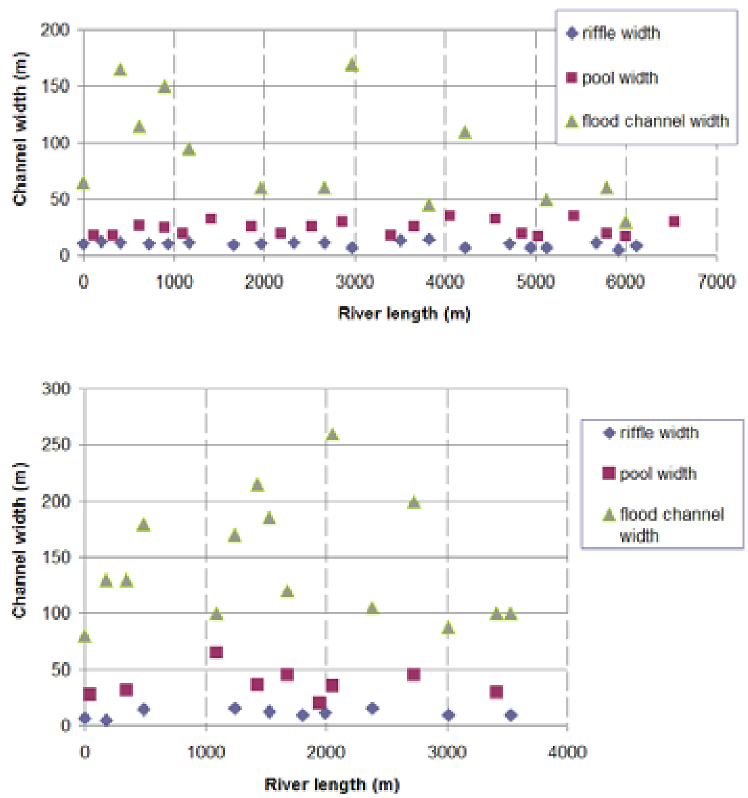

Figure 3-6. Variations in low-flow channel width (riffles and pools) and flood channel width for the Sycamore Creek confluence canyon reach (upper) and the Tuzigoot-Dead Horse Ranch State Park alluvial reach (lower). Estimated widths were measured in a GIS framework using orthophotos from July 2005.

may reflect increasingly shallow depths entering the next riffle downstream. In most riffles the low-flow channel maintained a single, narrow channel, but two or more narrow flow threads were observed in 25 percent of the riffles in the canyon reach and 50 percent of the riffles in the alluvial reach. Low-flow channel positions commonly change in floods, especially in alluvial reaches.

The extent of inundation associated with the low-flow channel is certainly discharge-dependent. The precise relationships between flow rates and the extent of inundation have not been quantitatively evaluated for the Verde River, but the following scenario is reasonable. At relatively high flow, inundation in riffles is relatively broad and may involve one or several flow paths. As flow decreases, the number of flow paths may decrease and the remaining flow paths become very narrow. Flow paths may even become discontinuous, as flow continues downstream in the interstices between gravel clasts. The lateral extent of pools will also diminish with decreasing flow, but the amount of decrease in wet area will depend on local bed geometry. The deepest pools will likely be the most resilient and diminish the least as flow decreases.

<u>Flood Channel</u>

The flood channel is the most dynamic element of the Verde River geomorphic system. For this report, the flood channel is defined as lightly vegetated areas adjacent to the low-flow channel that are bounded by more densely vegetated and somewhat higher floodplain or flood terrace areas. In classification systems that focus on low-flow channels or channel areas that are fairly frequently inundated (1- to 2-yr flows), most of the "flood channel" as described here is considered floodplain (e.g., Neary et al., 2001). Sediment in flood channels is dominantly sand, but also includes pebbles and cobbles in gravel bars, and silt and clay in swales and small channels (Figure 3-7).

Local topography typically is undulating, with gravel bars several feet higher than adjacent dry channels. Vegetation size and density varies with the time since the most recent flood, as vegetation typically is removed or substantially reduced in large floods and recovers between floods. In the same canyon reach above and below the Sycamore Creek confluence discussed above, flood channel widths estimated from 2005 orthophotos vary from 30 to 170 m, with an average width of 90 m (Figure 3-6). The widest canyon flood channel is just downstream of the Sycamore Creek confluence. Presumably, the flood channel is quite deep where it is narrow. The width of the flood channel in the alluvial reach in the Tuzigoot – Clarkdale area varies from 80 to 260 m. The widest flood channel is associated with a river bend in an area of former aggregate operations near Dead Horse Ranch State Park.

The flood channel of the river has been

subject to substantial changes in size, position and vegetation cover during floods, especially along alluvial reaches. In most of the canyon reaches of the river, the flood channel occupies almost the entire canyon bottom, with small and laterally discontinuous flood terraces perched above it. Given this situation, the potential for dramatic changes in the flood channel are rather limited in the canyons. Alluvial reaches are much different, as large historical floods have substantially increased the apparent size of the flood channel through the removal of vegetation, deposition of fresh sediment, and lateral bank erosion. In Verde Valley, human attempts to control bank erosion during floods have generally been limited and their effects on channel change and migration are not obvious.

Low Terraces

Low terraces flank the flood channel along most of the alluvial reach of the river and are also found in parts of the canyon reach. These landforms are considered part of the active fluvial system (the floodplain) if they are subject to inundation in floods – areas that are lower or closer to the flood channel are inundated more frequently. Most low terraces are densely vegetated with trees and shrubs (Fig. 3-3; Fig 3-7b); areas that are more open commonly are grass- or shrub-covered. Flood terraces are small and discontinuous in the upper canyon reach. In alluvial reaches in Verde Valley, floodplain terraces commonly are wide and extend continuously along the flood channel for long distances. Low flood terraces and floodplain areas are inundated fairly frequently, whereas higher flood terraces and marginal floodplain areas may only be inundated in the largest floods. Sand and silt deposited by floods cover most low terrace / floodplain surfaces, although gravel deposits are found locally. Cuts into these landforms commonly reveal evidence of multiple stacked flood deposits (e.g., House et al. 2002). Soils typically are dark brown and relatively rich in organic material. Most of the low terraces in the Verde Valley have been cultivated historically.

Bounding Landforms

The Verde River fluvial system is constrained topographically by a wide range of landforms. In the upper canyon reach of the river, cliffs formed in Paleozoic bedrock, consisting mostly of limestone but also including sandstone and shale and Tertiary basalt (Richard et al. 2000) bound the fluvial system. The actual physical boundaries of the active river system typically are steep slopes of colluvium or talus derived from the bedrock cliffs. In Verde Valley, the river has eroded into the fairly resistant late Tertiary Verde Formation, which provides the primary topographic constraints on the river. In addition, the river system is bounded by Pleistocene alluvial fans deposited by tributaries and older river terrace deposits (Pearthree 1993, House and Pearthree 1993, House 1994). Where the river has eroded into older rocks or deposits, the margin of the active river system usually is well-defined by a prominent change to a much steeper slope, although in canyon reaches large floods may lap onto the lower portions of bounding slopes.

The interface of the Verde River and tributary drainages is more dynamic. The active Verde River fluvial system widens downstream in the areas where large, perennial tributaries join the river, and deposits of the river and tributaries must intermingle in these areas (see Figure 3-5). Smaller, ephemeral washes typically deposit small to moderately large alluvial fans on the margins of the Verde River floodplain (House and Pearthree 1993, House 1994). These washes obviously flow infrequently, and nearly all significant sediment transport and deposition on these washes occurs during floods, when large amounts of relatively coarse sediment may be deposited on the floodplain. Floods on the Verde River may then erode these deposits and incorporate some of the tributary sediment into its bedload, depending on the location of the flood channel over time, or the tributary fan may force the river to move around the fan.

Figure 3-7. Examples of the flood channel. Flood channel deposits consist of silt through boulders, but typically sand and gravel is dominant. Adjacent, slightly higher areas that are inundated in floods (lower photo) may be considered floodplain or flood terraces. Top photo is about 2.5 miles downstream from the Paulden gage; the bottom photo is U.S. Mines site, about 10 miles downstream from the Paulden gage, courtesy of J. Haney.

Flood Hydrology and Channel Change

As is typical of large fluvial systems in the southwestern United States, the flood regime of the Verde River is highly variable, with a spectrum of peak discharges ranging up to one thousand times greater than average flow conditions. A primary consequence of this flow variability is that the important geomorphic work is done in floods. Thus, erosion and deposition during floods are the principal processes through which the Verde River has evolved over time, and the forms of the river channel and adjacent floodplains and terraces are shaped primarily by floods.

Historical Flood Record

The USGS has operated stream gages at several locations on the Verde River from the early to mid-1900's to the present (Pope et al. 1998, U.S. Geological Survey on-line data, http://waterdata.usgs.gov/az/nwis). The length and continuity of records varies substantially between gages, however, and between 1891 and 1925 only notable peaks were estimated in a few locations (Figure 3-8). The gage record for the lower Verde is continuous since 1925; records from other parts of the basin are less complete and in some cases gage locations have moved. Between the various gages and miscellaneous flood investigations, however, a reasonably complete record of Verde River flooding exists for the past 115 years.

Four continuous recording gages are located along the river. The uppermost gage on the Verde near Paulden has a contributing drainage area of about 2,000 mi^2, which is about 40% of the total basin area. Despite its large size, this portion of the basin has contributed little runoff to the peak discharges of large floods recorded at the gages downstream because flood peaks recorded at Paulden almost always follow those at the Clarkdale gage downstream by several hours. The contributing area of the Clarkdale gage is 3,200 mi^2, accounting for about 60% of the total basin area. More importantly, several fairly large tributaries draining the western Mogollon Rim join the Verde River between the Paulden and Clarkdale gages. The next gage downstream near Camp Verde has a contributing drainage area of 4,700 mi^2, which is 85% of total basin area. Three large tributaries draining the Mogollon Rim join the Verde River between the Clarkdale and Camp Verde gages: Oak Creek, Beaver Creek, and West Clear Creek. They account for about 55% of the drainage area between the Clarkdale and Camp Verde gages. The lowermost gage on the unregulated portion of the Verde River basin below Tangle Creek records runoff from a total of 5,500 mi^2.

The sizes of floods recorded at the Paulden, Clarkdale, and Camp Verde gages reflect the increasing size of the flood-producing watershed downstream through the upper canyon reach and Verde Valley. Since 1963, there have been 5 floods of greater than 10,000 cfs at the Paulden gage, derived from either Granite Creek or Big Chino Valley. At the Clarkdale gage, there have been 14 floods greater than 10,000 cfs over this same interval, and the largest floods in 1920 and 1993 were about twice as large as the largest peak at Paulden. The largest flood recorded at the Camp Verde gage sites is more than twice as large as the largest peak at Clarkdale, reflecting the substantial contributions of the major tributaries in Verde Valley. Thus, we would expect the capacity of the flood channel to increase substantially downstream as well.

The historical record is most complete for the lower Verde River, so these data are most useful for evaluating variations in flood occurrence. Since 1891, 20 floods larger than 50,000 cfs have occurred on the lower Verde River. The largest floods occurred in February, 1891, January, 1993, and February, 1993. Other large floods occurred in 1906, 1920, 1938, 1978 (2 floods), 1980, and 1995 (2 floods). As is the case with some other rivers in Arizona, large floods occurred more frequently in the late 1800's and early 1900's, and in the late 1900's, with a general absence of large floods in the mid-1900's (e.g., Webb and Betancourt 1992). On the lower Verde River, however, at least one moderately large flood greater than 50,000 cfs has occurred in each decade of the historical record.

All of the largest historical floods on the Verde River have occurred in the winter and typically

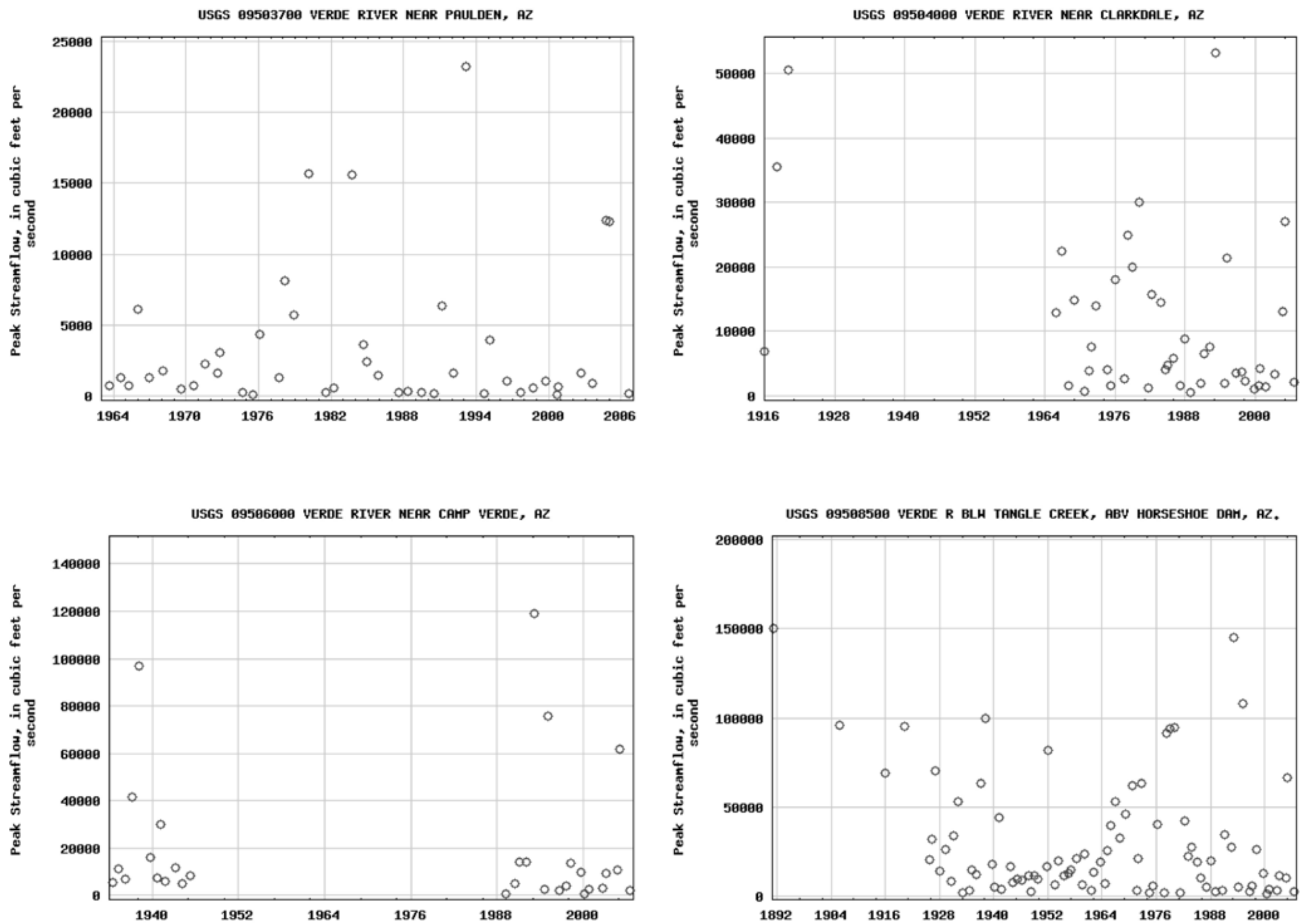

Figure 3-8. Annual peak discharges for the 4 stream gages on the Verde River above Horseshoe Reservoir. The Paulden gage records flow from Granite Creek and Big Chino Valley; the Clarkdale gage near the head of Verde Valley incorporates Sycamore Creek and several sizable tributaries; the Camp Verde gage at the lower end of Verde Valley incorporates Oak, Beaver, and Clear Creeks; the Tangle Creek gage records floods from all of the unregulated portion of the Verde watershed, including Fossil Creek and East Verde River. See Figure 2-1 for gage locations.

have resulted from successions of frontal storms that culminate in heavy rain-on-snow in the upper basin and heavy rain in lower altitude portions of the basin (House and Hirschboeck, 1997). Only one moderately large flood in the gage record (September, 1970) was generated by a dissipating warm-season tropical storm. Summer thunderstorms have not generated sizable floods on the Verde River. The incursion of multiple winter storm fronts and dissipating tropical storms into the Southwest is commonly associated with El Nino (positive ENSO) conditions (Ely et al. 1994, House and Hirschboeck 1997). Since 1950, all of the floods greater than about 50,000 cfs (13 floods) recorded at the Tangle Creek gage on the lower Verde River occurred during positive ENSO conditions or during transitional periods between positive and negative ENSO conditions (3 floods). All 6 floods greater than 90,000 cfs occurred during positive ENSO conditions, and winter flooding has not occurred during La Nina (negative ENSO) conditions. The correlation between El Nino and flooding is far from perfect, however, as no notable winter floods occurred during the strong El Nino conditions of 1972-73, 1982-83, 1986-87, and 1997-98 (ENSO index from Wolter 1987, 2005). Although the relationship between El Nino and Verde River flooding evidently is not straightforward, the likelihood of flooding is higher during periods of positive ENSO conditions (e.g., Webb and Betancourt 1992).

Paleoflood Record

Paleoflood investigations at various locations along the Verde River have greatly extended the flood record, but at a resolution level that is far coarser than the historical period. Quiet-water deposits associated with historical and prehistoric floods have been investigated in detail at 4 sites on the mainstem of the Verde River (House et al. 2002; Figure 3-1). The upper 2 sites record floods on the upper canyon reach of the river above Verde Valley. The Bear Siding site is located below the confluence of the Verde River and Hell Canyon, and thus records floods from Big Chino Valley, Granite Creek, and Hell and Bear canyons, the first sizable tributaries draining the western Mogollon Rim. The Duff Canyon site is near the Clarkdale stream gage just above the Verde Valley alluvial reach and includes input from Sycamore Creek. The Chasm Creek site is located at the stream gage near Camp Verde. It records floods derived from all of Verde Valley, including Oak, Beaver, and Clear creeks. The Horse Creek paleoflood site is located very near the Tangle Creek stream gage just above Horseshoe Reservoir. The quality and length of the paleoflood record at each site depends on local conditions, but all sites contain at least 650-year-long records of large floods.

Record length and quality through time vary from site to site, and fairly broad age-constraints on particular flood deposits complicate correlation of deposits among the sites. The historical record indicates that most large floods affect the entire watershed, so floods from generally equivalent time intervals probably correlate between sites. The Bear Siding and Duff Canyon sites in the upper canyon reach both record floods from the upper watershed, and correspond closely. The historical record demonstrates that floods can and typically do become much larger because of runoff from the middle and lower watersheds, so links between the upper basin sites and middle and lower basin sites are more tenuous.

The composite record from the upper canyon reach spans 3200 years. Deposits from 2 floods as large as or larger than any historical floods were emplaced at Duff Canyon and Bear Siding during the past 700-800 years. The highest deposit at Bear Siding and one of the two highest deposits at Duff Canyon were probably emplaced by the same large prehistoric flood, which was larger than the 1993 flood at both sites. The youngest pre-1993 deposit at the Duff Canyon site may record the 1891 flood, but more likely this unit records the 1920 flood, which was comparable to the 1993 event in magnitude in the upper basin. In this scenario, we tentatively conclude that the 1891 flood, like the Jan. 1993 flood, increased greatly in magnitude in the lower basin.

The Chasm Creek site below the southern end of Verde Valley records three floods in the past 650 years that were substantially larger than the February, 1993 flood. The youngest and highest deposit is probably less than 300 years old, and the peak water surface associated with this deposit was at least 2.5 m above the peak of the 1993 flood. Hydraulic modeling of this reach indicates that the minimum discharge corresponding to the highest deposit at Chasm Creek is 175,000 cfs, which is the largest discharge estimate we calculated for any Holocene flood deposit on the Verde River.

Channel Change

The portion of the Verde River in the Tuzigoot-Cottonwood area illustrates the sort of changes in flood channel, flood plain, and low-flow channel character that have occurred along alluvial reaches in response to the varying flood regime and human activity during the past ~70 years (Figure 3-9). This particular reach was chosen because of the ready availability of historical aerial photographs spaced between 1940 and the present, and detailed patterns of channel change are undoubtedly different on other reaches. Nonetheless, the responses of the Verde River to floods and intervening periods observed in this area provide an interesting example. A shorter sequence of aerial photographs of the Verde River in a canyon reach above and below the confluence with Sycamore Creek shows far less change (Figure 3-10). Vegetation was clearly removed from flood channel areas in the floods of

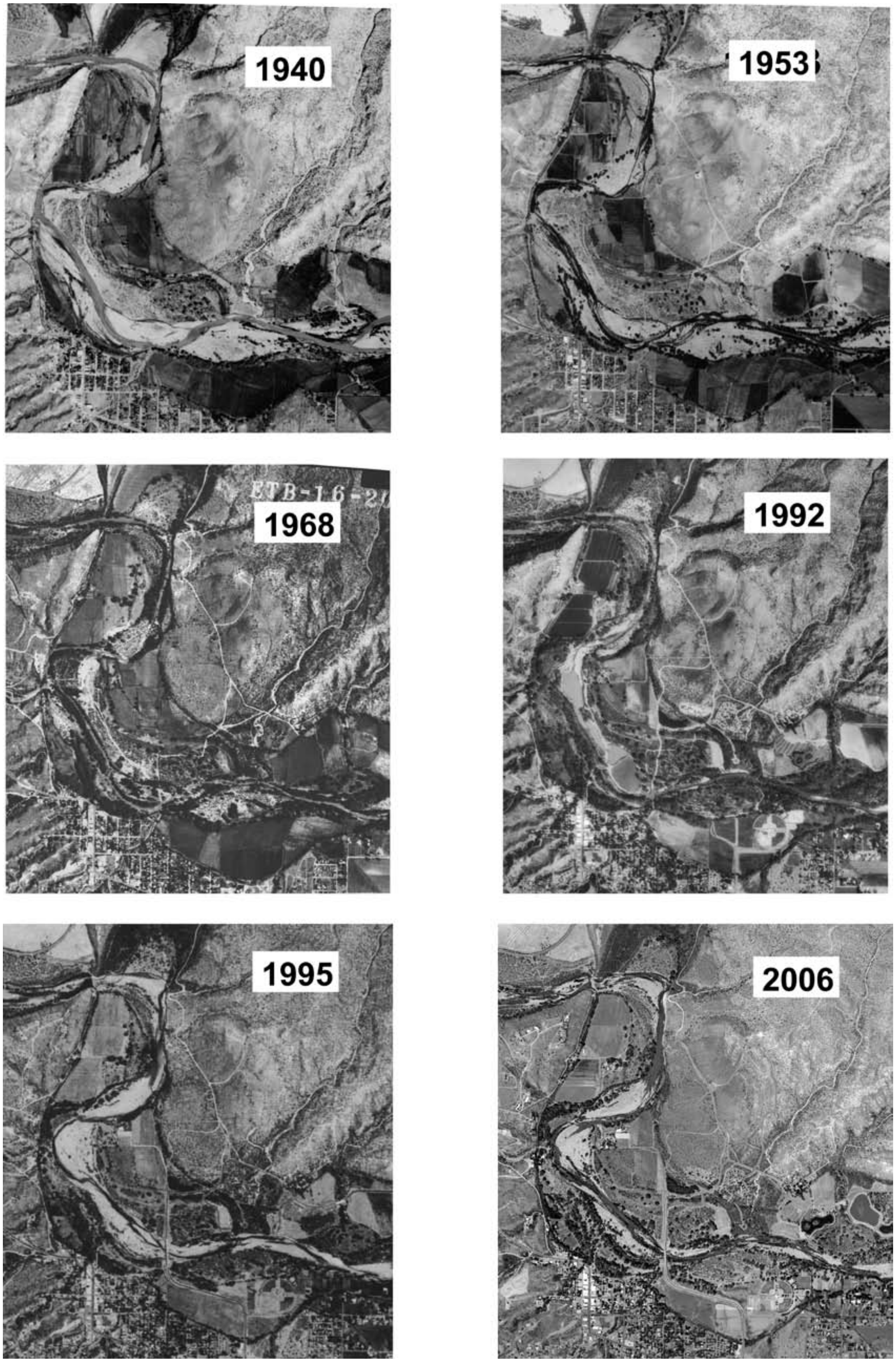

Figure 3-9. Historical channel changes on the Verde River near Cottonwood. Tuzigoot National Monument is in the upper left part of each photo, and Dead Horse Ranch State Park is in the lower center. Major changes in flood channel width and location of the low-flow channel occurred during floods along this reach.

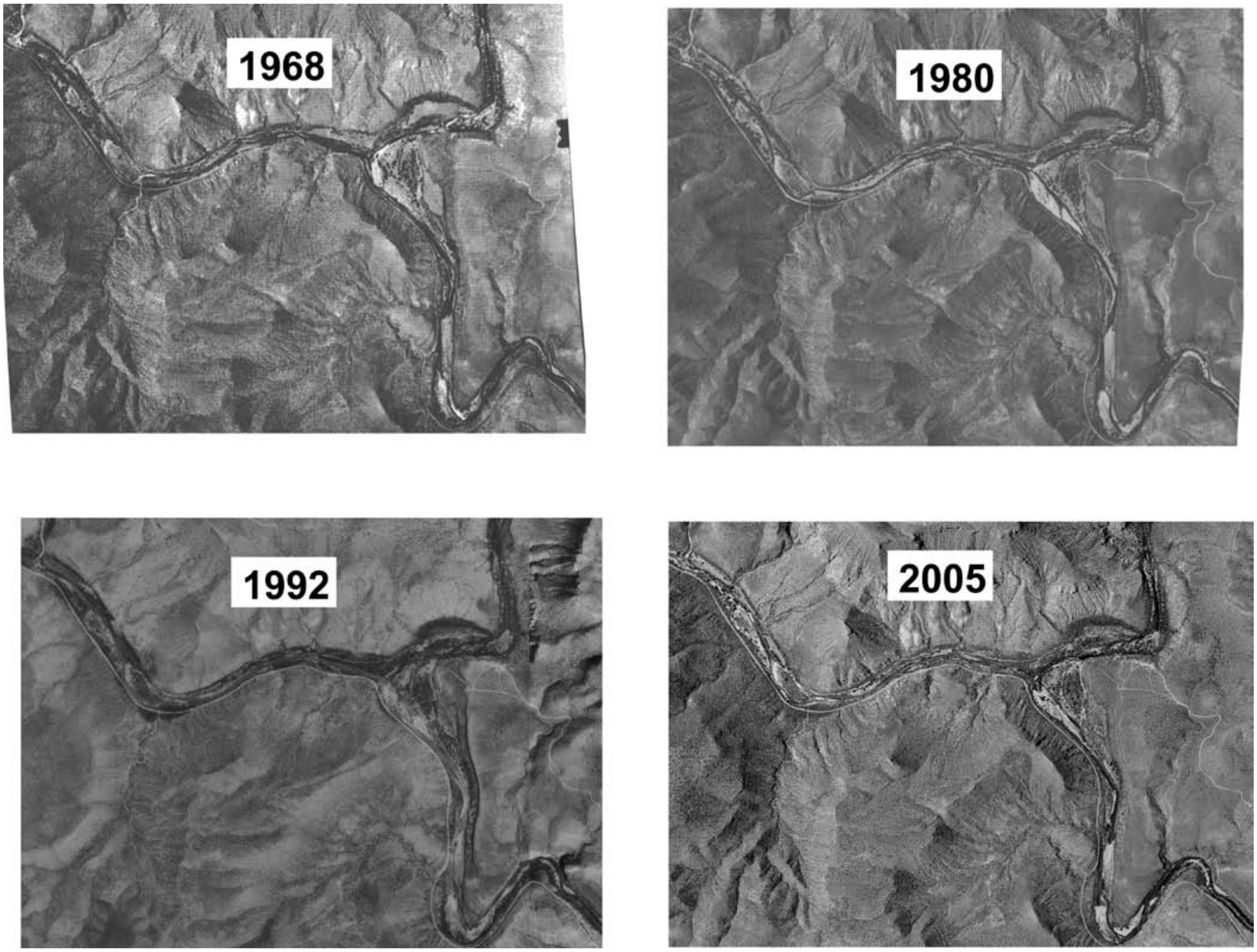

Figure 3-10. Channel changes in the canyon reach above and below the confluence with Sycamore Creek, the large tributary that joins the Verde River in the upper right part of each photograph. Changes in the size of the flood channel and the positions of the low-flow channel during floods have been relatively minor along this reach.

1978-80 and in 1993. The overall character of the flood channel changes little through this period, however, and even the position and character of the low-flow channel does not change very much after floods.

The flood record for the Verde River above Cottonwood is continuous only to the early 1960's, with several miscellaneous flood peak discharge estimates for the Clarkdale gage going back the early 1900's (Figure 3-8). The largest documented floods occurred in 1920, 20 years prior to the earliest aerial photography, and in 1993. Sizable floods also occurred in 1967, 1978-1980, 1995, and 2004-05. The following are brief descriptions of the character of the geomorphic elements of the alluvial reach of the river near Tuzigoot National Monument through the photographic record (see Figure 3-9).

1940 – Although it had apparently been 20 years since the previous large flood, the size and clarity of the flood channel in the 1940 photo (Figure 3-9a) strongly suggests that the 1938 flood, which was a large flood on the lower Verde River, was also a large flood in this reach. In 1940, a fairly large, unvegetated alluvial fan had been deposited at the southern end of Tavasci Marsh. Not including this fan, the active flood channel, defined by fresh sediment and a general absence of vegetation, generally varied from about 130 to 1000 ft wide and was typically at least 500 ft wide. The low-flow channel at the time of the photograph was sinuous, varied in width from about 40 to 120 ft, and generally consisted of a single channel but locally split into multiple threads. Obvious human alterations of the fluvial system at that time were restricted to agricultural cultivation of low terraces.

1953 – There almost certainly were no floods between 1940 and 1953, so the primary changes in this period consisted of vegetation growth in the flood channel. Most of the flood channel of 1940 was still evident, but the margins of the channel were more diffuse and uncertain in many areas. Some of the new vegetation consisted of sizable trees, but most of the growth appears to have been shrubs. The low-flow channel was in about the same location but was narrower and more complex, with several anastomosing channels in several areas. This more complex pattern may be the product of lower flow than in 1940. Human use and alteration of the river corridor was similar to 1940.

1968 – The moderately large flood of 1967 does not appear to have had much impact on this part of the Verde River. There was increased vegetation growth in flood channel areas, including the fan at Tavasci Marsh. New growth consisted of both trees and shrubs, and the result was that lightly vegetated areas of the flood channel were much reduced. The position of the low-flow channel was very similar to 1953. There is evidence of human alteration of the flood channel that may have signaled the beginning of aggregate extraction.

1984 (not shown in Figure 3-9) – Several years after the moderately large floods of 1978-80, changes were fairly modest along most of this reach. Vegetation was removed and fresh sediment deposited along relatively minor portions of the flood channel, well within the limits of the 1940 flood channel. The position of the low-flow channel changed in many places. By far the most dramatic changes were associated with aggregate extraction and the development of small artificial lakes along the reach west of Dead Horse Ranch State Park.

1992 – More than a decade after floods of 1978-80, change in the fluvial system was dominated by continued vegetation growth and apparent stabilization of former flood channel areas. Apparent flood channel area diminished throughout the reach; the unvegetated flood channel width was less than 150 ft in most areas. Low-flow channel locations were generally similar except in the area of aggregate operations. This photo records the maximum human alteration of the flood channel, with several large artificial lakes in the area of aggregate extraction.

1995 – Shortly after multiple floods, particularly the February, 1993 flood of record, there is substantial evidence of removal of vegetation and sediment deposition all along channel. The active flood channel at this time was typically 300 ft wide and was up to 850 ft wide locally. There was some freshening of the fan at Tavasci Marsh, but it was much smaller than in 1940 (a low bank was eroded into the fan along the margin of the modern flood channel). Some fairly dramatic increases in channel width occurred, especially in area of former artificial lakes, which are no longer evident on the photo. The position of the low-flow channel shifted through most of this reach.

2005 – Soon after moderately large floods in late 2004 and early 2005, the flood channel areas are quite similar to 1995. There are more or larger trees in a few areas. Changes in the position and characteristics of the low flow channel are minor.

This sequence of aerial photographs illustrates both the natural cyclicity of enlargement of flood channels in floods and revegetation of flood channel areas between floods and the local impacts of human activities on the fluvial system. Large floods apparently are the dominant mechanism shaping the fluvial geomorphology of this reach. Major increases in flood channel area and major changes in low-flow channel position occurred in the 1993 flood, and they probably had occurred in the 1938 flood. Lesser changes occurred in the floods of 1978-80. Few changes were evident after the moderately large floods of 2004-05 and 1967. Based on the aerial photographs, the modern flood channel area is relatively extensive, but the flood channel was more extensive in 1940 than at any time since. Agricultural activity on low terraces does not appear to have significantly impacted channel morphology, as farming has not involved encroachment into the flood channel and lateral bank erosion has not significantly impacted agricultural areas. Aggregate extraction from the flood channel in the 1960's through the early 1990's profoundly affected the channel locally, although most evidence of mining activity was obliterated in the floods of 1993 to the present.

Channel Assessment

The upper 30 miles of the upper Verde River (much of the canyon reach) was assessed using the classification system developed by Rosgen (1996) after the 1993 floods (Neary et al. 2001). They collected a variety of morphological data on the channel (probably the low-flow channel as described in this report, or possibly a channel slightly larger than the low-flow channel) and several terrace levels above the low-flow channel (many of which would be included in the flood channel in the terminology used in this report) in the field. They also evaluated historical aerial photographs to assess trends in channel evolution. Based on this analysis, they found that most of the low-flow channel was moderately entrenched with variable sinuosity, with common rapids or riffles. They interpreted the lack of any significant channel braiding to indicate that the river was not experiencing high sediment loading rates. Overall, the authors concluded that the river continues to be in a degradational phase, with many sections in quasi-equilibrium.

Human Impacts

Human activities have impacted the fluvial geomorphology of the Verde River in a variety of ways. The most obvious and direct effect on the system was aggregate extraction from the flood channel of the river in several places in Verde Valley. Removal of sand and gravel from the flood channel area resulted in lowering of the channel bed and the temporary development of artificial lakes, commonly in association with the low-flow channel (Figure 3-8). This activity obviously affected the position and character of the low-flow channel. Aggregate operations in the channel apparently were closed in the early 1990's, and closure was followed by the largest floods of the 20th century.

At least based on aerial photos, the effects of the mining activity near Dead Horse Ranch State Park were obliterated, although more subtle effects on the channel upstream and downstream might not be apparent on the photos. Mining has indirectly altered the river system, as the massive slag pile on the right (southwest) bank of the river at Clarkdale clearly limits the potential for lateral channel migration and some mining residue was piled at the entrance to a cut-off meander (Peck's Lake) just upstream of Tuzigoot National Monument (Figure 3-11).

Agricultural activity has been primarily restricted to low terraces. In the alluvial reach investigated for this report, agricultural fields have survived several large floods. Without detailed field investigations, it is not possible to assess if bank protection has been emplaced along these fields, and if so, how it has fared in floods.

Urban encroachment onto the Verde River floodplain has been relatively limited. There clearly are some dwellings that are subject to inundation in large floods, and other dwellings that may be at risk due to lateral bank erosion during floods.

Possible Future Impacts

Many human activities have the potential to impact the fluvial geomorphology of the Verde River, but the effects of some activities are likely to be more significant than others. The most difficult potential impact to assess is the effect of human-caused global and regional climate change on the flood regime of the river. Flow on the Verde River was obviously extremely variable prior to the current interval of global warming. All large floods have occurred as a result of exceptionally wet winter conditions, and many have involved a component of rain-on-snow. No large floods have occurred during La Nina winter conditions, so the chance of flooding is clearly greater during El Nino winters. If climate change results in less snowpack, which seems likely, then that could reduce the chances of generating large winter floods. The affect of global climate change on ENSO is less certain and may be more important for the generation of floods on the Verde River.

Urban development increases the amount of impervious surface and may increase runoff

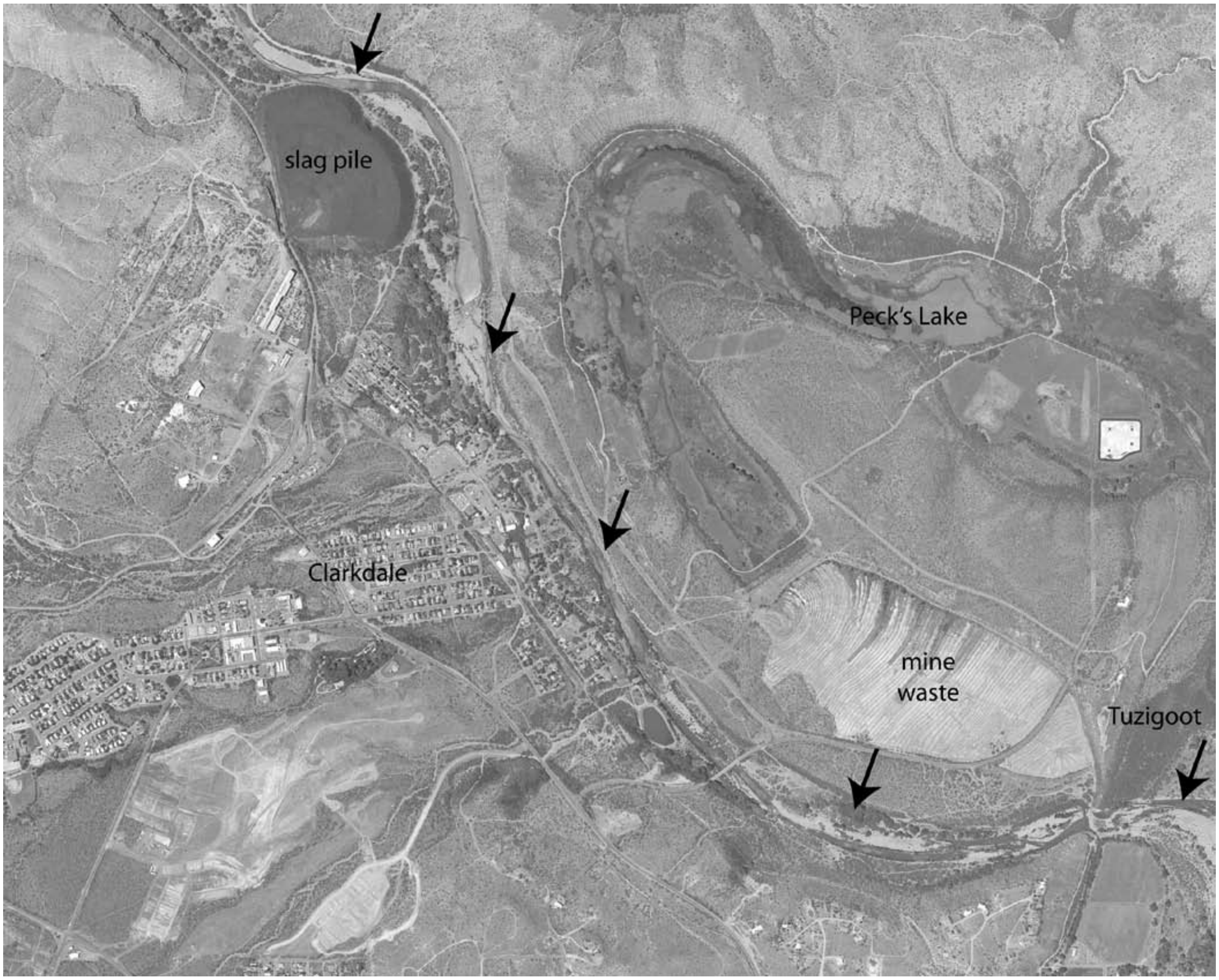

Figure 3-11. Human impacts to the river in the Clarkdale area. Arrows point to the Verde River. The slag pile and mine waste date to mining activity in the 20 century. Urban encroachment in the Clarkdale area has been limited, although some dwellings are almost certainly within the floodplain of the river.

during storm events. The percentage of the Verde River watershed that is developed is likely to remain relatively small, however. In addition, modern floodplain management regulations typically require that discharges to downstream areas not be increased by the development through the use of detention and retention structures. It is very unlikely that increased runoff due to urban development will significantly impact the Verde River.

The most likely deleterious human impact on the fluvial geomorphology of the Verde River would be further urban encroachment onto the floodplain or the flood channel. Human activities have impacted the river geomorphology in the recent past, most obviously through aggregate operations in the flood channel. Development of houses and businesses on the Verde River has generally been limited or of low density, however. Intense urban development on floodplains of major rivers in metropolitan areas of central and southern Arizona led to the perceived need for channel bank stabilization because of economic and health and safety issues. Construction of soil-cement bank protection along rivers has proven to resist erosion effectively, but because bank erosion, lateral channel migration, and in some cases overbank flooding no longer occur the fluvial systems are profoundly altered. Development of this type in Verde Valley would change the fluvial geomorphology of the river far more profoundly than any previous activity.

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Chapter 4. Background: Stream Flow Regimes and Riparian Vegetation of the Verde River

By Juliet C. Stromberg

Overview of riparian vegetation types

In the Verde River watershed, Great Basin conifer woodland is the most prevalent vegetation type, followed by Rocky Mountain Montane Conifer Forest, Sonoran Desertscrub, Plains Grassland, and Mogollon Chaparral Scrubland (Arizona NEMO, 2007). According to GAP classification, riparian vegetation comprises 0.44% of the Verde watershed and is distributed among the following four types: Mohave Emergent Marshland (present only in Upper Verde River watershed), Sonoran Interior Marshland (present only in Lower Verde Watershed), Sonoran Deciduous Swamp and Riparian Scrub, Sonoran and Oasis Riparian Forest. A mapping effort by the Arizona Game and Fish Department classifies the riparian vegetation into finer categories: they recognize 10 riparian vegetation types in the Verde Watershed, totaling about 14,000 acres (Arizona NEMO, 2007) (Table 4-1).

Verde riparian vegetation types.

The classification scheme used in this report reflects the structuring of riparian assemblages by water availability, flood disturbance, and edaphic factors (Fig. 4-1). These abiotic drivers vary laterally within the riparian zone between low-flow channels, floodplains, terraces and other landforms. They also vary longitudinally in response to the changes in elevation, climate, and geology that occur over the length of the Verde River.

The main riparian vegetation types (and plant associations) found along the Verde are listed below, in approximate order of sensitivity to stream flow decline. Names of species present in each type are based on information provided in USGS (2006a), Stromberg (1993), Beauchamp (2004), Davis and Turner (1986), SWCA (1994), and other sources.

Table 4-1. Area of riparian and wetland plant communities in the Verde Watershed, according to mapping by Arizona Game and Fish Department. Natural communities are listed in approximate order of sensitivity to stream flow decline. Data from a watershed report by Arizona NEMO (http://www.srnr.arizona.edu/nemo/). Subwatersheds here are slightly different from those elsewhere in this report, with the “Upper Verde River subwatershed” equivalent to the combined Little Chino and Verde Valley basins.

Plant community	Big Chino Wash subwatershed (acres)	Upper Verde River subwatershed (acres)	Lower Verde River subwatershed (acres)	Verde Watershed (acres)
Wet meadow	0	12	0	12
Cottonwood-willow	0	375	692	1066
Mixed Broadleaf	0	3024	1782	4806
Tamarisk	0	9	59	67
Strand	0	426	536	961
Mesquite	0	909	2323	3232
Conifer-Oak	0	129	2392	2521
Mountain Shrub	0	0	39	39
Flood scoured	0	495	410	905
Agriculture	0	47	4	51
Areas not ground verified	0	163	84	247
Total Riparian Acres	0	5587	8321	13908

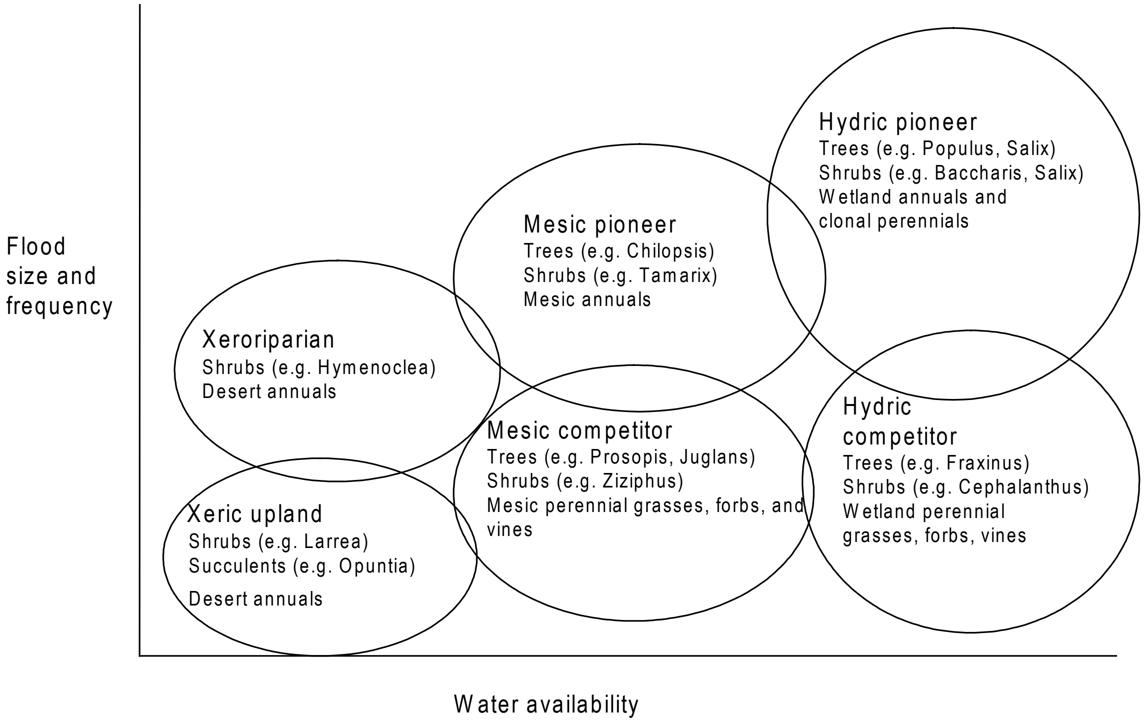

Figure 4-1. Schematic of general changes in riparian vegetation with changes in water availability and flood intensity/frequency along Southwestern desert rivers.

1. *Marshlands or wet meadows*. Marshlands occupy the wettest portions of the Verde riparian zone. They occur in areas where surface soils either are saturated year-round or have shallow standing water. Such areas include abandoned meanders or other depressions in the floodplains or terraces where the water table is very near the ground surface, areas of the floodplains or terraces receiving constant discharge of groundwater from springs or seeps, and areas upstream of beaver dams. One of the largest wetlands along the Verde River is Tavasci Marsh, which occupies an abandoned meander of the Verde River and is sustained by spring discharge and inflow from Pecks Lake. Common species in this and other wetlands along the Verde River include species of cattail *(Typha*), bulrush (*Scirpus validus)*, rush (*Juncus*) and spikerush (*Eleocharis*). This group of plants often are referred to as emergent macrophytes, and as wetland graminoids.

2. *Disturbed wetlands (channel bar wetlands)*. Wetlands also can develop in the saturated soils that border the low-flow channel of perennial streams. The composition of the wetland vegetation differs between frequently flooded channel edges and less flood-disturbed areas. Wet meadow vegetation that develops along the bars and banks of perennial stream channels typically includes a mix of annual and perennial species, and species composition fluctuates between years due to changing stream flow patterns. Disturbance-adapted wetland annuals, such as willow smartweed (*Polygonum lapathifolium*), yellow monkey flower (*Mimulus guttatus*), and cocklebur (*Xanthium strumarium*), are common after recent flooding, and can be the dominant streamside cover in high stream power reaches. Clonal wetland perennials, such as knot grass (*Paspalum distichum*), cattail, bulrush, rush and spikerush, become abundant during periods in between major flood events.

3. *Hydromesic pioneer forests and shrublands.* Riparian pioneer plants establish on surfaces that have been cleared by flooding or other types of ecosystem disturbance. Species in this group have high water needs. Surface soils must be moist during seedling establishment, but often are dry in mature stands of trees and shrubs. Root zones remain wet, however, due to presence of a shallow water table.

Willow/seep-willow shrublands. The shrubs narrowleaf willow (*Salix exigua*), seep-willow baccharis (*Baccharis salicifolia*), and arroyo willow (*Salix lasiolepis*) form thickets along the river channel in places.

Cottonwood/willow forests. One common pioneer forest association along the Verde is Fremont cottonwood (*Populus fremontii*)- Goodding willow (*Salix gooddingii*) gallery forests (Lopez and Springer, undated). Multiple age classes of these trees typically occur in the floodplain, with each age class (or cohort) typically having established after some major flood event.

Mixed broadleaf pioneer forests. Fremont cottonwood and Goodding willow often grow intermixed with other pioneer trees, notably Arizona sycamore (*Platanus wrightii*) and Arizona alder (*Alnus oblongifolia*) to form mixed broadleaf pioneer forests.

A wide variety of shrubs, grasses, forbs, and vines (e.g., milkweed vine, *Funastrum cyanchoides*) grow in the interspaces and understory of the pioneer trees. Shrubs include indigo bush (*Amorpha fruticosa*), brickellbush (*Brickellia),* and greenspot nightshade (*Solanum douglasii*). Among the perennial grasses are spike dropseed (*Sporobolus cryptandrus*), bermuda grass (*Cynodon dactylon*), vine mesquite (*Panicum obtusum*), and green bristlegrass (*Setaria viridis*). Perennial forbs include sacred thorn apple (*Datura meteloides*). Many annual species become seasonally abundant following winter rains and summer rains and floods.

4. *Riparian grasslands*. Grasslands can develop in a variety of riparian settings. One setting includes areas with fine-textured and thus poorly drained and often semi-saline soils. For example, at Tavasci marsh, the silty soils adjacent to the wetland are vegetated by riparian grasses including alkali muhly (*Muhlenbergia asperifolia*), saltgrass (*Distichlis stricta*), and alkali sacaton (*Sporobolus airoides*).

5. *Mesoxeric pioneer woodlands*. This group of riparian plants is associated with flood-disturbance, but typically grow in areas that have fairly dry surface soils and highly fluctuating water availability. They occur in areas where water tables are deep, or where water drains very rapidly through very coarse soils. These plants have lower water needs, greater drought tolerance, and often deeper roots than plants in the hydromesic pioneer group. Desert willow (*Chilopsis linearis)* is an example of such a plant.

Saltcedar shrublands. Saltcedar (*Tamarix* spp.) shrublands occupy limited area of the Verde riparian zone. They also occur as an understory shrub layer in the cottonwood forests.

6. *Successional forests and shrublands*. In contrast to the hydromesic pioneer group, plants in this group occupy areas of the riparian zone that have somewhat drier surface soils and less frequent disturbance. They are moderately drought tolerant, sometimes very deep-rooted, and fairly intolerant of flood disturbance, and tend to occupy high floodplains, terraces and hillslopes. They typically produce large seeds that are adapted for animal dispersal. In addition, plants in this group are shade-tolerant, and often establish in the understory of mature cottonwood forests.

Mesquite woodlands. The most common tree species in this group along the Verde is velvet mesquite (*Prosopis velutina*), a deep-rooted tree that often accesses water in the stream aquifer. It is most abundant along the Lower Verde. Riparian shrubs that are commonly associated with mesquite include graythorn (*Ziziphus obtusifolia*), and wolfberry (*Lycium* spp.).

Mixed broadleaf successional forests. In addition to mesquite, many other tree species can occur in the successional forests, with some of these becoming more common at the higher elevations. Common species include box-elder (*Acer negundo*), tree-of-heaven (*Ailanthus altisissima*), Arizona walnut (*Juglans major*), soapberry (*Sapindus saponaria*), net-leaf hackberry (*Celtis reticulata*), Mexican elderberry

(*Sambucus mexicana*), and Texas mulberry (*Morus microphylla*). Box-elder, tree-of-heaven, and Arizona walnut are among the trees that grow along the edge of Pecks Lake (an artificial lake that occupies an ox-bow of the Verde River) (Davis and Turner 1986).

7. *Xeroriparian shrublands.* Xeroriparian shrublands occupy flood disturbed areas with very dry soils. Examples of xeroriparian shrubs include desertbroom (*Baccharis sarothroides*) and burrobrush (*Hymenoclea monogyra*).

Riparian plant diversity and stream hydrology

Diversity levels. In arid regions, riparian zones typically support more plant species than occur in equivalent areas of upland. Diversity is high because resources (notably water) are abundant while disturbance is frequent, and because fluvial processes (e.g., flooding) create high spatial and temporal heterogeneity in the riparian zone. Several hundreds of plant species can be present in riparian corridors (Makings 2006). Plant species lists are available for limited sections of the Verde (e.g.; Tuzigoot National Monument; USGS 2006a) but a complete flora for the Verde River riparian corridor is not available.

Floods and riparian diversity. Flood-driven fluvial processes create high geodiversity, thereby creating potential for high diversity of plant species and functional types in riparian zones. Flood pulses also influence diversity by transporting water and nutrients from the uplands into the riparian zone. Diversity of herbaceous plant species in desert riparian zones typically increases substantially after moderate river flooding but can decrease in the short-term after intense scour (Stromberg 2007). Diversity increases not only in response to wetting of floodplain and channel bar soils, but also in response to short-term increases in the level of the water table. Very large runoff events, by raising water tables and stream flows for several months, can affect plant productivity and diversity over longer time periods (Bagstad et al. 2005).

O*bligate vs. facultative riparian species*. About one-third of the plant species that occur in riparian zones have high water needs and are obligately dependent on the riparian environment (Mouw and Alaback 2003; Bagstad et al. 2005). Another two-thirds of the plants that grow in riparian zones also occur in upland settings and are referred to as facultative riparian species (Mouw and Alaback 2003; Bagstad et al. 2005). Because riparian zones are highly connected to their surrounding landscapes, their diversity reflects that of the watershed they drain.

O*bligate phreatophytes, facultative phreatophytes, and non-phreatophytes*. Plants in the riparian zone can be classified by their water use patterns. Some riparian plants are obligate phreatophytes, meaning that they use groundwater (or soil water in the overlying capillary fringe) as their primary water source. Although the water table may fluctuate seasonally, it provides a permanent water source for these plants. Verde River riparian trees and shrubs in this category of obligate phreatophytes likely include Fremont cottonwood, Goodding willow, Arizona alder, arroyo willow, narrowleaf willow, and seep-willow baccharis. However, water sources are well documented for only the first two species in this list (Fig. 4-2). For most riparian species, water sources and degree of reliance on groundwater are poorly known.

Facultative phreatophytes use groundwater, but also use soil water derived from more seasonally variable sources (e.g., rainfall or flood pulses). They are more drought-tolerant than obligate phreatophytes, and in some settings can survive (albeit often with reduced growth rate) on seasonally available rain or flood water. Verde River riparian trees and shrubs in this category likely include box-elder, saltcedar, mesquite, Arizona walnut, desert willow, and probably many more. (Note that these water source categories are not 'fixed'. Some plants are facultatively phreatophytic when growing at sites with abundant rainfall or along river reaches with frequent flooding, but become obligately phreatophytic in settings where rain and flood water are less available).

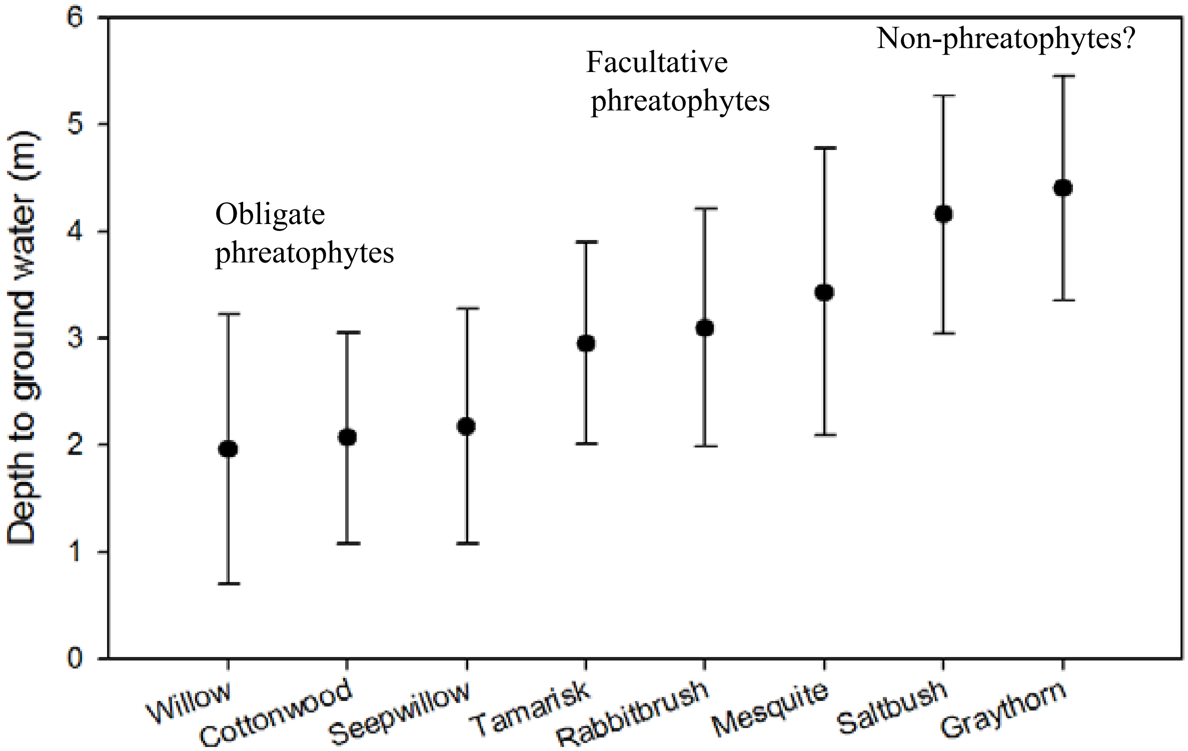

Figure 4-2. Means (plus and minus one standard deviation) for the seasonal maximum depth to groundwater at sites occupied by common tree and shrub species along the Upper San Pedro River (after Leenhouts et al. 2006). Species are *Salix gooddingii, Populus fremontii, Baccharis salicifolia, Tamarix* sp., *Ericameria nauseosa, Prosopis velutina, Atriplex canescens,* and *Ziziphus obtusifolia*.

Yet other riparian plants can complete their life cycle strictly on rain or flood water. Such plants tend to be shallow-rooted, and to possess some strategy for tolerating or avoiding seasonal drought. An example of a species in this category is the xeroriparian shrub *Hymenoclea salsola*. Desert annuals, that persist in seed form during seasonal dry period, and drought tolerant grasses, that go dormant during seasonal dry periods, also are in this category. Rainfall patterns can influence riparian zone diversity, with small-scale diversity of herbaceous plants (i.e. number of plants per small sampling areas) being greater in higher elevation (and thus less arid) reaches of desert rivers (Bagstad et al. 2005).

Rare plant species. Several rare plant species occur in the Verde watershed (Flagstaff Arboretum, 2007). Arizona bugbane (*Cimicifuga arizonica*) is a rare perennial forb that grows in Oak Creek (a tributary of the Verde) and a few other riparian canyon habitats. Several rare plants, including the endangered *Purshia subintegra*, and U.S. Forest Service sensitive species, *Salvia dorrii var. mearnsii, Eriogonum ripleyi*, and *Eriogonum ericifolium* occur in desert scrub communities of the Verde Valley. The *Salvia* occurs in association with archaeological sites. *Tetraneuris verdiensis* is a rare edaphic endemic that occurs on gypsum hills near Camp Verde. None of these rare or endemic species are known, at this time, to occur in the Verde River riparian zone.

Life histories and stream flow relationships of selected plant species of the Verde River riparian ecosystem

1. *Populus fremontii and Salix gooddingii*. Shallow groundwater is the primary water source for Fremont cottonwood and Goodding willow in most (but not all) riverine settings (Busch et al. 1992, Smith et al. 1998; Cooper et al. 1999; Leffler and Evans 1999; Synder and Williams 2000). The trees are moderately deep rooted. Cottonwood-willow forests on the San Pedro River had high density and high age class diversity where the mean depth

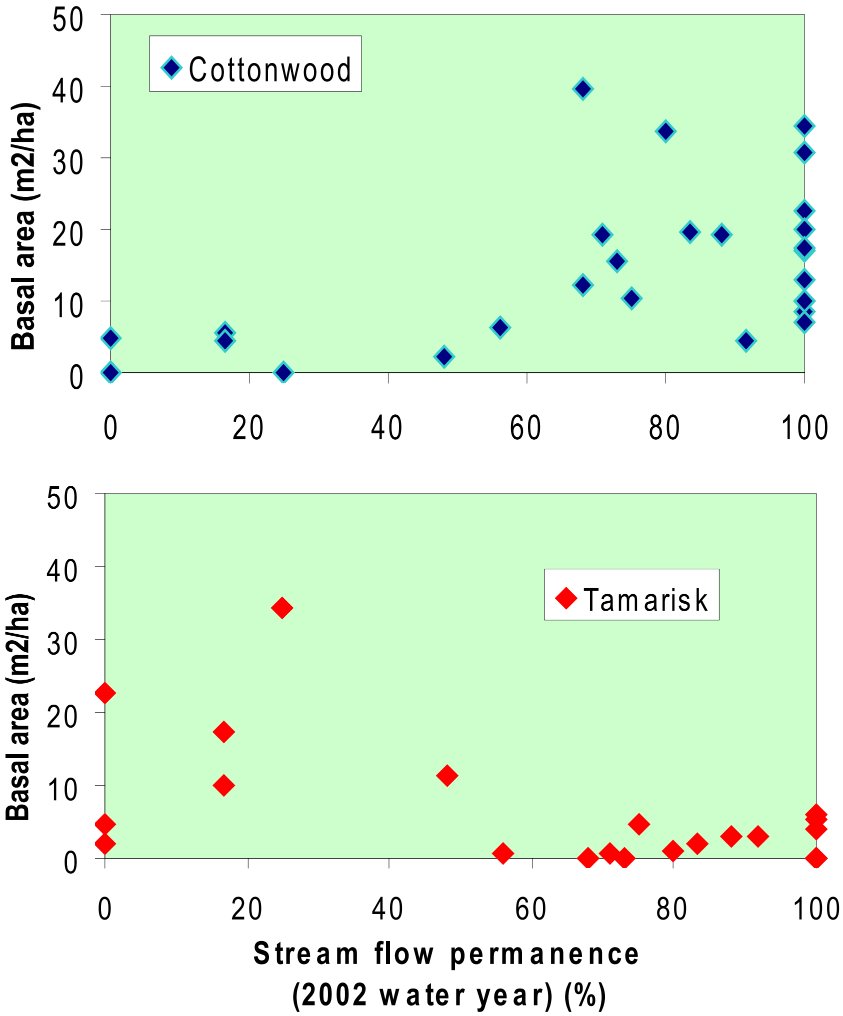

Figure 4-3. Abundance of Fremont cottonwood (top) and tamarisk (aka saltcedar) (bottom) in the floodplain of the San Pedro River as a function of the degree of stream flow intermittency at the site (after Leenhouts et al. 2006). Each data point represents a study site.

to groundwater during the summer dry season was less than 3 meters (10 feet) and where the water table did not vary seasonally or annually by more than about 1 m (Lite and Stromberg 2005). These values are consistent with those reported along other desert rivers (Anderson 1996, Stromberg et al. 1991, Shafroth et al. 1998, Shafroth et al. 2000, Horton et al. 2001a, b). Such shallow groundwater conditions are most common along perennial river reaches. As baseflow decreases and streams become increasingly intermittent, the water table under the floodplain shows increasingly more seasonal and inter-annual fluctuation. In response, cottonwood and willow decline in abundance (Lite and Stromberg 2005) and in productivity and water use (Gazal et al. 2006) (Fig. 4-3).

Cottonwood and willow are highly sensitive to drought (Pockman and Sperry 2000, Amlin and Rood 2002). Groundwater decline during the hot summer dry season can strand roots above the water level and reduce tree productivity and, in some cases, cause death. Seasonal declines of one meter have killed saplings of cottonwood and willow, with those plants acclimated to a stable water level undergoing greater mortality than those acclimated to fluctuating water levels (Shafroth et al. 2000). Mature cottonwood trees have been killed by abrupt, permanent drops in the water table of one meter, with lesser declines (0.5 m) reducing stem growth or causing stem dieback (Tyree et al. 1994, Scott et al. 1999, Scott, Lines and Auble 2000, Horton et al. 2001a,b). Rate, extent, and duration of the water table decline all influence plant growth and survivorship rates.

Seedling establishment patterns of both of these tall, broad-leaved deciduous tree species are linked with flood disturbance (Stromberg 1998; Shafroth et al. 1998). A typical pattern is for large winter floods to remove existing vegetation and deposit sediment to form areas of bare mineral soil. As flood waters recede in spring, the soil is wetted; this stimulates germination of the short-lived seeds of Fremont cottonwood and Goodding willow, which are usually dispersed in spring (e.g., typically March-April, but varying with elevation and climate; Stella et al. 2006). As the flood waters recede, the seedling roots grow downward, tracking the decline in the water table. Dry conditions are a frequent cause of seedling and sapling mortality (Adair and Binkley 2002). Seedlings during their first year typically have high survivorship if water levels decline at rates no greater than two or three cm per day (Segelquist et al. 1993, Mahoney and Rood 1998, Shafroth et al. 1998) and if groundwater declines throughout the summer to levels no lower than one or two meters below the establishment surface (depending in part on soil texture and other factors) (Kalischuk et al. 2001, Amlin and Rood 2002).

2. *Alnus oblongifolia*. Arizona alder is a deciduous broadleaf tree that appears to be highly drought sensitive. Little quantitative information is available but anecdotal evidence suggests that it may be sensitive to loss of perennial stream flow and moist soil conditions. One study of a small number of small perennial and non-perennial streams showed Arizona alder to be essentially restricted to the perennial reaches, where it typically grew in a narrow band along the edge of the low-flow channel (Stromberg 2001a; Stromberg, unpublished data). Wasklewicz (2001), in a study of perennial streams in central Arizona, found that Arizona alder occurred on geomorphic surfaces that were closer to the channel and that were wetter than were those occupied by Arizona sycamore. Another study in central Arizona showed that Arizona alder had high radial growth rate compared to most other tree species, suggesting access to and use of readily available water (Galuszka and Kolb 2002).

Regeneration patterns of Arizona alder are linked with winter/spring floods. Along Clear Creek (Arizona), Arizona alder showed a pulse of regeneration, together with ash, sycamore, cottonwood, and willow, during a period with large winter floods and high spring surface flow (Galuszka and Kolb 2002).

3. *Platanus wrightii*. Arizona sycamore is a tall, broadleaved, deciduous riparian pioneer tree. Across a range of ephemeral to perennial streams, Arizona sycamore trees grew on surfaces with water table depth ranging from about one to five meters (Stromberg 2001a). The trees had highest productivity where groundwater averaged less than two meters below the floodplain surface during the growing season. Annual radial growth rate of Arizona sycamore increases with annual (and growing season) stream flow rate on intermittent streams, a relationship that likely reflects the strong connection between stream stage and water table levels in sandbed streams (Stromberg 2001b). On perennial reaches, however, its annual radial growth rate declines under conditions of very high stream flow, perhaps because of intolerance of saturated conditions (and anoxia) in the root zone (Stromberg 2001b; Galuszka and Kolb 2002).

Similar to cottonwood and willow, seedling establishment patterns of Arizona sycamore are linked with winter flood events. Along various rivers in Arizona, successful seedling establishment occurred in years typified by large winter floods, high annual flow rate, and small to absent summer flooding (Stromberg 2002; Galuszka and Kolb 2002). Seedlings also establish in the year or two following large events that caused extensive geomorphic change. This species also reproduces asexually, but establishment of the vegetative sprouts (ramets) is less strongly associated with stream flow characteristics.

4. *Baccharis salicifolia* and Salix exigua. Seep-willow baccharis *(Baccharis salicifolia*) and emory baccharis (*Baccharis emoryi)* are tall (up to 3.5 m) evergreen shrubs in the sunflower family (Asteraceae). They often form thickets along the margins of frequently flooded intermittent to perennial streams. The degree to which seep-willow relies on groundwater is not well researched, but Williams and others (1998) found that it utilized mostly groundwater over soil water. At the Upper San Pedro River, the annual maximum depth to groundwater under seep-willow thickets was 2.1 m (Leenhouts et al. 2006). Seep-willow has most root mass limited to either unsaturated sediments or the top of the saturated zone (Gary 1963; Schade et al. 2001). Seep-willow establishes from seed following flood scour, and also can rapidly re-establish via vegetative propagation if prostrated by floods (Stromberg et al. 1993).

Narrow-leaf or coyote willow (Salix exigua) is locally common in riparian forests of lower terrace deposits and stabilized gravel bars. They are found near water, and require a bare gravel or sand substrate with adequate moisture for germination and development (USDA plant guide: http://plants.usda.gov/). This species spreads clonally by rootsprouting, and has been observed to colonize dry sandy mounds in the middle of the channel as long as a few plants are near shallow water (R. Valencia, personal communication). There is very little published information about this species and its ecological role.

5. *Typha spp.* Cattail is a tall, emergent macrophyte. The depth of standing water in a wetland, and the seasonal patterns of water level fluctuation and drawdown, are strong determinants of marsh species composition. Various studies have described the water depth conditions (means and ranges) occupied by *Typha* species in various climatic and topographic settings (e.g., Wei and Chow-Fraser 2006). Typical water depth values for this genus range from about 10 cm to about 70 cm; in a southern Arizona wetland, *Typha domingensis* occurred in areas where the standing water depth was about 10 to 40 cm (Yatskievych and Jenkins 1981). Specific relationships between plant abundance and standing water depth and fluctuation have yet to be described for emergent macrophytes along the Verde River.

Cattails reproduce from seed as well as from rhizomes. Although mature plants of emergent macrophytes grow in standing water, seedlings typically establish on moist soils during periods of water drawdown. *Typha domingensis*, however, has fairly broad tolerance range, and seedlings can establish under a range of hydrologic conditions with respect to initial standing water depth and water drawdown rate (Nicol and Ganf 2000).

6. *Tamarix ramosissima* (and related species and hybrids). Saltcedar is a riparian pioneer species that is classified as a large shrub or small tree. Although it occurs along perennial rivers, it also can thrive at sites with deep and fluctuating water tables because of a suite of morphological and physiological adaptations (Horton and Clark 2001; Glenn and Nagler 2005). Studies suggest capacity for rooting depths of 10 m or more in *T. ramosissima* and other members of its genus (Gries et al. 2003). Saltcedar is a facultative phreatophyte, using groundwater when available but also using water from unsaturated soil layers (Busch et al. 1992, Busch and Smith 1995). When growing at wet sites, its abundance can be reduced by competitive interactions with cottonwood (Sher et al. 2000; Sher and Marshall 2003). Along the San Pedro River, saltcedar increased in abundance as groundwater deepened and fluctuated more, and as stream flows became more intermittent, the reverse of the pattern shown by cottonwood and willow (Lite and Stromberg 2005) (Fig. 4-3). Whereas Fremont cottonwoods were most abundant where depth to groundwater was less than about 3 m, saltcedar remained abundant on sites where groundwater was at depths of up to 7 m.

7. *Prosopis velutina*. Velvet mesquite is a facultative phreatophyte that demonstrates high plasticity in rooting depth and growth form. It has very deep tap roots, that can tap into floodplain aquifers, and also has extensive lateral roots that take up rain and flood water from shallow soil layers. When surviving on rainfall in the Sonoran Desert, velvet mesquite grows to only 4 or 5 m tall, has a shrubby growth form, and occurs at low density (Stromberg et al. 1993, Martinez and Lopez-Portillo 2003). Where groundwater is accessible, velvet mesquite develop a tree-like growth form and reach canopy heights of 18 m. As groundwater deepens, velvet mesquite uses proportionately more water from shallow soil layers, and its height and canopy cover decrease (Stromberg et al. 1992, Scott et al. 2000, 2003). Whereas velvet mesquite is able to tap into deep groundwater, the herbaceous species in its understory tend to be shallow-rooted responders to seasonal rains or floods (Scott et al. 2003).

Velvet mesquite is not dependent on flood pulses for establishment, although floods often do provide the moisture that stimulates germination and seedling establishment (Stromberg et al. 1991). Seedlings also can establish following abundant summer rains.

8. *Acer negundo*. Box-elder is a deciduous, broadleaf tree. It grows along perennial and intermittent to ephemeral stream reaches, but has greater densities

on the perennial reaches (Medina 1990). Isotopic analysis of water sources indicates that box-elder trees use a mix of 'deep water sources' (probably groundwater) and shallow soil water (derived from rainfall) with greater use of the latter on the non-perennial streams (Kolb et al. 1997). Some studies report that box-elder is fairly sensitive to water stress (Ward et al. 2002) while others also suggest intolerance of saturated soils. For example, a study along a perennial stream in central Arizona (West Clear Creek) showed that annual growth rate of mature box-elder trees was reduced in years with very high winter or spring surface flows (Galuszka and Kolb 2002), while another study along a river in Colorado showed that prolonged inundation (>85 days) causes mortality of box-elder trees (Friedman and Auble 1999). Box-elder is dioecious, and male and female trees differ in some aspects of their physiology. Female trees, for example, are less conservative in their water use than are male trees (Ward et al. 2002).

In contrast to patterns for pioneer trees such as cottonwood and sycamore, seedling establishment of box-elder is not associated with large winter floods (Galuszka and Kolb 2002).

9. *Juglans major*. Arizona walnut is a deciduous, broadleaf tree. It occurs along ephemeral to perennial streams, often occurring at great distances from the active channel along the latter. It is fairly drought tolerant, and appears to be a facultative phreatophyte. In some ephemeral stream settings, summer precipitation is a key component of its water supply (Hultine et al. 2003). Along a perennial stream, Arizona walnut had low radial growth rate compared to other riparian trees, and its growth was more closely linked to precipitation than for most other species (Galuszka and Kolb 2002). Arizona walnut is monoecious, and trees growing in drier sites, such as hillslopes, become functionally male (Stromberg and Patten 1990a, b).

Seedlings of Arizona walnut can establish in response to seasonal rains. One study showed that seedlings survived a mid-summer dry period by shedding leaves (a drought-deciduous response) (Stromberg and Patten 1990c).

10. *Hymenoclea monogyra*. Burrobrush is a xeroriparian pioneer shrub. It propagates vegetatively, a trait that is adaptive in frequently disturbed environments, and has very small leaves, a trait that helps to confer drought tolerance. Little information is available on water relationships of this species. In addition to occurring on coarse-textured sediment deposits on aggraded floodplains of perennial rivers, it also grows along ephemeral drainages (aka washes, arroyos). A related species, *Hymenoclea salsola*, was shown to be dormant (not actively transpiring) for most of the year when growing in a desert wash setting (Smith et al. 1995).

Summary of effects of stream drying on riparian vegetation

Low-flow channel communities. As perennially-flowing desert rivers are converted to intermittently flowing rivers, major changes occur in the vegetation that borders the low-flow channel (Stromberg et al. 2005). Without year-round water, emergent macrophytes and other wetland plants decline sharply in abundance, with each species showing a characteristic pattern of decline (Fig. 4-4). With increasing stream drying, species composition shifts from wetland graminoids such as cattail, rush and spike rush that require saturated to moist soils year-round, to mesic species such as bermuda grass.
In addition to these changes in composition, the diversity of plant species growing along the channel edge also changes; species diversity decreases as the number of no-flow days during the year increases.

Prior to complete cessation of summer flows, the wetland plant communities that border the low-flow channel may decline in spatial extent. As summer low-flow rates decline, the width of the wetted perimeter that sustains wetland plants may decline and the band of wetland vegetation may shift closer to the channel. Wetland plants along the channel exist in a tension zone, with plants on high surfaces risking mortality from drought and those

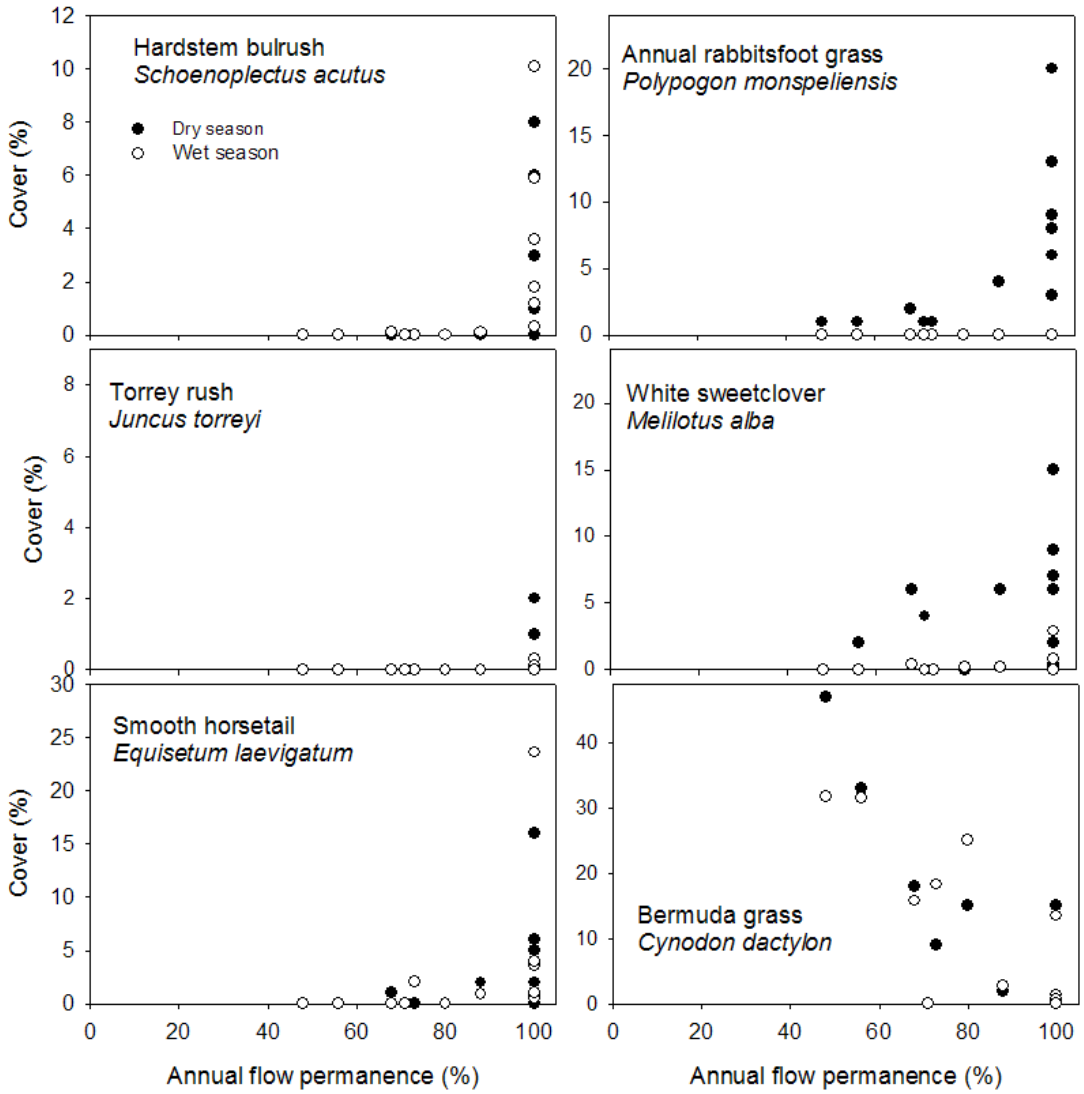

Figure 4-4. Examples of stream flow-riparian vegetation response curves, based on data from the San Pedro River (after Stromberg et al. 2005). Each data point represents a study site. Cover of each plant species in the low-flow channel zone is expressed as a function of the degree of stream flow intermittency at the site (e.g., 100% flow permanence indicates perennial, or year-round, surface flow).

on low surfaces risking mortality from flood scour. Plants that are restricted by low flows to the very low surfaces thus risk a high probability of death from subsequent flood scour or sedimentation.

The Verde River presently has perennial flow in most areas, but does seasonally go dry below major agricultural diversions. Studies are needed to document effects of loss of perennial flow on the abundance and composition of Verde River channel-side vegetation, and to document effects of reduction in summer dry-season flow rates.

Marshlands. Groundwater declines in the stream aquifer may reduce water flows to depressional wetlands or to spring-fed marshlands. Such reduced flows of water to marshlands of the Verde River would initially drive shifts in composition from emergent macrophytes associated with standing water (such as cattails) to those wetland plants associated with saturated soil (but no standing water). Greater reductions would drive shifts to more mesic riparian communities (such as perennial grasslands). Details of such a scenario would require thorough understanding of flow pathways and hydrologic linkages between surface

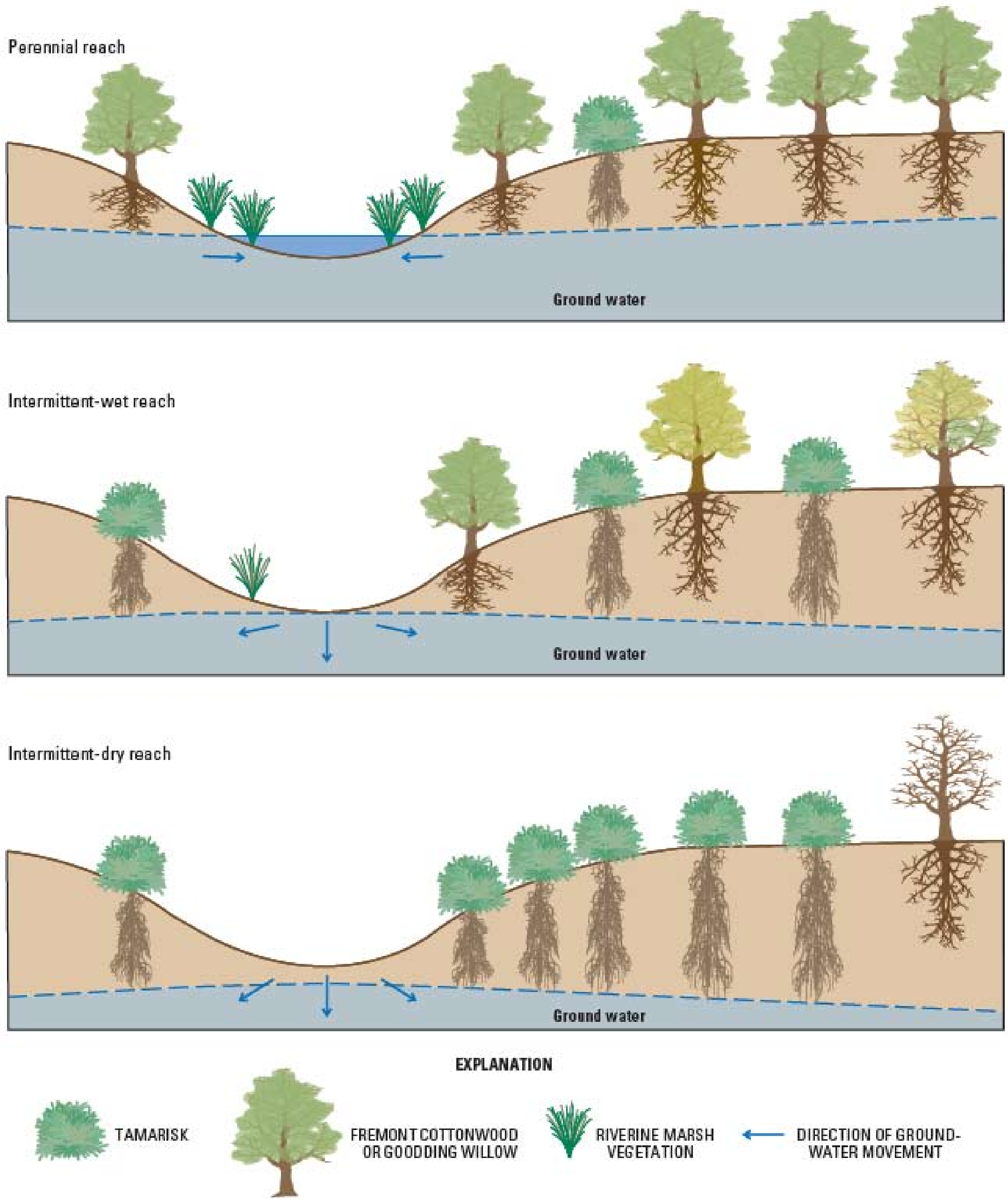

Figure 4-5. Schematic diagram of some changes in riparian vegetation of Southwestern desert rivers in response to declines in surface flow and water table level (after Leenhouts et al. 2006).

and groundwater on the Verde, and more thorough understanding of relationships between water levels and wetland plant distribution in the Verde River riparian zone.

Floodplain pioneer forests. If inflow of regional groundwater to the riparian zone declines, the water table in the stream aquifer will show increased seasonal and annual fluctuation, and the mean annual depth to saturated soils (from the floodplain and terrace surfaces) will increase. Initially, these hydrologic changes will manifest in the vegetation as reduced growth rate and branch death of drought-sensitive, shallow-rooted obligate phreatophytes (such as cottonwoods, willows, and Arizona alder) during dry seasons. If threshold values are exceeded (if water tables exceed 2 to 3 m), mortality will ensue. As the plants die, they will be replaced, after flood scour, by other pioneer plants (such as saltcedar or desert willow) that tolerate seasonal drought and can survive on seasonally high water tables (Fig. 4-5). The change in water table conditions may results in shifts from tall trees to short trees or shrublands, resulting in a decline in forest canopy and foliage height diversity.

The declines in the water table under the floodplain also may affect herbaceous vegetation, and drive shifts towards more drought tolerant species (Stromberg et al. 1996). Little is known, however, about the rooting depth and reliance on groundwater of the common riparian grasses and forbs of the Verde River riparian zone.

Terrace, high floodplain and hillslope successional communities. Many of the riparian plant species characteristic of high floodplains, terraces and hillslopes, such as mesquite, Arizona walnut, and box-elder, are facultative phreatophytes that are not as sensitive to small water level changes as are cottonwood and other obligate phreatophytes. If groundwater levels decline, productivity of these plants may decline, but survivorship should remain high.

Changes in riparian ecosystem functions with changing stream flows

Riparian ecosystems carry out many functions and services valued by people. Provision of wildlife habitat is one such function, and is discussed in Chapter 5. This section discusses a few other riparian functions, with respect to potential changes in response to base flow reductions.

Evapotranspiration. One key ecosystem process carried out by riparian vegetation is evapotranspiration, which includes transpiration of water from plants to the atmosphere and direct evaporation of water from the stream, soil and plant surfaces. The amount of evapotranspiration in a riparian ecosystem influences local climate and also influences the overall water budget. Evapotranspiration rates vary among sites as a function of local hydrology, climate, and vegetation type and density. Rates also vary between years depending on weather and hydrology.

Evapotranspiration rates are high in the densely canopied hydromesic riparian forests. But, rates can vary substantially as stream flow changes, even within vegetation types. For example, cottonwood stands along the San Pedro River evapotranspired about 970 mm per year in a perennial reach but only about 480 mm per year in an intermittent reach (Scott et al. 2006). ET rates of mesquite stands on the San Pedro varied more substantially with mesquite growth form and density than they did between hydrologic reach types. ET values for mesquite ranged from about 330 mm per year in sparse shrublands to up to 690 mm per year in denser woodlands (Scott et al. 2000, 2004, 2006).

Arizona residents value riparian corridors, and will pay more to live near a densely vegetated river (Bark-Hodgins et al. 2006). Part of the attraction for desert dwellers is the cool, shady conditions created by the phreatophytic trees that grow on the river floodplains. Along the San Pedro River, for example, the cottonwood gallery forests create a more humid environment in comparison to the adjacent desert upland (C. Soykan, unpublished data). The forests modify weather conditions through direct shading and through evapotranspiration. As water table levels change, rates of evapotranspiration also change, resulting in changes in the aesthetic appeal of the riparian forest.

Flood flow attenuation. As desert rivers become drier, vegetation changes in structure; this affects hydrogeomorphic processes including flood flow attenuation. In some cases, riparian vegetation structure shifts from forests to tall shrublands and then to sparsely vegetated short shrublands as streams are progressively dewatered; the associated changes in stem size and density lead to changes in hydrogeomorphic processes. Stands with high woody stem density have high hydraulic roughness and thus greater dissipation of energy and higher rates of sedimentation. Study is needed to assess the specific effects of stream low-flow changes on flood energy dissipation processes on the Verde River.

Bank stability and soil erosion prevention. In general, stream banks are less stable, and streams have greater width/depth ratios, in areas where streamflow is ephemeral or intermittent (vs. perennial). The reduction in cover of densely-rooted wetland plants that occurs as streams become increasingly intermittent further contributes to bank instability. Several native herbaceous plants, such as Nebraska sedge (*Carex nebrascensis*), Baltic rush (*Juncus balticus*), and deergrass (*Muhlenbergia rigens*) have been shown to grow dense root systems that are highly effective at bank stabilization. As water tables drop and substrates become dryer in the river bottom, these graminoids that are typically found along the stream banks will drop out of the plant community. If they are replaced by species such as Bermuda grass (*Cynodon dactylon*), knotgrass (*Paspalum distichus*), rabbit's-foot grass (*Polypogon monospeliensis*), smooth horsetail (*Equisetum laevigatum*), or sweet clover (*Melilotus* sp.)(see figure 4-4), the result may be changes in bank erosion and bank water holding capacity due to steepened bank and loss of soil (Cornwall et al. 1998, Steed 2001). The specific nature of this response on the Verde remains an area in need of study.

<u>Water quality and biogeochemical functions.</u> Riparian zones have been characterized as filters because they remove nutrients from urban-agricultural watersheds. As nutrients flow to the stream, microorganisms and riparian vegetation transform and assimilate these potential pollutants. Specific studies demonstrating linkages between stream flow changes, changes in riparian biota, and stream water quality on desert rivers remain an area in need of study.

<u>Riparian forest composition.</u> Transitions from cottonwood/willow communities to those dominated by saltcedar with changing depth to groundwater have been well-documented in other river systems and can result from changes in stream flow (e.g. Leenhouts et al. 2006). Less is known about the potential spread of other non-native tree species which are present along the Verde River, such as tree-of-heaven or Russian olive (*Elaeagnus angustifolia*), and how those would affect other ecosystem functions.

Information needs

1) <u>Flora</u>:

Complete flora of the Verde River riparian corridor, ideally by river reach and for specialized habitats such as mainstem spring sites.

2) <u>Water sources</u>:

Development of comprehensive list of groundwater-dependent riparian plant species (according to criteria of Eamus et al. 2006).

Quantification of water sources and rooting depth for perennial plants believed to be obligate phreatophytes (e.g. *Salix exigua, Salix lasiolepis, Alnus oblongifolia)* and for those believed to be facultative phreatophytes (e.g. *Muhlenbergia asperifolia)*

3) <u>Hydrologic thresholds for sensitive plant species</u>:

Determination of hydrologic thresholds, with respect to mean and maximum water table depth, standing water depth, or surface flow hydroperiod, for maintaining high cover of hydrologically-sensitive plant species including obligate phreatophytes and other wetland plants.

4) <u>Quantification of plant community change along hydrologic gradients</u>:

Quantification of changes in plant community attributes (cover, diversity, species composition) in relation to changes in stream/groundwater availability:

- Cover, composition, and diversity of low-flow channel vegetation vs. degree of stream intermittency (aka surface flow hydroperiod, or number and duration of no-flow days).

- Width of the zone occupied by wetland vegetation along the low-flow channel vs. dry season stream flow rate.

- Composition and abundance of wetland plant communities vs. surface water levels (to accompany hydrologic studies on relationships between stream flow rate and standing water levels in marsh habitats).

- Abundance, age structure, and productivity of floodplain forests vs. water table depth and fluctuation (to accompany hydrologic studies on relationships between stream flow rate, stream stage, and water table depth under the floodplain, by river reach).

5) Water use:

Measurement of evapotranspiration rates for main riparian vegetation types along the Verde River, in a range of hydrologic settings.

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Chapter 5. Background: Wildlife and Flow Relationships in the Verde River Watershed

By Lawrence E. Stevens, Dale S. Turner, and Vashti Supplee

INTRODUCTION

The Verde River supports an enormous diversity of Arizona's invertebrate and vertebrate species, but anthropogenic activities pose immediate and potentially irrecoverable threats to its aquifers, surface flows, habitat availability and connectivity. The introduction of non-native crayfish, fish, and other species further exacerbates those threats. In this report we assemble and review the historical information available on the invertebrates, fish and wildlife of the upper and middle reaches of the Verde River, demonstrating it to be one of the State's richest river systems. We develop habitat relationships for these species, with emphasis on obligate aquatic, wetland, and riparian taxa. We describe how the river basin's size, elevation range, geographic configuration, and geologic history support such a large proportion of Arizona's animal diversity.

METHODS – Verde River Habitats

For this assessment of ecological flows, we recognize that habitat is often used as a surrogate for species management. Although a policy of "restore the habitat and the species will return" is naïve and often does not work because it fails to account for external impacts on the target taxa (e.g., the loss of wintering habitat in Central America for migrating birds) or microhabitat fidelity and irreplaceability (e.g., cases in which habitat destruction directly equates to species loss), it is nonetheless the most important first experiment in conservation-oriented resource management. Improved understanding and management of some kinds of habitats, such as rivers, can be used to protect or enhance some target species. Therefore, one of the first steps in large-scale river basin assessment is definition of habitat types and how biota, particularly species of management concern, are distributed among them.

To develop a comprehensive habitat list, we assembled available literature and queried experts as to the array of available data on habitat type definition and faunal associations with those habitat types. Information provided by Dr. Phil Pearthree and Dr. Julie Stromberg (see chapters 3 and 4) revealed a suite of 20 discrete geomorphic and/or vegetation-based habitat types in the upper and middle Verde River drainages (Table 5-1). These habitat types are subject to various forms of natural and anthropogenic disturbance, as indicated in Table 5-1. The list of aquatic hydrogeomorphic habitat types was condensed to lentic (all) and three subcategories of low-flow lotic habitat (pools, runs, and riffles/rapids), all of which can vary by source (i.e., springs versus streams) and depth. In addition, we retained shoreline cobble or sand bars, as well as flood-formed terraces, upper floodplain terraces, barren bedrock exposures (i.e., cliff faces), and adjacent uplands habitats as habitat descriptors.

We referred to the existing literature to describe the habitats typically used by selected invertebrate groups and each vertebrate species in the Verde River basin, with most emphasis placed on the upper and middle reaches. For fish, we described habitat use variation across life stages and conducted a comparative habitat use analysis (described below). For non-fish vertebrates, we developed a 1 (low) to 3 (high) scale of species' habitat preference and evaluated each species use of each habitat type. Obligate aquatic, wetland, and riparian taxa were considered most relevant to this analysis, but we recognize the importance to facultative and some upland taxa as well. Habitat use intensity rankings were used to calculate a cumulative rank-based score for each habitat for each category of non-fish vertebrates. Such an analysis provides a summary comparative value for different habitat types to terrestrial vertebrate life.

Table 5-1: Twenty dominant habitat types of the Verde River. HG= hydrogeomorphic.

Habitats of the Upper and Middle Verde River Basins	Habitat Structuring Mechanism	Typical Disturbances
Barren riparian shorelines	HG – fluvial/non-fluvial	Flooding, drought, grazing, mining
Barren rock surfaces, incl. Cliffs	Geomorphic - non-fluvial	Flooding, drought, rockfall
Open water - lentic (all)	HG – fluvial	Flooding, drought, flow regulation
Open water – lotic	HG – fluvial	Flooding, drought, flow regulation
Lotic pools	HG – fluvial	Flooding, drought, flow regulation
Lotic runs	HG - perennial (low flow) fluvial channels	Flooding, drought, flow regulation
Lotic riffles/rapids	HG – fluvial	Flooding, drought, flow regulation
Marshes, cienegas	HG-vegetated-palustrine	Flooding, drought, grazing, flow regulation
Channelbar wetlands	HG-vegetated-riparian sand-silt bars (low stage)	Flooding, drought, grazing, flow regulation
Salix-Baccharis shrublands	HG-vegetated-riparian gravel and sand bars (low stage)	Flooding, drought, grazing, flow regulation
Salix-Populus woodland-forest	HG –vegetated floodplain riparian	Flooding, flow regulation, drought, grazing, fire
Mixed deciduous pioneer forest	HG –vegetated floodplain riparian	Flooding, flow regulation, drought, grazing, fire
Xeric grasslands	Vegetated - uplands (native and exotic)	Drought, grazing, fire, development
Riparian grasslands	HG -vegetated floodplain riparian (native and exotic)	Flooding, drought, grazing, fire
Mesoxeric pioneer woodlands	Vegetated with strong upland influ-ences	Drought, grazing, fire
Prosopis woodlands	HG -vegetated floodplain riparian and uplands	Flooding, drought, grazing, fire
Mixed deciduous (riparian) forest	HG –vegetated floodplain riparian	Flooding, drought, grazing, fire
Xeroriparian	HG –vegetated floodplain riparian	Flooding, drought, grazing, fire
Upland xeric vegetation	Vegetated	Drought, grazing, fire
Developed land	Anthropogenic	Ecological dysfunction from exten-sive disturbance
Pine-oak woodlands	Vegetated	Drought, grazing, fire, woodcutting
Mixed coniferous forest	Vegetated	Drought, grazing, fire, lumbering, development
Conifer-forest meadows	Vegetated	Drought, grazing, fire, development

INVERTEBRATES

Overview

The aquatic, wetland, and riparian invertebrate diversity of the Verde River is substantial but generally poorly known. Recent progress in aquatic invertebrate biogeography for selected taxa supports the above hypotheses regarding the river's role in regional diversity and its flow-related ecology. Here we briefly describe the diversity of Odonata and the aquatic and semi-aquatic Hemiptera in the Verde River drainage. These taxa are obligatorily restricted to aquatic, wetland, or riparian habitats for most or all of their life cycles, and therefore may provide general insight into how flow management can affect Verde River aquatic macroinvertebrates. In addition, we discuss several non-native invertebrate taxa that presently or likely will soon further threaten the ecological integrity of the Verde River ecosystem. We are not aware of substantial investigations of hyporheic (region beneath and beside a stream bed, where there is mixing of shallow groundwater and surface water) habitats in the Verde River basin, but such habitats can support numerous other, including undescribed, invertebrate species.

Odonata

The Odonata (dragonflies and damselflies) of the Verde River are primarily known from Bailowitz et al. (2007) and Stevens and Bailowitz (unpublished). A total of 59 species have been detected from the basin thus far. Some species, such as *Telebasis salva*, are top predators in Verde River basin springs (Runck and Blinn 1993). While no endemic Odonata are known from the Verde River basin, several species appear to be rare, such as *Argia oenea*, a southwestern species that has only been found at one locality in the Verde River basin thus far (Stevens and Omana 2007). The Verde River also likely serves as a corridor for the massive northward movement of dragonflies in the summer months. It is not unusual to see more than 12 species of Odonata flying simultaneously at a single site along the middle Verde River in August.

Aquatic habitats and mainstream flow relationships vary considerably among Verde River Odonata species. Some species, such as *Brechmorhoga mendax*, require relatively dense vegetation overhanging flowing water, while most larger dragonflies (e.g., *Anax junius* and *Tramea oneusta*) require open expanses of water and shoreline. Odonata larvae are generally benthic, and with a few exceptions prefer slow to lentic water bodies. The Verde River's natural hydrograph provides an array of summer and autumn aquatic and shoreline habitats and water velocities that likely contribute to the basin's relatively high diversity of Odonata.

Aquatic and Semi-aquatic Hemiptera

Aquatic and semi-aquatic Hemiptera (ASH) are important predators and sources of food for higher trophic levels in most of the habitats in which they occur. The ASH of the Verde River are known from collections housed at the Colorado Entomological Institute in Englewood, and at the Museum of Northern Arizona in Flagstaff. These true bug species occupy a wide array of open to vegetated shoreline, as well as shallow lentic and slow lotic habitats, including springs. A total of 59 ASH are reported or documented from the Verde River, including at least two endemic species (*Ranatra montezuma* and *Rupisalda saxicola*), as well as numerous apparently rare species (e.g., *Buenoa scimitar, Hebrus majo, and Microvelia glabrosulcata, M. hinei,* and *M. rasilis*; Stevens and Polhemus in press). The Verde River supports approximately 40 percent of the ASH species known from Arizona, and the Verde's ASH diversity is greater than that in Nevada, a state recognized for its abundance of ASH species (Polhemus and Polhemus 2002). Conservation of the great diversity of Verde River ASH can be accomplished only by consideration of their microhabitat relationships, although knowledge of those relationships remains outstanding for many taxa.

Non-native Invertebrates

As with vegetation and vertebrates, non-native invertebrates threaten the ecological integrity of the Verde River. The non-native red crayfish (*Procambarus clarki*) is native to the Mississippi River drainage in the eastern U.S. It is widely established throughout the Verde River and its springs, and is moving into the lower headwaters. Another non-native crayfish, *Orconectes virilis*, occurs at higher elevations in the Verde Basin. It is native from Montana and Utah to Arkansas, north to the Great Lakes, and east to New York. These crustaceans now dominate many drainages throughout the Southwest, including the Verde River basin. Although they were originally introduced as food for non-native sport fish, numerous native vertebrates feed on crayfish, including: Common Black Hawk, various herons and egrets, several duck species, raccoons, and river otters. However, crayfish are significant predators on native aquatic vegetation, invertebrates, fish, amphibians, and small reptiles, and crayfish are one of the most dire threats to the integrity of the Verde River and other southwestern stream-riparian habitats (Creed 1994, Kubly 1997, Nowak and Santana-Bendix 2002).

Other non-native invertebrates presently or may soon threaten the integrity of the Verde River ecosystem. Aquatic invasives include: New Zealand mudsnail (*Potamopyrgus antipodarum*), quagga and zebra mussel (*Dresseina* spp.), Asian clams (*Corbicula* sp.), and other taxa. Terrestrial non-native invertebrate species such as the now-common predatory ladybird beetle, Anatis lecontei, exert unstudied but potentially profound impacts on the basin's riparian invertebrate populations. Various diseases, from anchorworms (*Lernaea* sp.) and Asian tapeworm (*Bothriocephalus acheilognathi*), to West Nile virus also threaten the basin's fish and wildlife populations, but such impacts are not much studied.

FISH

Overview

Stream fisheries are primary targets for river management in the Southwest, but flow regimes that support native fish may differ from those needed to support riparian resources (Stevens et al. 2001). Tradeoffs for the protection and enhancement of native aquatic and terrestrial riparian species often involve consideration of the frequency, magnitude, duration, and timing of low, normal, and high flows and flow variation. Adaptive management is needed to achieve ecologically supportive flows for native species, and management of high flows generally involves taking advantage of natural flood events, particularly when competing environmental and economic constituencies exist (e.g., Stevens and Gold 2002). The magnitude and persistence of low flows in the upper Verde form a primary topic of concern for maintaining fish populations, and have the potential to affect both native and sport fish. The small diversion dams currently on the upper and middle Verde do not appear to be a major influence on the overall flow regime, but must be considered in any local-scale assessment of fish habitat.

Historically, at least 13 native fish species occurred in the Verde River basin, including: Gila trout (*Onchorhynchus gilae*); desert and Sonora suckers (*Catostomus clarki* and *C. insignis,* respectively); speckled dace (*Rhinichthys osculus*); razorback sucker (*Xyrauchen texanus*); longfin dace (*Agosia chrysogaster*); Gila, headwater, and roundtail chubs (*Gila intermedia, G. nigra, and G. robusta*); spikedace (*Meda fulgida*); Colorado pikeminnow (*Ptychocheilus lucius*); loach minnow (*Tiaroga cobitis*); and Gila topminnow (*Poeciliopsis occidentalis*).

Several other native fish species may have been present historically in the Verde River basin, but do not currently occur there and were never documented by museum specimens. These include flannelmouth sucker (*Catostomus latipennis*), woundfin (*Plagopterus argentissimus*), and Desert pupfish (*Cyprinodon macularius*) (Minckley 1973, Rinne 2005, USFWS 1993).

These species historically varied in their distribution within the basin, and in relation to the timing of natural flows. However, native species are presently most abundant and have the highest biomass only in the upper Verde River (Minckley 1973, Minckley and DeMarais 2000, Bonar et al. 2004, Rinne 2005).

As has occurred throughout the Southwest, anthropogenic influences involving flow regulation and introduction of non-native species has decimated the Verde River's native fish assemblage (Minckley and Deacon 1991, Rinne et al. 1998, Bonar et al. 2004, Rinne 2005). All of the native fish taxa are regarded as species of management concern, at least four species have been extirpated, and nearly one third of the Verde River's assemblage is federally listed as endangered or threatened (Table 5-2). Although efforts to restore pikeminnow and razorback sucker have been initiated in the Verde River basin, only ten of the native species are still found in the Verde River basin and only three are common throughout the basin (desert sucker, Sonora sucker and roundtail chub; Bonar et al. 2004). Longfin dace has recently been detected only in the lowermost reaches (Bonar et al. 2004), and spikedace have not been detected since 1999. Thus, the Verde River's native fish assemblage is in dire and declining condition.

Table 5-2: Verde River fish (Minckley 1973, Bonar et al. 2004, Rinne 2005). Nativity: Na – native; Na-Extr – native but extirpated; NN – non-native. Arizona Status: WSC – Wildlife of Special Concern. US Status: LE – listed endangered, LT – listed threatened, SC – species of concern.

Common Name	Family	Scientific Name	Nativity	AZ Status	US Status
Desert sucker	Catastomidae	*Catostomus clarki*	Na	---	SC
Sonora Sucker	Catastomidae	*Catostomus insignis*	Na	---	SC
Razorback Sucker	Catastomidae	*Xyrauchen texanus*	Na	WSC	LE
Longfin Dace	Cyprinidae	*Agosia chrysogaster*	Na	---	SC
Gila Chub	Cyprinidae	*Gila intermedia*	Na	WSC	
Headwater Chub	Cyprinidae	*Gila nigra*	Na	WSC	
Roundtail Chub	Cyprinidae	*Gila robusta*	Na	WSC	SC
Spikedace	Cyprinidae	*Meda fulgida*	Na	WSC	LT
Colorado Pikeminnow	Cyprinidae	*Ptychocheilus lucius*	Na	WSC	LE
Speckled Dace	Cyprinidae	*Rhinichthys osculus*	Na	---	SC
Loach Minnow	Cyprinidae	*Tiaroga cobitis*	Na	WSC	LT
Gila Topminnow	Poeciliidae	*Poeciliopsis o. occidentalis*	Na	WSC	LE
Gila Trout	Salmonidae	*Oncorhynchus gilae*	Na-Extr	WSC	LT
Rock Bass	Centrarchidae	*Ambloplites rupestris*	NN	---	---
Green Sunfish	Centrarchidae	*Lepomis cyanellus*	NN	---	---
Bluegill	Centrarchidae	*Lepomis macrochirus*	NN	---	---
Smallmouth Bass	Centrarchidae	*Micropterus d. dolomieui*	NN	---	---
Spotted Bass	Centrarchidae	*Micropterus punctulatus*	NN	---	---
Largemouth Bass	Centrarchidae	*Micropterus salmoides*	NN	---	---
Striped Bass	Centrarchidae	*Morone saxitalis*	NN	---	---
White Crappie	Centrarchidae	*Pomoxis annularis*	NN	---	---
Black Crappie	Centrarchidae	*Pomoxis nigromaculatus*	NN	---	---
Tilapia	Cichlidae	*Tilapia* sp.	NN	---	---
Threadfin Shad	Clupeidae	*Dorosoma petenense*	NN	---	---
Goldfish	Cyprinidae	*Carassius auratus*	NN	---	---
Common Carp	Cyprinidae	*Cyprinus carpio*	NN	---	---
Golden Shiner	Cyprinidae	*Notemigonus crysoleucus*	NN	---	---
Red Shiner	Cyprinidae	*Notropis lutrensis*	NN	---	---
Fathead Minnow	Cyprinidae	*Pimephales promelas*	NN	---	---
Northern Pike	Esosidae	*Esox lucius*	NN	---	---
Black Bullhead	Ictaluridae	*Ictalurus melas*	NN	---	---
Yellow Bullhead	Ictaluridae	*Ictalurus natalis*	NN	---	---
Channel Catfish	Ictaluridae	*Ictalurus punctatus*	NN	---	---
Flathead Catfish	Ictaluridae	*Pilodictis olivaris*	NN	---	---
Yellow Bass	Percichthyidae	*Morone mississippiensis*	NN	---	---
Yellow Perch	Percidae	*Perca flavescens*	NN	---	---
Walleye	Percidae	*Stizostedion vitreum*	NN	---	---
Mosquitofish	Poeciliidae	*Gambusia a. affinis*	NN	---	---
Sailfin Molly	Poeciliidae	*Poecilia latipinna*	NN	---	---
Shortfin Molly	Poeciliidae	*Poecilia mexicana*	NN	---	---
Rainbow Trout	Salmonidae	*Oncorhynchus mykiss*	NN	---	---
Brown Trout	Salmonidae	*Salmo trutta*	NN	---	---
Brook Trout	Salmonidae	*Salvelinus fontinalis*	NN	---	---

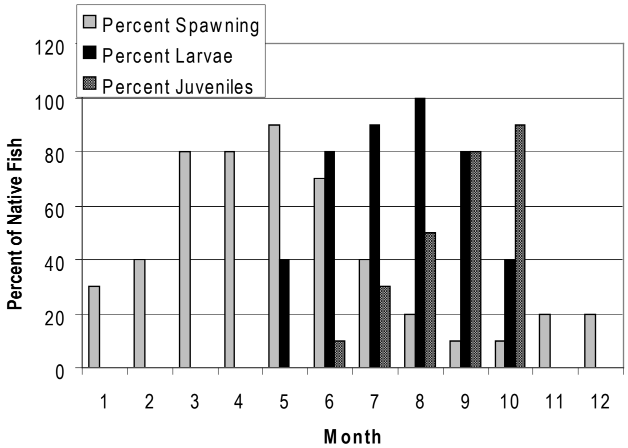

Figure 5-1: Percent of native fish spawning, egg production, and larval rearing across the year in the Verde River basin.

Non-native fish species strongly dominate the Verde River's fish assemblage (Minckley 1973, Rinne 2005), which contains 30 species, including many highly piscivorous species and potentially highly competitive species (Table 5-2, Appendix 2). These include more than a dozen species which were introduced for recreational fishing, including catfishes, bass, sunfish, and trout, with more than 15 million individual fishes stocked over the past six decades (Rinne et al. 1998, Rinne 2005). Fisheries management in the Verde basin has provided a significant and economically valuable recreational resource, with an emphasis on warm-water fishes in the two reservoirs and cold-water fishes in the tributary streams. In recent decades, wildlife managers have also made significant efforts to reintroduce several native species, including Colorado pikeminnow and razorback sucker, and conducted a massive effort to restore Fossil Creek as an exclusive refuge for native fishes (USFWS 2002 a, b; Weedman et al. 2005). Thus, changing public values and conflicting agency mandates have affected the river's fish fauna.

Non-native fish abundance and dominance increased over distance downstream in the Verde River drainage, with relatively low concentration in the headwaters but strong dominance in the middle and lower reaches (Bonar et al. 2004, Rinne 2005). Bonar et al. (2004) reported that non-native fish were 2.6-fold more abundant, and had a 2.8-fold greater standing mass than that of native fish. Therefore, the ecological functionality of the native fish assemblage in the Verde River has been severely compromised.

Many non-native fish species exert ecologically important impacts on the trophic structure of the river system by functioning as predators on different life stages of native fish (Appendix 2). Bonar et al. (2004) identified three guilds of non-native fish: 1) a strongly piscivorous assemblage including largemouth and smallmouth bass, flathead and channel catfish, and yellow bullhead; 2) a primarily insectivorous guild with minor piscivory consisting of bluegill and green sunfish, rainbow trout; and 3) an herbivorous and insectivorous group consisting of tilapia, common carp, red shiner, mosquitofish, and threadfin shad. Of these, largemouth bass were the most important basin-wide piscivore on native fish, although smallmouth bass was the only non-native fish that consumed native fish in the headwaters reach. Consumption of native species eggs, and competition between non-native and native fish can negatively affect the integrity of the native fish assemblages, but those topics have not yet, to our knowledge, been demonstrated through rigorous field experimental studies in this region.

The fish assemblage transitions over distance downstream from the headwaters with increasing dominance of nonnative species, which may be related to increasing levels of hydrologic alteration (Rinne 2005). The upper Verde has an essentially natural hydrograph, while the Verde Valley has some small impoundments and artificially-low base flows due to water diversions. The lower Verde has been highly altered by two dams and their associated reservoirs. Natural flood regimes in small to mid-sized streams (such as the Verde River) provide native fishes some advantage over nonnative taxa in the arid Southwest (Minckley and Meffe 1987, Eby et al. 2003). Periodic large floods have caused short-term reductions in nonnative fish abundance and relative dominance, accompanied by increases in native fish (Rinne 2005). Assuming no new dams are constructed, floods will likely continue to benefit native fishes in the upper and middle reaches, but reductions in base flows could increase the impact of other stressors, including that of non-native fish.

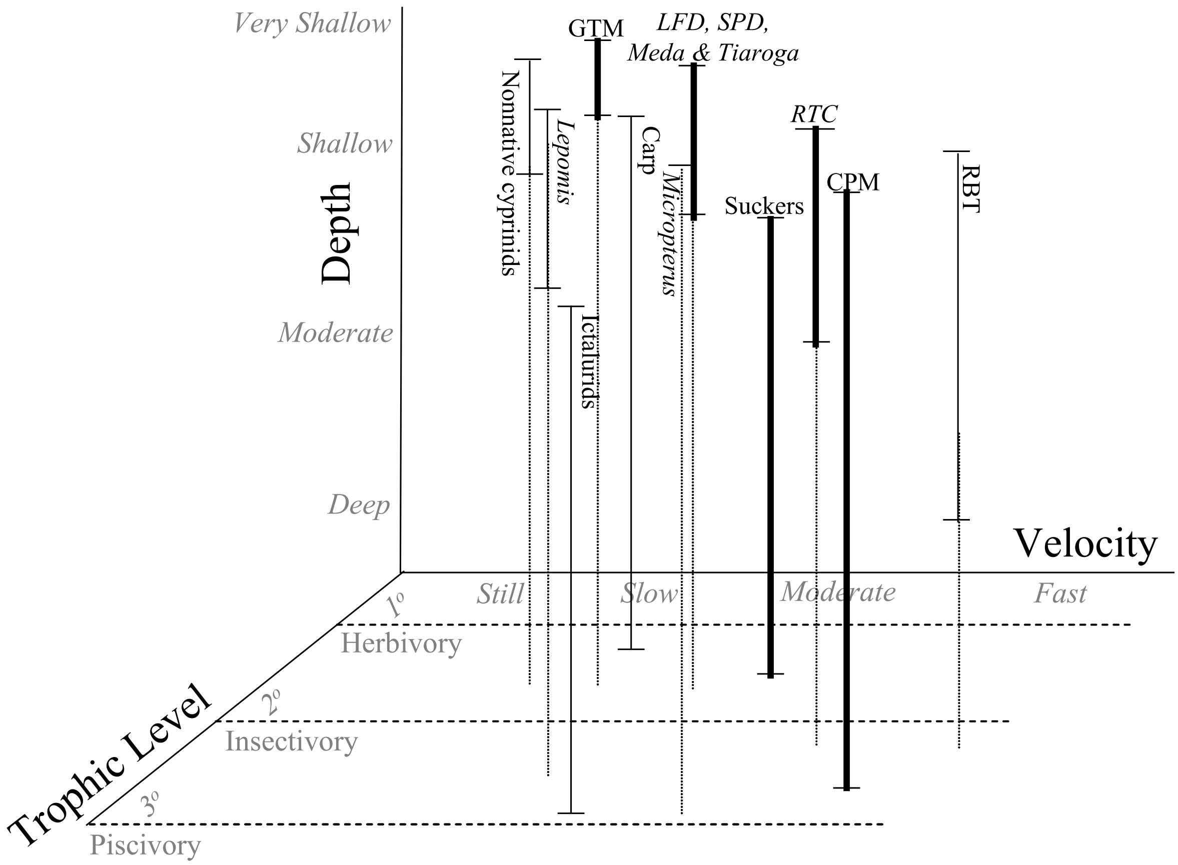

Figure 5-2: Comparative niche analysis of native Verde River fishes as a function of depth and velocity preferenda, and trophic position. Axis scores were generated from the literature on these species. Niches of dominant non-native species are indicated by lighter lines. Abbreviations: CPM – Colorado pikeminnow, GTM – Gila topminnow, LFD – longfin dace, RBT – rainbow trout, RTC – round-tailed chub, SPD – speckled dace

Fish Life History Characteristics

We describe habitat criteria for ten native fishes and the dominant non-native fishes in the Verde River, and provide a synthesis of each species' habitat use (Table 5-3, Appendix 2) and reproductive phenology (Fig. 5-1; Appendix 2). An excerpt of that analysis showing only native species is presented in Table 5-3. Spawning varies by species, with most species spawning from March into June, but some species, such as Sonoran sucker and Gila topminnow spawning until middle-late summer (Table 5-3; Fig. 5-1). Larval fish hatch and drift during late spring and summer, and juveniles are found in mid-late summer and autumn; however, there is much variation in reproductive phenology among species.

Spawning generally takes place over fine to moderately coarse gravels and typically after the annual spring spates (Minckley and Meffe 1987). Nearly all native fishes in the upper and middle Verde River spawn over fine- to moderately-coarse gravel beds or sometimes in vegetation. Their larvae typically require shallow, near-shore habitats as nursery habitat. Growth rates, distribution of juveniles, and adult habitats are more variable.

Comparative Niche Analysis

The focus of this project is on definition of ecologically supportive flows for native biota; however, effective protection and enhancement of the Verde River's native fish assemblage is likely to require conservation of the natural hydrologic regime, management of non-native fish species, and perhaps control of fish parasites. Nonetheless, determination of ecologically supportive flows for Verde River fish requires understanding and comparison of niche requirements and timing of life history events. Such a synthesis has not previously

Table 5-3. Native fish habitat needs in the Verde River, where known. Nonnative fish data and references provided in Appendix 2.

Common Name	Scientific Name	Ecological Role	Spawning Habitat	Rearing Habitat	Adult Habitat	Spawning Period	Flow Needs
Longfin Dace	*Agosia chrysogaster*	omnivorous and opportunistic in feeding behavior and diet	fine sand	open high temperature waters	shaded, deep, high temperature waters	December- July or perhaps September	Usually in water less than 0.6 ft (0.2 m) deep with moderate velocities of around 1.1f/s (0.3m/s)
Desert sucker	*Catostomus clarki*	adults are largely herbivores, feeding on algae and organisms scraped from stones	Riffles	quiet pools near the banks	pools during day, riffles at night	late winter or early spring	rapids and flowing pools
Sonora Sucker	*Catostomus insignis*	feed on larvae of aquatic insects	“cleaned” gravel bottoms	stream margins	gravelly/rocky pools in relatively deep quiet waters		relatively deep, quiet waters
Roundtail Chub	*Gila robusta*	carnivorous, top predator in mid-elevation streams, also feed on inverts	gravel bottoms, preferring submerged cover	shallow margins and undercut banks	pools, eddys below rapids, low-gradient riffles	May- July in other systems	spawning triggered by rising water temp (14-24 C) during receding flow
Spikedace	*Meda fulgida*	feed mainly on aquatic and terrestrial insects, some fish fry	shallow sandy bottoms		riffles; moving water less than 1 meter deep; Verde mean depth 26.5 +/- 6.7 cm; Verde mean velocity 21.0 +/- 10.0 cm/s	May- June	Verde mean velocity 21.0 +/- 10.0 cm/s
Gila Topminnow	*Poeciliopsis o. occidentalis*				in moderate current below riffles and in margins	January- August	moderate current
Colorado Pikeminnow	*Ptychocheilus lucius*	formerly the top carnivore of the Colorado River basin	adults run upstream to streams	warm, low-velocity backwaters	deep, low-velocity eddies, pools and runs	July to August in the Green River	adapted to large spring peak flows and low stable base flows; spawning triggered by rising water temp (18-23 C) after spring runoff peaks
Speckled Dace	*Rhinichthys osculus*	Omnivorous benthic feeders	moderate to swift water	gravel bottoms	less than 0.5 m depth, congregated below riffes and eddies	2 spawns: spring and late summer	water less than 0.5 m (1.6 ft.) deep, with current averaging about 0.4m/sec (1.3ft/sec)
Loach Minnow	*Tiaroga cobitis*	feed on larvae of riffle-dwelling insects	riffles; velocity 0-100 cm/sec, depth 6-40 cm (Gila R)	riffles; 33.0 +/- 23.2 cm/sec, 14.9 +/- 7.0 cm depth (Gila R)	on the bottom of gravelly riffles; 24-80 cm/sec, 12-27 cm deep (Gila R)	late winter- early spring	riffles maintained by flooding; spawning triggered by rising water temp (16-20 C); eggs need large gravel to cobbles, free of fine sediments, with flowing water
Razorback Sucker	*Xyrauchen texanus*	feed on aquatic and terrestrial insects, filamentous algae, and other fish	along shorelines or in bays	quiet backwaters	1-15m depth; over sand, mud or gravel bottoms	February- early summer	adapted to large spring peak flows and low stable base flows; spawning triggered by rising water temp (9.5-22 C) after spring runoff peaks

been undertaken for this assemblage to our knowledge.

One approach that has been useful for understanding habitat needs of native fish and the impacts of non-native fish in the Southwest was provided by Schmidt et al. (1998). They conducted a quantitative niche comparison of depth, temperature, and movement preferenda among co-occurring Colorado River mainstream fish species in Grand Canyon to reveal the extent to which non-native species are embedded in native species' niches.

A similar approach for the Verde River fish assemblage is presented using depth, velocity, and trophic status (Fig. 5-2). This conceptualized niche comparison reveals a broad overlap of native fish niches by the many non-native fish present in the Verde system. Native Verde River fishes may be susceptible to non-native fish impacts in the following ways: 1) potential native egg and larvae consumption in very shallow to shallow, still-to-moderate velocity habitats by smaller non-native individuals and species; 2) potential competition in those habitats by herbivorous and omnivorous non-native species; and 3) direct predation by bass, catfish, and other non-native piscivorous species in shallow to deep, still to moderate velocity habitats. Little available nonnative-free niche space appears to be available to support native fish species. The loss of most of the smaller native fish species indicates two elements important to fish conservation in the Verde River basin. First, the shallow, low velocity habitats used by those species likely have been most strongly affected by non-native species and potentially reduced flows. Secondly, because smaller fish are generally short-lived, recruitment failure and the loss of larger, more long-lived native fish is simply a matter of time.

AMPHIBIANS AND REPTILES

The upper and middle reaches of the Verde River was found to support at least 6 species of amphibians, 5 species of turtles and tortoises, 21 species of lizards, and 24 species of snakes, for a minimum total of 56 aquatic, wetland, and obligate or strongly facultative riparian herpetofaunal species (data primarily from Brennan and Holycross 2006). This assemblage varied widely in habitat use, with some species facultatively using riparian habitats. Some toads and other species (e.g., *Spea, Scaphiopus*, and some other toads) were not included in the list because they use ephemeral pools for reproduction, rather than the fluvial environment.

An overall habitat use analysis indicated that aquatic, wetland, and shrub-dominated riparian habitats are the most important herpetofaunal habitats in the Verde River basin. Therefore, flow management that promotes natural geomorphic features, such as post-flood pools of standing water, and mixed successional stages of riparian vegetation are most likely to serve in the long-term conservation of a large percent of the region's riparian reptile species.

We focused more detailed analysis on the 18 species of amphibians, turtles, garter snakes, and a few other species that are obligate aquatic, wetland, or riparian taxa, including several non-native species. We ranked each of these obligate herpetofaunal species' use of each habitat on a scale from 1 (low use) to 3 (high use primary and/or breeding habitat). If a species did not use a habitat, that cell was left blank. We calculated a habitat use index as the sum of habitat use rankings across species as a proportion of the total possible score (maximum use rank = 3, times 18 species, for a grand maximum score of 54). This habitat use index is a relatively conservative metric for illustrating the habitats needed by most species of obligate or strongly facultative fluvial herpetofauna, the species most likely to be affected by flow management.

Habitat use varies among obligate fluvial herpetofaunal taxa (Fig. 5-3). Index scores were highest for lotic and lentic open water, channel bar wetlands, marshes and cienegas (habitat scores from 0.65- to 0.72, 14-15 species), with lower but substantial importance of barren shoreline habitats, particularly used at night for foraging and breeding. cottonwood-willow strand shrublands (0.48, 13 species) were most productive vegetated habitat, with forested and grassland riparian habitats having lower scores and supporting fewer species.

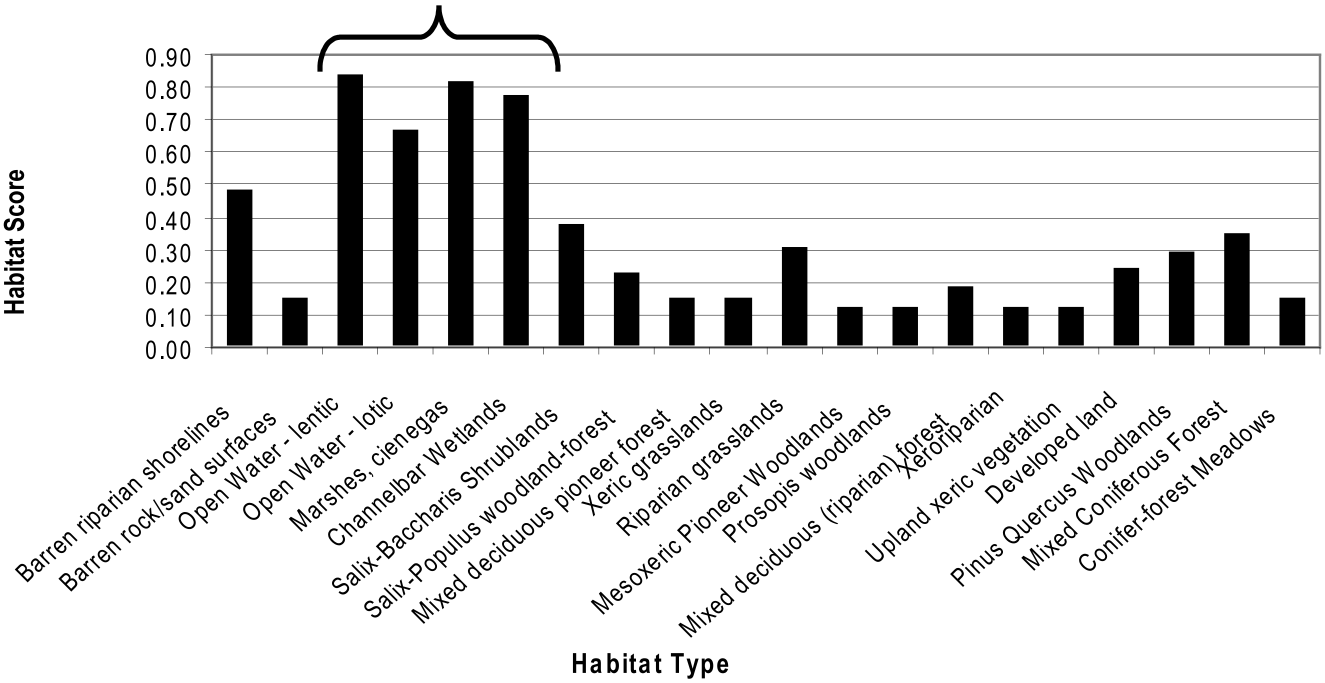

Figure 5-3: Cumulative habitat use score for amphibians and reptiles across the array of Verde River habitat types. Bracket indicates habitat types with the highest use scores.

Reproductive phenology among the 18 obligate or strongly facultative fluvial herpetofauna was determined through the literature on a seasonal basis, and scored as the number of species breeding, the number of species with eggs or larvae, and the number of species with juvenile present (Table 5-4). These life stages were considered be most susceptible to alterations or management of mainstream flows. The proportion of species in each those three reproductive stages was used as an index of sensitivity to alteration of flows in each season. This analysis revealed that spring and early summer are the primary breeding seasons, but that several species breed in late summer, and some breeding occurs in fall and winter.

The most sensitive obligate or strongly facultative herpetofaunal taxa whose population status is relatively well known are the native leopard frogs (*Rana pipiens, R. yavapaiensis,* and *R. chiricahuensis*). These species typically occur in lentic or slow-moderate lotic fluvial settings with shores lined with marsh vegetation. The non-native American bullfrog now dominates along the mainstem Verde River, but *R. yavapaiensis* persists in a few places on the river as well as tributary streams and upland waters. *Rana chiricahuensis* and *R. pipiens*

Table 5-4: Seasonal reproductive phenology of 18 obligate and strongly facultative aquatic, wetland, or riparian Verde River herpetofaunal species (data primarily derived from Brennan and Holycross 2006).

	Season				
Statistic	Winter	Spring	Early Summer	Late Summer	Autumn
No. Spp. Breeding	1	16	3	4	1
Breeding Index	5.6	88.9	16.7	22.2	5.6
No. With Larvae or Eggs	1	13	8	5	1
Larval or Egg Index	5.6	72.2	44.4	27.8	5.6
No. Spp. Juvenile	2	6	9	18	18
Juvenile Presence Index	11.1	33.3	50.0	100.0	100.0

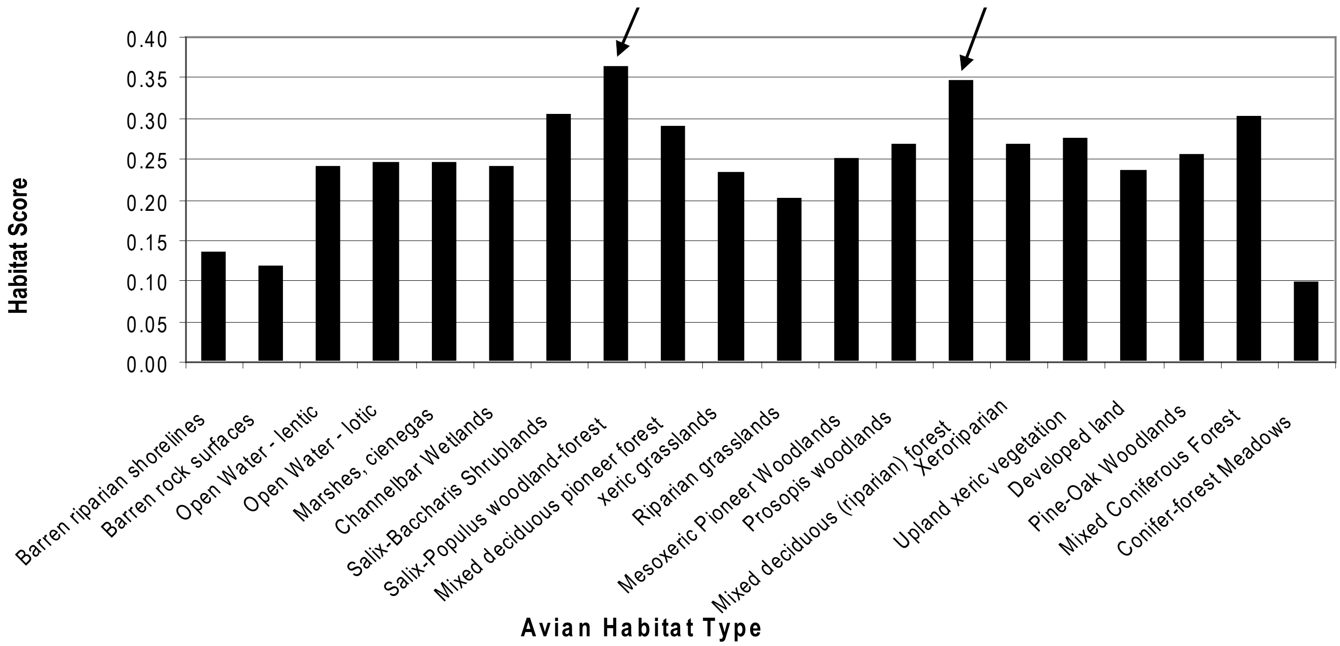

Figure 5-4: Cumulative habitat use score for Verde River bird species across the array of habitat types. Arrows indicate habitat types with the highest use scores.

are found only in upland tanks and springs, along with a few headwater streams.

Two snake species, the narrow-headed gartersnake (*Thamnophis rufipunctatus*) and Mexican gartersnake (*T. eques*), are closely tied to the health of the aquatic and riparian communities. Both have small and declining ranges in the U.S., and have been nearly lost from the Verde River system. The narrow-headed gartersnake depends almost exclusively on small soft-rayed fish (suckers, dace, chub, and trout) for their diet, while the Mexican gartersnake eats primarily fish, frogs, and insects (Holycross et al. 2006, Nowak 2006). Flow needs for these snakes have not been studied explicitly, but they likely benefit from flood flows which reduce the abundance of nonnative predatory fish and base flows that are high enough to keep water temperatures relatively cool, thus supporting overall fish populations.

BIRDS

The avifauna of the Verde River has a relatively long history of study, with pre-1900 exploration of the region's birds by early ornithologists, such as Elliott Coues and Edgar Mearns (Fischer 2001), and detailed analyses of avian habitat relations by Carothers et al. (1974) and others. Recent biological inventory data (e.g., Schmidt et al. 2005) have contributed some additional information; however, much historical information has not been thoroughly compiled, and trends over time have not been monitored. We compiled a list of bird species of the Verde River drainage primarily from Corman and Wise-Gervais (2005), Schmidt et al. (2005) with additional data from Phillips et al. (1964), Carothers et al. (1974), and our own notes. We used these references and other literature to describe the habitats typically used by Verde River basin bird species. From this compilation, we ranked each species use of the 20 Verde River habitats on 1-3 scale, as described above for the herpetofauna, and similarly calculated a habitat use index. Because many upland bird species come to water to drink on a daily basis, we used all species in the habitat use analysis. Therefore, the analysis provides a comparative assessment of the importance of different habitat types to the overall avian assemblage in the Verde River basin.

Habitat use varied considerably among the Verde River's 221 avian species reported from the literature and our field notes (Fig. 5-4). Table 5-5 presents detailed information about a selected set of riparian associate or obligate breeding birds,

Table 5-5. Habitat needs for selected breeding birds of the Verde River basin (data compiled from Poole et al. and Corman and Wise-Gervais 2005).

Common Name	Scientific Name	Ecological Role	Primary Nesting Habitat	Adult Habitat	Nesting Period	Flow Needs
Common Merganser	*Mergus merganser*	Adults are largely piscivores, feeding on native and nonnative fish. Also feed on crayfish.	Cavities large trees	pools, still water, runs and riffles.	early spring	Sufficient for base flow and deep pools that support fish.
Mallard	*Anas platyrhynchos*	Adults feed on microinvertebrates, algaes	Marsh and stream edge	pools, still water, runs and riffles.	early spring	Sufficient for marsh and stream edge habitat
Wood Duck	*Aix sponsa*	Adults feed on microinvertebrates, algaes	Cavities large trees	Forested wetlands and streams with pools, still water, runs and riffles.	early spring	Sufficient for base flow and deep pools that support fish.
Bald Eagle	*Haliaeetus leucocephalus Adults*	Adults are piscivorous and scavengers	Large trees, occasionally cliffs	Open water, barren shorelines, open canopy riparian	late winter to early summer	Sufficient for maintaining abundant and diverse fish prey base, and runs and pools for fishing
Great Blue Heron	*Ardea herodias*	adults are largely piscivores, feeding on native and nonnative fish. Also feed on crayfish.	Colonial nester in riparian gallery forest	Riparian gallery forest	Late spring and early summer	Sufficient to maintain cottonwood-willow gallery forest and shallow water (<1 m) habitats that support fish.
Spotted Sandpiper	*Actitis macularius*	Adults largely feed on aquatic and terrestrial invertebrates	Open marsh and stream edge	pools, still water, runs and riffles.	spring and early summer	Sufficient for marsh and stream edge habitat
Belted Knigfisher	*Ceryle alcyon*	adults are largely piscivores, feeding on native and nonnative fish and aquatic invertebrates	Cavity nester in riverbanks	pools, still water, runs and riffles with streamside cliff and riparian gallery forest adjacent habitats for hunting perches	Late spring and early summer	Sufficient for base flow and deep pools that support fish.
Virginia Rail	*Rallus limicola*	Adults feed on microinvertebrates	Marsh cattails and reeds	Marsh habitats	early to late spring	Sufficient for marsh habitat
Sora	*Porzana carolina*	Adults feed on microinvertebrates	Marsh reeds and sedge	Marsh habitats	early to late spring	Sufficient for marsh habitat
Yellow-billed Cuckoo	*Coccyzus americanus*	Adults are insectivorous	Riparian gallery forest	Riparian gallery forest	early summer to late summer	Sufficient to maintain cottonwood-willow gallery forest

Table 5-5 continued.

Common Name	Scientific Name	Ecological Role	Primary Nesting Habitat	Adult Habitat	Nesting Period	Flow Needs
Southwestern Willow Flycatcher	*Empidonax traillii extimus*	Adults are insectivorous	Young (3-10 yr old) willow and/or tamarisk forest with standing and slow moving water	Young (3-10 yr old) willow and/or tamarisk forest with standing and slow moving water	Late spring to mid or late summer	Sufficient to maintain appropriate tree composition and structure, and water adjacent to or under the canopy.
Yellow Warbler	*Dendroica petechia*	Adults are insectivorous	Riparian gallery forest	Riparian gallery forest	Late spring and early summer	Sufficient to maintain cottonwood-willow gallery forest
Summer Tanager	*Piranga rubra*	Adults are insectivorous; bee and wasp specialist. Also fruit	Riparian gallery forest	Riparian gallery forest	Late spring and early summer	Sufficient to maintain cottonwood-willow gallery forest
Red-winged Blackbird	*Agelaius phoeniceus*	Adults are insectivorous and seed eaters	Marsh cattails and reeds	Marsh habitats, agriculture, adjacent upland and rural developed habitats	Late spring and early summer	Sufficient for marsh habitat
Bullocks Oriole	*Icterus bullockii*	Adults are insectivrous and eat fruit and nectar as available	Riparian gallery forest	Riparian gallery forest	Late spring and early summer	Sufficient to maintain cottonwood-willow gallery forest
Lesser Goldfinch	*Carduelis psaltria*	Adults are small diameter seed-eaters	Riparian gallery forest	Riparian gallery forest	Late spring and early summer	Sufficient to maintain cottonwood-willow gallery forest

including species of conservation concern. As reported in Carothers et al. (1974) and elsewhere, cottonwood-willow riparian forest and woodlands, and mixed deciduous riparian forest habitats had the highest avian habitat use index values. Riparian shrublands, pioneer stands, and coniferous forests had the next highest values, followed by upland, marsh, open water, and xeroriparian habitats. This analysis may be refined for obligate and strongly facultative avian species. The use of riparian habitats by upland birds is extensive, and some riparian birds, such as Bewick's wren (*Thryomanes bewickii*), and kingbirds and other tyrannid flycatchers, actively forage in peripheral riparian and adjacent upland habitats (Bewick's Wren and kingbirds also nest in the pine and oak woodlands). Therefore, more restrictive analyses may obscure understanding of habitat usage.

Avian reproductive activity commences in the Verde Valley in mid March and generally concludes by early July, with lingering breeding activity by a few species into mid-July (Table 5-5). Therefore, we evaluated habitat use in relation to the presence of avifauna during this time period. Migratory and wintering bird habitat use is generally more opportunistic and variable, and the implications for flow management are more likely to involve consideration of whether water is present than specific habitat configuration issues.

Two bird species of particular management concern in the middle and upper Verde River system are the yellow-billed cuckoo (YBCU; *Coccyzus americanus occidentalis*) and the southwestern willow flycatcher (SWFL; *Empidonax traillii extimus*). These species both breed rather late in the breeding season, with breeding activity in June and July. These species are in decline in Arizona and are of management concern throughout the state. YBCU is

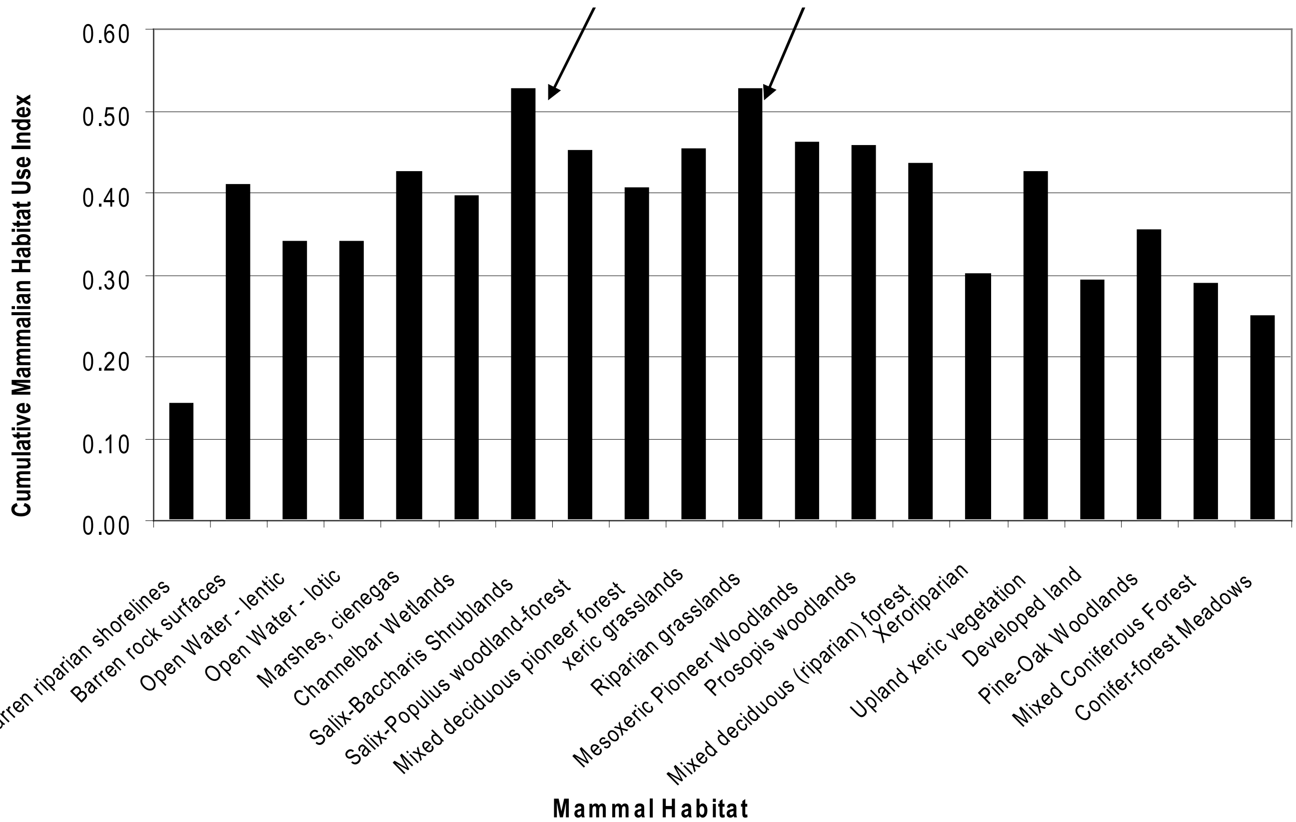

Figure 5-5: Cumulative habitat use score for Verde River mammals across the array of habitat types. Arrows indicate habitat types with the highest use scores.

a candidate for federal listing under the Endangered Species Act, and generally nests in large, well-connected stands of riparian gallery forest and/or mesquite bosque habitats (http://www.gf.state.az.us/w_c/edits/documents/Coccamoc.fi_002.pdf; accessed 1 May 2007). SWFL is a federally-listed endangered species that generally breeds in native or non-native shrub and mid-level canopy riparian stands immediately adjacent to standing or flowing water throughout the state(Paradzick and Woodward 2003). Slight variations in depth to groundwater has been shown to affect nesting vegetation structure and composition, which influenced breeding suitability (Paradzick 2005). Its population has decreased in many locations, but recolonization and colonization of new habitats has been reported (Unitt 1987, Paradzick and Woodward 2003).

MAMMALS

Verde River basin mammal distribution and habitat data were summarized from Hoffmeister (1986), Feldhamer et al. (2003), and Schmidt et al. (2005). A total of 92 species are reported from the basin. Of this total, and like the basin's herpetofauna, most mammal species in the Verde drainage are upland taxa, using riparian areas in an opportunistic fashion for watering, hunting, and as facultative habitat, or not at all (e.g., kangaroo rats). Three obligate aquatic mammal species occur in the Verde Valley in historic time: beaver (*Castor canadensis*), muskrat (*Ondatra zibethecus*) and river otter (*Lontra canadensis*; Hofffmeister 1986). In addition, three other contemporary species (all Procyonidae) are considered to be closely affiliated with riparian habitats, including: raccoon (*Procyon lotor*), ringtail (*Bassariscus astutus*), and coatimundi (*Nasua narica*). Several species that existed in the Verde Valley in historic times but now have been extirpated or driven to extinction also were likely have preferentially used riparian zones as movement corridors, including: Mexican gray wolf (*Canis lupus baileyi*), grizzly bear (*Ursus arctos horribilis*), ocelot (*Felis pardalis*). A recent addition to the upper Verde River riparian corridor is Rocky Mountain elk (*Cervus elaphus*). Merriam elk were historically present in associated uplands, but were extirpated prior to 1900. Elk are often associated with the marsh and willow habitats, and strongly affect wetland, grassland, and riparian habitats in northern Arizona.

A general mammal habitat use analysis, similar to that conducted for herpetofauna and birds revealed that riparian shrublands and riparian grasslands had the highest habitat use, with riparian forests, woodlands, marshes, and upland habitats having slightly lower mammalian habitat use values (Fig. 5-5). Maintaining permanent open water habitat of sufficient area is essential for maintaining populations of the three aquatic mammal species in the drainage.

Muskrats occur in moderately deep to deepwater lentic and slow lotic aquatic habitats in Verde River basin (Hoffmeister 1986, Erb and Perry 2003). The native status of muskrat in this system is in question, as many populations were transported around the state in the late nineteenth and twentieth century (Hoffmeister 1986). Muskrat are open water marsh specialists, and are particularly found in habitats dominated by cattail; however, they wander through stream systems rather widely , and may be found in almost any flowing water segment. They occasionally occupy unlined irrigation ditches.

Beaver are habitat engineers, affecting aquatic, wetland, and riparian habitats by constructing dams, excavation of banks that may increase groundwater infiltration, and movement and storage of large quantities of organic carbon on floodplains through the cutting of trees (Hoffmeister 1986, Baker and Hill 2003). Beaver may forage hundreds of meters from water, and their tree cutting can alter riparian forest stand structure and the standing water behind their dams may enhance larval and adult fish habitats. Beaver in Arizona may briefly dam small streams or irrigation ditches; however, such dams are generally washed away in monsoonal or snowmelt floods in short order. Beaver on larger streams burrow into banks, creating not only their own burrows, but also additional habitat. Muskrat also may marginally affect hydrogeomorphic conditions, and their burrowing may similarly enhance groundwater infiltration. However, their impact upon the Verde River is considerably less than that of beavers.

River otters are wide-ranging aquatic habitat generalists, feeding on fish, crayfish, terrestrial animal and insects (Hoffmeister 1986, Melquist et al. 2003). They commonly co-occur with beaver, and commonly use beaver dens for resting sites and beaver trails for access to riparian zones.

The type specimens of Southwestern river otter (*Lontra canadensis sonora*) were collected and described from Montezuma Well (Mearns 1891, Rhoads 1898). The subspecies was restricted to the Colorado River drainage and is now functionally extinct. Never abundant in historic times (Bailey 1935, Hoffmeister 1986), this subspecies did not receive federal designation as an endangered species. Van Zyll de Jong (1972) reviewed the genus and reiterated the taxonomic integrity of the subspecies, based on the few known specimens. Despite occasional reported sightings of Southwestern river otter along the Colorado River in Grand Canyon, no reliable documentation exists of their presence in Arizona since the 1970's, and recent searches for this species in Arizona have been unsuccessful (Britt et al. 1984, Spicer 1987; E. Leslie, Grand Canyon National Park Wildlife Biologist, personal communication, 2005).

Otters are particularly susceptible to inbreeding depression, and causes for this extinction include habitat fragmentation (especially dam and reservoir construction) and trapping. Otters from Louisiana were introduced into the Verde River in the 1980's by the Arizona Game and Fish Department, and that population has persisted in low numbers in the drainage ever since (Britt and Phelps 1980, Christensen 1984). A study of their current distribution, diet in relationship to native and exotic fish, taxonomic relationship, and genetics is needed (Polechla 2002).

Obligate aquatic mammals like beaver, muskrat, and otter, are likely to respond negatively to reduced flow, flooding, and increased low-flow duration, frequency, magnitude, and timing. Beaver and muskrat are particularly likely to be more susceptible to summertime low flows as they are

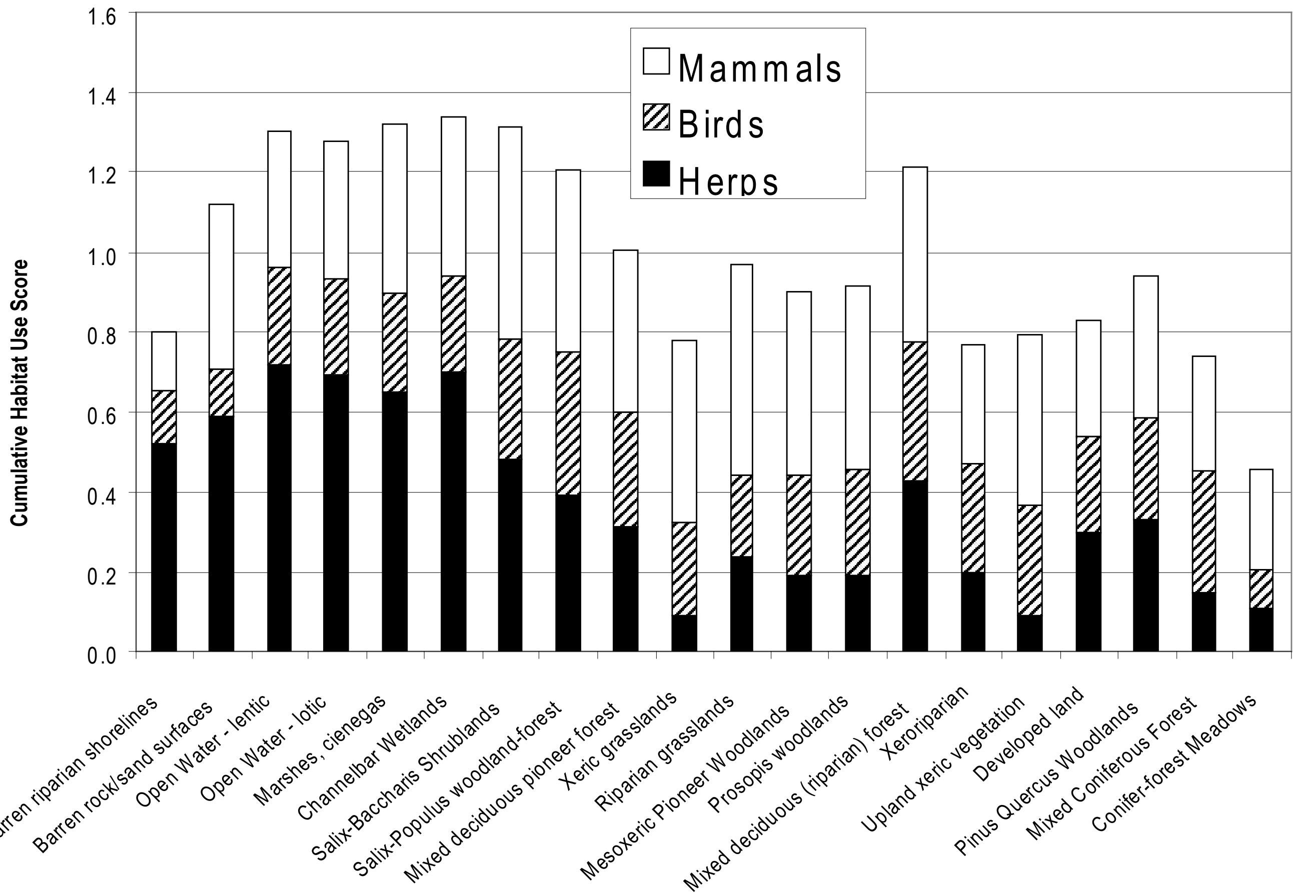

Figure 5-6. Cumulative habitat use score for Verde River vertebrates, excluding fish, across the array of habitat types.

less able to move long distances along ephemeral channels than are otters, and they are generally more susceptible to predators. However, insufficient information is available on these species' ecological roles to adequately predict population and trophic cascade effects.

OVERALL VERTEBRATE HABITAT USE

As expected, combining the above habitat data into a single cumulative score provided evidence of strong differences in habitat use among the non-fish vertebrates of the Verde River basin (Fig. 5-6). Lotic and lentic open water, riparian shorelines that were scoured of vegetation or occupied by early seral successional stands of grasslands or shrubs, and cottonwood-willow and mixed riparian tree habitats are more widely used as habitat than are other habitat types. Such an array of habitats is characteristic of unmanipulated rivers, in which those features are maintained by natural variation in flows.

SOURCES OF VERDE RIVER BASIN BIODIVERSITY

The upper and middle reaches of the Verde River are known for diverse assemblages of plants, invertebrates, fish and riparian taxa, particularly birds. For example, with 248 species, Tuzigoot National Monument near Cottonwood, Arizona on the Verde River reports more birds than any other national park unit in central or southern Arizona (Schmidt et al. 2005). In this section we explore the sources of the Verde River's elevated biodiversity, including its biogeographic configuration, the ecotonal influences of two geologic provinces, and the many springs that provide its base flow.

Riparian corridors have long been known to be movement corridors for fish and wildlife, as well as stopover habitat for migrating birds (Stevens et al. 1977, Skagen et al. 1998). The Verde River is the longest south-flowing river that heads in Arizona, and its corridor likely has supported wildlife movement over millennial time scales. Adding to its biogeographic significance, the Verde River forms a fluvial/riparian connection through the Salt-Gila River system with the north-flowing San Pedro River in southern Arizona. This Verde-Salt-Gila-San Pedro River alignment forms a lengthy N-S axis through Arizona that reaches nearly to Mexico and drains the sky islands ranges of southeastern Arizona. Such an alignment may help account for the strong neotropical affinity of the Verde basin's Odonata (dragonflies and damselflies), aquatic Hemiptera (true bugs), and its butterflies and skippers, not to mention the historic presence of mammals, such as coatis, ocelot, and jaguar (Hoffmeister 1986, Stewart et al. 2001, Bailowitz et al. 2007). Although the Verde River has a higher base flow than most other nearby rivers, such as Tonto Creek or the Bill Williams River, it is no more than a middle-sized river for the Southwest. An emerging pattern in fluvial biogeography is that middle stream order rivers tend to have the highest levels of biodiversity. However, likely due to the river's connectivity to other Arizona rivers and its lack of barrier falls, the Verde River mainstream does not, to our knowledge, support unique fish or invertebrate species.

Ecotones are also known to be places where mixing of assemblages creates elevated diversity. The Verde River traverses the geologic province boundary between the Colorado Plateau division of the Rocky Mountain province and the Basin and Range province. The Verde River drainage captures flow from near the Aubry Cliffs and the area west of the San Francisco Peaks, as well as a large portion flow from of the Mogollon Rim. The Verde River is the only Arizona river that bridges two geologic provinces. Only the Colorado River also accomplishes this transition, albeit at an interstate-scale (we discount as artificial the diversion of the East Fork of the Sevier River south of Bryce Canyon National Park into the Paria River basin). This southern Colorado Plateau-Transition Valley connectivity and associated ecotones also is a source of diversity for the Verde River system.

Another factor strongly contributing to the Verde River basin's elevated biodiversity is the large number of springs in the basin. These springs vary tremendously in water quality, including cold, shallow-aquifer, high water quality springs (e.g., Peiper Hatchery Springs in the northeast portion of the drainage) to warm, heavily mineralized springs, such as Montezuma Well near McGuireville. Some springs host rare or endemic taxa, including: damselflies (e.g., Coenagrionidae: *Argia oenea*) at Russell Springs; *Pyrgulopsis* (Hydrobiidae) springsnails at Page and Poison Springs and Montezuma Well; a unique amphipod (Gammaridae: *Hyallela montezuma*), a water scorpion (Nepidae: *Ranatra montezuma*) and a leech (*Motobdella montezuma*) at Montezuma Well (Blinn and Davies 1990, Dehdashti and Blinn 1991, Runck and Blinn 1992, Stevens and Omana 2007). Montezuma Well, a limnocrene carbonate mound spring tributary to Wet Beaver Creek, appears to support the highest diversity of endemic species of any spot in North America (Stevens and Meretsky in press). This is likely due to the Well's long-term ecological constancy, year-round warm and highly mineralized water quality, and perhaps the naturally high concentration of arsenic in its waters. Overall, the unique geochemistry and isolation of the Verde River's many tributary springs contributes substantially to its elevated biodiversity.

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Chapter 6. Workshop Results: Steps Toward Understanding Ecological Response to Hydrologic Variation in the Verde River

Dale S. Turner and Jeanmarie A. Haney

Growing demands on groundwater resources in the Verde River watershed may have significant effects on base flow in the river, and surface-water diversions have already changed the conditions of some reaches (Springer and Haney, this volume). At the same time, annual precipitation has been reduced during the recent drought cycle and forecasts of climate change suggest that precipitation in the near future will be substantially less than historic averages (Seager et al. 2007). Water managers in the Verde River watershed are increasingly challenged to provide reliable and affordable water supplies to a growing population. Yet there is a societal expectation that perennial flows in the Verde River will be maintained, along with the associated riverine ecosystem. The collaborating partners in this study seek to understand both the hydrologic processes in the system and the ecological consequences of potential changes in Verde River flow.

Sustaining vibrant human communities and a healthy freshwater ecosystem requires that adequate water be maintained in the ecosystem while also accommodating human uses of water. The act of explicitly managing water flows through ecosystems is referred to as “environmental flows,” i.e., allowing an appropriate volume and timing of water flows to remain in an ecosystem to sustain key environmental processes and ecological health and to support the livelihoods of communities dependent on freshwater ecosystem services. The process for developing environmental flow recommendations is collaborative, science-based, and iterative, utilizing the best available science and expert input (Richter et al. 2006). Environmental flow recommendations have been developed for the Bill Williams River in Arizona and at locations around the globe, including Florida, Australia, and South Africa (Arthington and Pusey 2003, Gore et al. 2002, King 2003, Richter et al. 2006, Shafroth and Beauchamp 2006,). Because the protection of environmental flows entails trade-offs with other potential uses of water, it is very important that the water needs of a river ecosystem be defined using current, best-available scientific information and knowledge.

Ecosystem responses to flow regimes are complex, especially in the Southwest where rivers exhibit a large degree of variability. The flow requirements for some species and communities have been subjects of intense study and are fairly well understood, while the details remain unknown for others. These challenges can be addressed through an iterative process of describing relationships between streamflow changes and the responses of aquatic and riparian species. Although significant work remains to make detailed predictions about the full range of impacts from potential flow alterations, we have sufficient information to detect trends and to identify the additional research needed to develop higher levels of detail. Our understanding can be refined by developing a set of expert-derived hypotheses in the form of flow-ecology response curves, testing the hypotheses using existing data, and then refining the curves as needed with additional monitoring data.

The Verde River Ecological Flows workshop was conducted as an initial step in this process. Because data are not yet sufficient to quantify many of the flow-ecology response relationships and thresholds, the workshop setting was used to develop initial hypotheses on the general nature of the relationships and direction of expected change based on potential flow alteration scenarios. An important outcome of the workshop was the identification by the experts present of data gaps and priority research needs.

Participants in the Verde River Ecological Flows workshop discuss their findings.

Numerous studies of hydrologic, biological, and ecological conditions have been conducted in the Verde River watershed, but this report constitutes the first attempt to systematically address the flow-ecology response functions for a full range of key ecosystem components.

Flow-Ecology Response Curves

Flow-ecology response curves describe the relationship between hydrologic variability and ecological response (e.g., change in a species' population). The main objective in developing these relationships is to capture a "mechanistic" or process-based relationship between some component(s) of the hydrograph and one or more ecological response variables. Ideal ecological response variables are sensitive to existing or potential future flow alterations, can be validated with monitoring data, and are valued by society.

The first step in building flow-ecology response curves is to develop a set of hypotheses that describe presumed general relationships between alterations in the particular flow variables (e.g., reduced duration of low flows) and their ecological responses (e.g., decreased richness in aquatic invertebrate species). By going through the exercise of formulating mechanistic hypotheses, scientists developing the flow-ecology response curves explicitly state their understanding or assumptions about the influence of specific kinds of flow alteration on particular ecological processes and condition.

Development of flow-ecology response curves in an experts' workshop provides the platform for a great deal of synergy among experts in distilling various complex relationships into concise hypotheses. The curves provide a visual representation of what is understood and what data are still lacking. Hence, the curves are an important tool for developing a prioritized research agenda. Following the workshop, as the high priority research identified by workshop participants begins producing data, curves can be validated or rejected, refined, and further attributed with quantitative data.

For certain elements of the ecosystem, such as cottonwood trees, there are considerable data linking recruitment, sapling survival, and growth to streamflows and groundwater levels. Other elements of the ecosystem, such as fish, have more complex responses and thus are more difficult to quantify. However, for even the most complex organisms, certain aspects of the life cycle are known and can be documented with respect to flows. The long-term goal of the flow-ecology study is to develop quantitative flow-ecology (i.e. stressor-response) models linking flow alteration to ecological response on the Verde River and eventually throughout the watershed.

Methods

To better understand the relationships between water flows in the Verde River and the ecosystem it supports, the Arizona Water Institute, The Nature Conservancy, and the Verde River Basin Partnership convened a workshop of experts on May 23-24, 2007. Attendees included 35 people from 15 organizations, with expertise that included hydrology, geomorphology, riparian ecology, ichthyology, ornithology, mammalogy, herpetology, entomology, and water quality (Appendix 1). Prior to the event, all attendees received a draft background report that summarized current knowledge of the system; a revised version of that report is included here as chapters 2-5.

Workshop Format

The workshop had three primary goals:

1. To identify streamflow conditions that are necessary to support viable populations of native species, and to make predictions of the ecological effects on those species that can be expected from hypothetical changes in streamflow;
2. To build on the scientific understanding that is summarized in the background report, integrating the knowledge and data of scientists in the physical and biological disciplines to develop a comprehensive understanding of the Verde River ecosystem; and
3. To identify key information gaps in our understanding of the ecosystem.

The geographic scope of the workshop was constrained, with discussions focusing on the main stem of the Verde River from its headwaters through the Verde Valley. This aligns with the Verde River Basin Partnership's guidance under Public Law 109-110, Title II.

The workshop was facilitated by Brian Richter and Andy Warner from The Nature Conservancy's Global Freshwater Team who have facilitated similar workshops around the nation and globally. The workshop began with a plenary session in which workshop goals and approach were described, questions addressed and input acquired, and each lead author of the background report gave a presentation. Participants were then divided into two workgroups according to their specialties, and tasked with describing effects of various flow regimes on key animal and plant species. Experts on riparian vegetation and birds worked in one group, with experts on aquatic species in the other, with the hydrology/geomorphology experts divided between the two groups. The framework for discussions was to develop ecological models showing the response of various species or taxonomic groups to changing flow conditions.

After initial identification of flow-ecological response models, participants reconvened in plenary session and focused on two geographically-broad reaches of the river: the canyon-bound reach from above the Clarkdale gage, and the Verde Valley from Clarkdale gage to the Camp Verde gage (Figure 2-1). Flow-ecology response curves were used in combination with selected river channel cross-sections in an attempt to visualize and discuss how reductions in base flow might be expected to change physical conditions and hence how flow-dependent plants and wildlife might respond. The task was to refine the response curves for each reach and describe species and community changes that could be expected under several flow scenarios. This approach recognizes the distinct hydrogeology of and human influences on each of these reaches, allows the use of historic flow data in developing predictive scenarios, and will allow better approximation of ecological thresholds.

Hypothetical Flow Scenarios

Flow scenarios (Box 6-1) were developed for comparison purposes only, and are not meant to be predictive of actual future conditions. Considerable data collection and hydrologic modeling is required before reliable predictions of future conditions can be made. The scenarios were generated in an attempt to qualitatively compare water level elevations, and thus habitat conditions, at different base flow conditions. Although not predictive, we believe the scenarios are within the bounds of possible future conditions.

The scenarios assume that the chief flow alteration would be due to "capture" of base flow by groundwater pumping in the Big Chino and Little Chino Valleys and in the Verde Valley. Loss of base flow due to irrigation diversions in the Verde Valley was not considered in scenario development, due to the lack of data on consumptive use and return flows. The scenarios are highly simplified and do not include a temporal component. In addition, flow conditions specified at each gage are assumed to apply to the reach downstream to the next gage. In reality, temporal and spatial conditions are more complex.

Scenario 1 assumes capture of half the base flow passing the Paulden gage (i.e., 12 cfs reduction; also applied at the Clarkdale and Camp Verde gages) due to groundwater pumping in the Big and Little Chino Valleys, plus capture of an additional 10,000 acre-feet per year (approximately 14 cfs) of base flow passing the Camp Verde gage due to groundwater pumping in the Verde Valley.

Scenario 2 assumes capture of all base flow passing the Paulden gage (i.e., 24 cfs; also applied at the Clarkdale and Camp Verde gages) due to groundwater pumping in the Big and Little Chino Valleys plus capture of an additional 20,000 acre-feet per year (approximately 28 cfs) of base flow passing the Camp Verde gage due to groundwater pumping in the Verde Valley.

These highly simplified scenarios provided a necessary framework for discussing potential changes to the ecosystem.

Box 6-1. Description of Hypothetical Flow Scenarios

Scenario 1:
50% reduction in base flow at Paulden gage
15% reduction in base flow at the Clarkdale gage
13% reduction in winter base flow at the Camp Verde gage

Scenario 2:
100% reduction in base flow at the Paulden gage
30% reduction in base flow at the Clarkdale gage
25% reduction in winter base flow at the Camp Verde gage

Results

The workshop discussions focused on potential consequences of reductions in the Verde River's base flow. This was based on analyses by USGS personnel and anticipated future pumping volumes (see Chapter 2).

Although natural flood regimes are known to play a critical role in maintenance of healthy riparian vegetation communities, especially for reproduction of cottonwoods and willows (Stromberg, this volume), the workshop participants did not focus on flood-related processes in the Verde. It was assumed that flood regime changes are not likely because no new dams are likely be constructed on the river in the foreseeable future.

There was also a clear recognition that surface-water diversions have substantially altered river flows in portions of the Verde Valley, to the point of removing all flow from short reaches below diversions during the dry season. While this certainly affects the Verde River ecosystem, it was not substantially addressed during this workshop due to lack of information about water withdrawals and return flows, including volume, location, and timing. Other information needs include direct and incidental ecological effects, both positive and negative, in the river and along the diversion ditch networks. Filling these information gaps was seen as critical to describing ecosystem flow needs for the Verde Valley.

Table 6-1. Flow-ecology relationships used for developing response curves.

Hydrologic Variable	Ecological Variable	Species
Depth to water table	Heath/vigor of:	Cottonwood – saplings
		Cottonwood – mature trees
		Mesquite bosque
		Tamarisk
		Beaver reproduction
		Coopers hawk, black hawk, heron rookery, kingfisher, bald eagle
Depth to water table	Relative abundance of:	Goodding willow (within early seral cottonwood/willow stands: less than 5 years since establishment)
		Insectivorous bird community
Depth to water table (dry season)	Areal extent of:	Sedge marsh
		Cattail marsh
Number of no-flow days per year	Abundance/diversity of:	Aquatic invertebrates
Percent of average historic base flow	Population size of:	Speckled dace
		Roundtail chub
		Sonora sucker
		Narrow-headed gartersnake
		Mexican gartersnake
	Recruitment of:	Larval and juvenile spikedace
	Response of:	Fish species biomass
		Fish species diversity
	Predation of:	Lowland leopard frogs
Magnitude of spring flood	Spawning success of:	Native fish

Workshop participants identified a set of key relationships that could be displayed as flow-ecology response curves (Table 6-1). Although these relationships do not represent the full range of flow-ecology relationships, they were selected in open discussion by workshop participants, and hence are representative of relationships deemed most critical by the participants. Some of the flow-ecology response curves indicate threshold relationships where we can expect a part of the biological community to decline rapidly once some environmental condition has reached a certain level. When refined with adequate data, they may provide warning signs in advance of species decline or loss from the river system.

Riparian vegetation

As described by Stromberg (this volume), there exists a strong body of literature on relationships between riparian plants, streamflow, and groundwater. Most of that was derived from the San Pedro River system, though some focused on the Verde, Bill Williams, and other southwestern rivers. While many specific questions remain, the over-arching hypothesis to be tested is that the relationships found elsewhere are the same as those in the Verde. The patterns are likely similar, but specific values may differ.

A key relationship is between the abundance of Fremont cottonwood, Goodding willow, mesquite, and tamarisk and the depth to groundwater (Figures 4-2, 6-1, 6-2). Cottonwood and willow trees are obligate phreatophytes (Chapter 4), relying on groundwater as their primary water source. Because the fine roots of cottonwood and willow trees are concentrated in the capillary fringe, just above the water table, these species are sensitive to fluctuation in water table depth, particularly in coarser soils with a narrower capillary fringe. Declines of 1 meter (summer season) have caused mortality of cottonwood and willow saplings

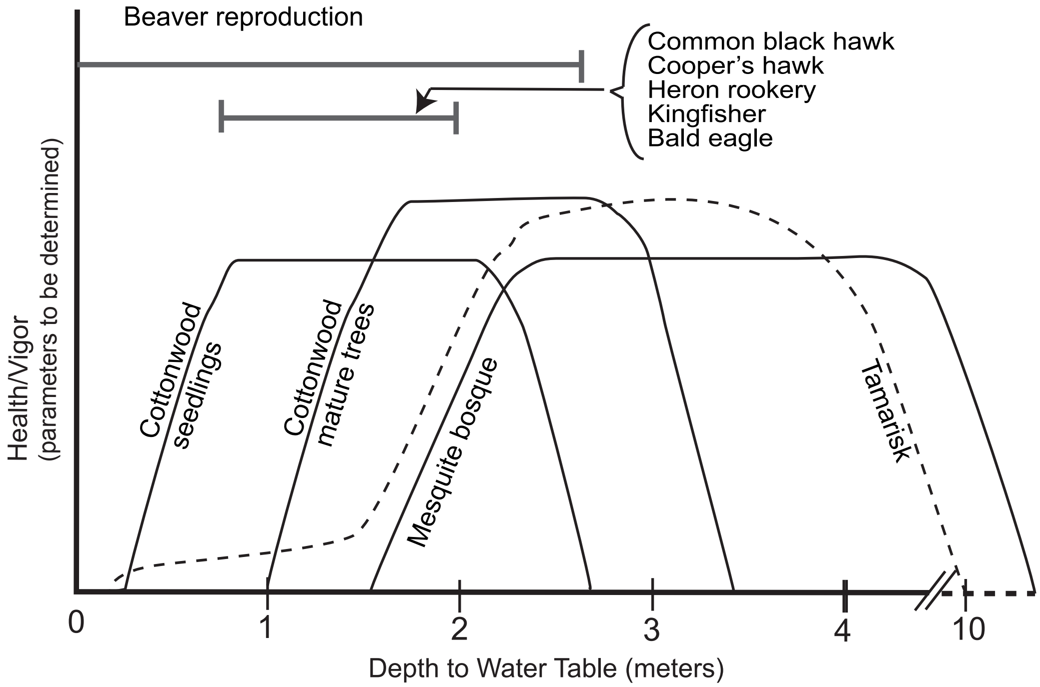

Figure 6-1. Hypothetical response of several woody species and associated wildlife to groundwater depth. Cottonwood seedlings need shallower depth to water during their recruitment year, and are also affected by the rate of water table decline. Woody species curves based on data from Leenhouts et al. (2006).

(Shafroth et al. 2000). Mature cottonwood trees have been killed by abrupt, permanent drops in the water table of 1 meter, with lesser declines (0.5 m) reducing stem growth (Scott et al. 1999, 2000). Tamarisk, on the other hand, is a deep-rooted facultative phreatophyte (Chapter 4) that can switch between water sources (e.g. from groundwater and rainfall soil water), giving them a higher tolerance to water stress.

The differing depth-to-water tolerances (Figures 6-1 and 6-2) exhibited by cottonwood, willow, and tamarisk leads to dominance of one species over another across the floodplain according to the height of different geomorphic surfaces above the groundwater. Similar replacement can take place over time at a given site with a rising or falling water table (Figure 4-5). Data from the San Pedro River show a shifting pattern of dominance from cottonwood/willow to tamarisk along reduced water-availability gradients, i.e. from perennial to intermittent to ephemeral reaches. The hydrologic variables most closely correlated with increasing tamarisk were streamflow permanence, depth to groundwater, and annual groundwater level fluctuation (Leenhouts et al. 2006). Overall, forests of cottonwood and willow were dense and multi-aged among sites where annual maximum groundwater depths averaged less than about 3 m, where streamflow permanence was greater than about 60 percent, and intra-annual groundwater fluctuation was less than about 1 m (Leenhouts et al. 2006).

The transferability from the San Pedro River to other southwestern streams of the quantified relationships among hydrologic variables and vegetation metrics needs to be tested by researchers. Another important information need is to determine the relationship between surface-water discharge and groundwater elevation (stage-discharge relations), i.e. how does groundwater elevation change with variation in surface-water elevation.

Examination of several cross-section graphs suggest that reductions in base flow would affect cottonwood-willow trees differently, depending on life stage. In the case of a partial decrease in flow (Scenario 1; Box 6-1), the cottonwood seedling recruitment zone would narrow, responding to the

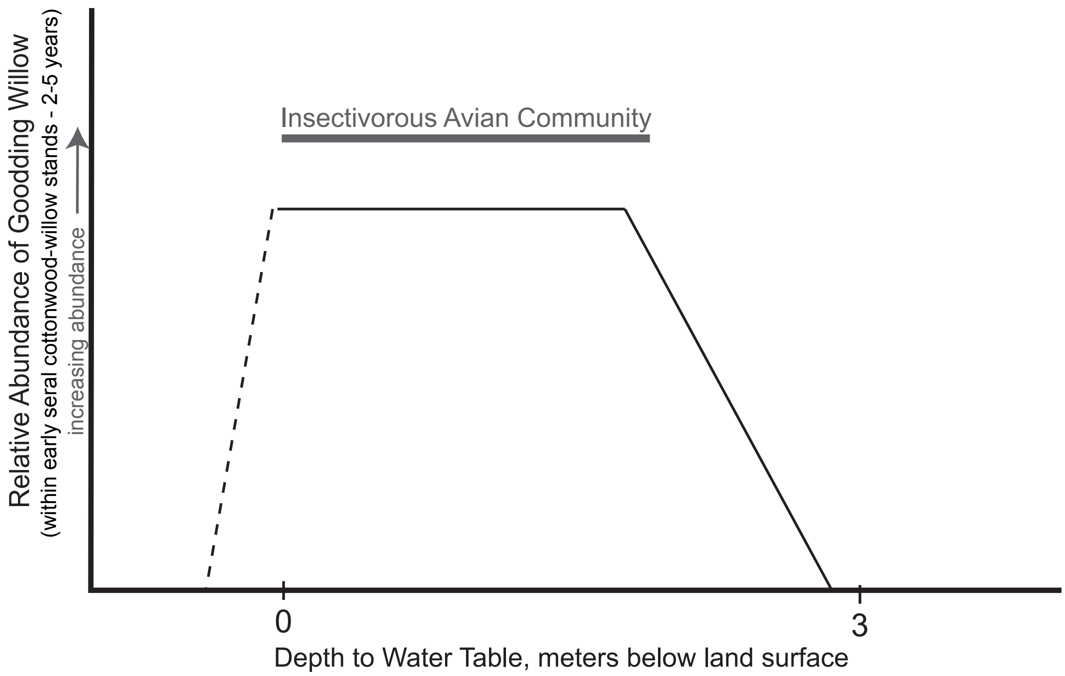

Figure 6-2. Hypothetical response of Goodding willow to groundwater depth. Left side of graph extends beyond zero because willow can tolerate shallow standing water above ground. Willow curve based on data from Leenhouts et al. (2006). Avian bar based primarily on needs of Southwestern willow flycatcher (Paradzick 2005).

narrower zone of permanent water, and recruitment would likely decline because groundwater depth would drop too low for survival across much of the floodplain. These responses would be exacerbated by a larger decrease in flow (Scenario 2; Box 6-1). Cottonwood saplings would not likely be affected by a partial drop in flow (Scenario 1; Box 6-1), but would decline with a greater drop (Scenario 2; box 6-1). Mature cottonwoods would likely not be affected by Scenario 1 because the expected drop in groundwater depth would stay within their root zone. Even with Scenario 2, mature cottonwood trees would likely persist, depending on their location on the floodplain, but might show some water stress by die-back or reduced growth rates. Existing stands of Goodding willow would probably not be lost due to small declines in base flow, but likely would decline with Scenario 2. A long-term effect would likely be smaller areas of cottonwood groves due to the shifting of suitable locations for establishment to lower geomorphic surfaces which are narrower and subjected to greater risk of flood scour. Tamarisk would likely increase, relative to cottonwood and willow, from a declining water table, especially with a larger drop in groundwater (Scenario 2).

Marshland plants are highly sensitive to declines in water level, as they depend on a range from shallow standing water to a shallow depth to groundwater. Cattail and sedges are among those, with water constraints that barely overlap (Figure 6-3). For most marsh communities along the Verde, a large decline in base flow (Scenario 2) would likely lower the water level in the floodplain alluvial aquifer, thus reducing the area of marsh and shifting the dominant species from aquatic emergent species such as cattail, rush, and bulrush, to saturated-soil species such as horsetail and ultimately to mesic herbaceous plants like Bermuda grass. The likely exception is the largest, Tavasci Marsh, which receives both surface-water diversions and groundwater contributions, and thus has water levels that are probably not sensitive to changes in base flow of the river. The sensitivity of these plants to seasonal water depth was discussed, but was not sufficiently understood to develop response curves.

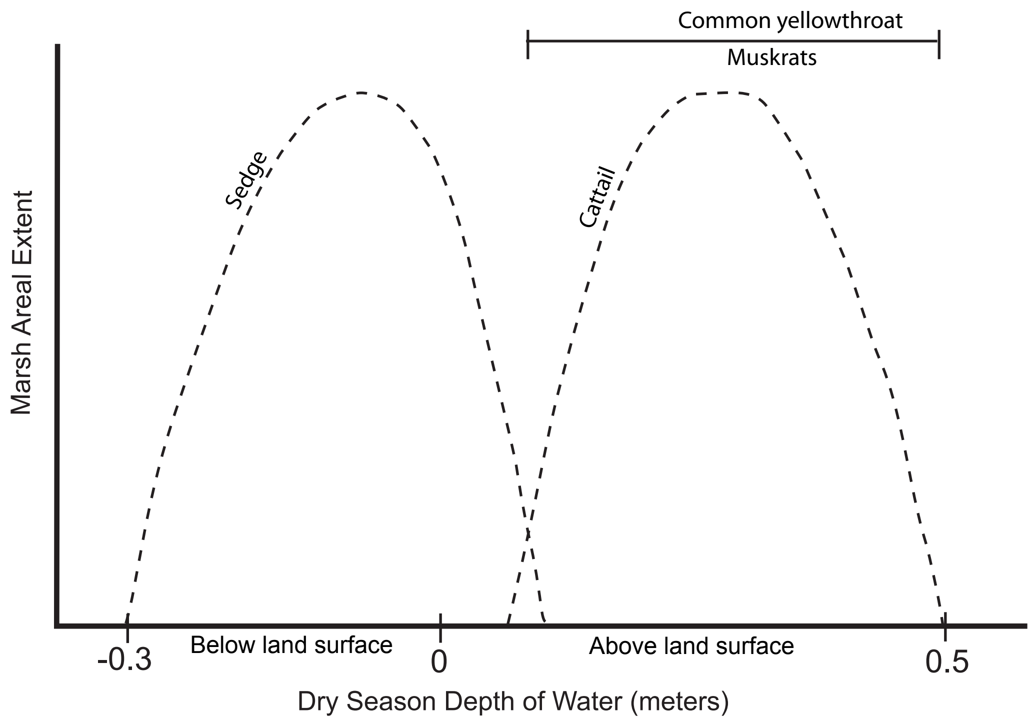

Figure 6-3. Hypothetical responses of sedge and cattail to depth of water during the dry season. There is a suspected competitive interaction between these species where cattail excludes sedge when they co-occur. The curves represent separate responses without the interaction.

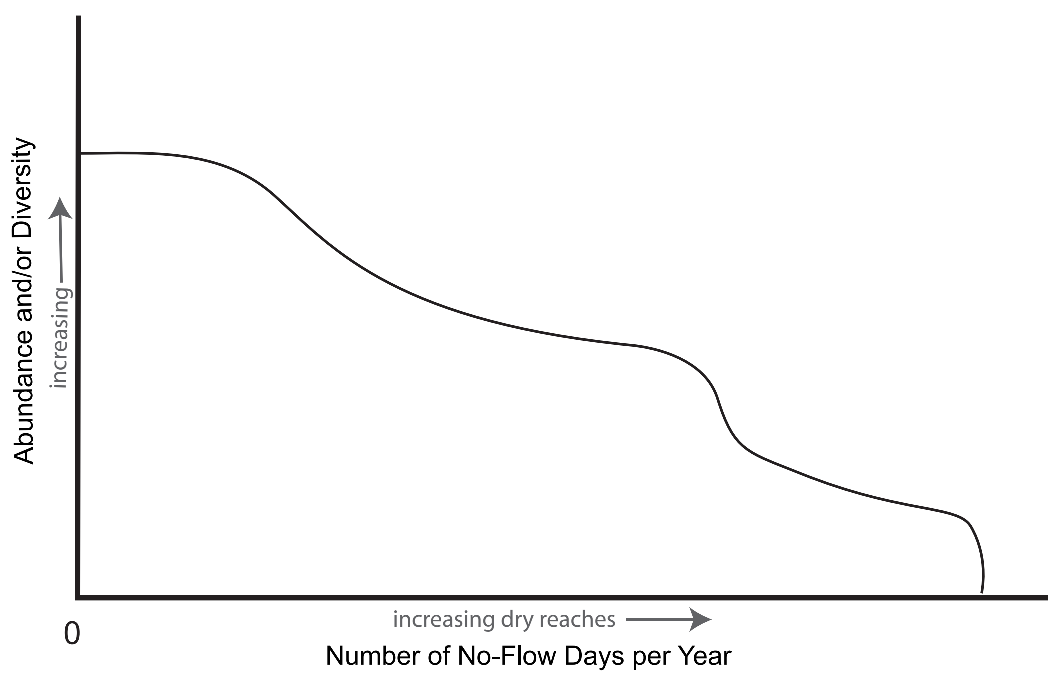

Figure 6-4. Hypothetical response of aquatic invertebrates in the hyporheic zone to changing number of no-flow days.

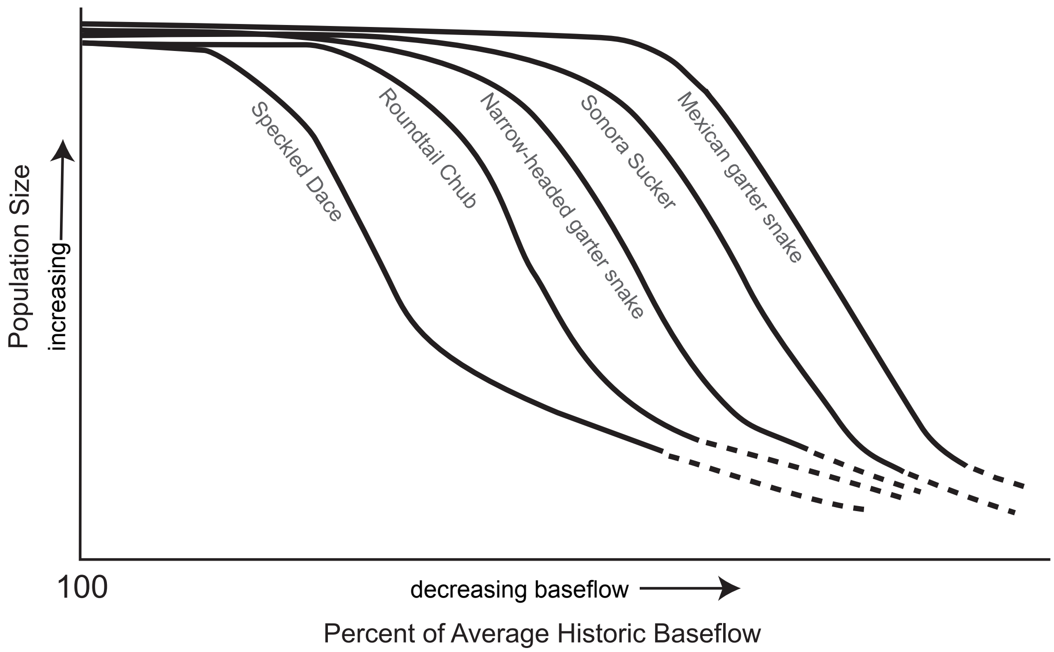

Figure 6-5. Hypothetical response of several vertebrate species to changes in base flow. Dashed lines indicate increased uncertainty. Curves for the snake species apply to different river reaches, with Mexican gartersnakes persisting in the Verde Valley and Narrow-headed gartersnakes possibly remaining in the upper Verde.

<u>Invertebrates</u>

The abundance, diversity, and primary productivity of invertebrates living in the hyporheic zone will likely decline if there is an increase in the number of days without surface flow. Participants attributed the expected decline to increased cementation of the stream bed, increased algae growth, and ultimately, dewatering of the zone (Figure 6-4). On a broader scale, similar responses could be expected with reduced river length that has perennial flow.

<u>Fish</u>

Riffle habitat is particularly sensitive to reductions in base flow. As described in the scientific literature (e.g. Rinne 1991, Propst et al. 1986), some fish species are habitat specialists, depending on riffles for spawning, feeding, and protection from predators (Table 5-3). Population size for these fish species would be expected to decrease with decreased base flow. This would affect Speckled dace first, followed closely by Roundtail chub and eventually by Sonora sucker (Figure 6-5). Partial reduction in Verde base flow (Scenario 1) would likely have negative effects, and major reduction (Scenario 2) would have greater effects. To quantify these effects, additional information is needed relating to stage-discharge and extent of riffle and other macro-habitat.

Spikedace recruitment may be affected by declines in base flow, because their fry and juveniles depend on the sheer zones between riffles and runs (Figure 6-6). However, nonnative fish seem to be the factor currently limiting spikedace success, and the nonnative population levels appear to be strongly affected by the frequency of flooding (Minckley and Meffe 1987, Rinne 2005). Magnitude of the spring flood peak is also important to spawning success and fry survival for many other native fish species (Figure 6-7). Thus maintaining the natural flood regime is critical for maintaining native fish diversity.

Reduced base flow would affect fish species diversity sooner than fish biomass (Figure 6-8). Several small fish species - riffle habitat specialists as described above - are likely to be lost first, as the few large species (with much greater biomass) can persist in pools.

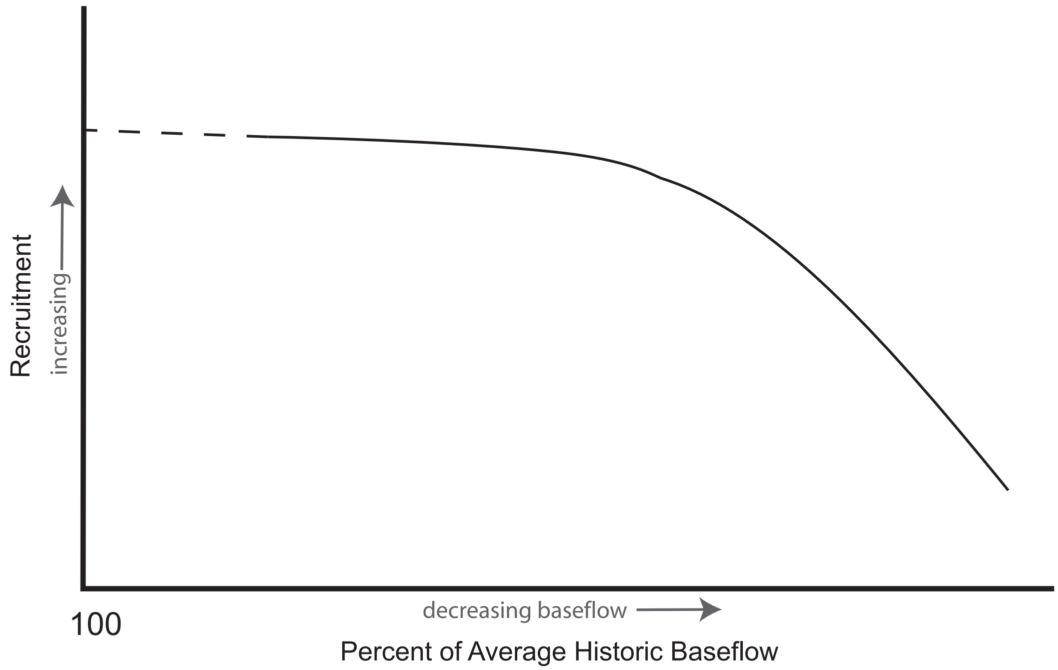

Figure 6-6. Hypothetical response of larval and juvenile spikedace to changes in base flow.

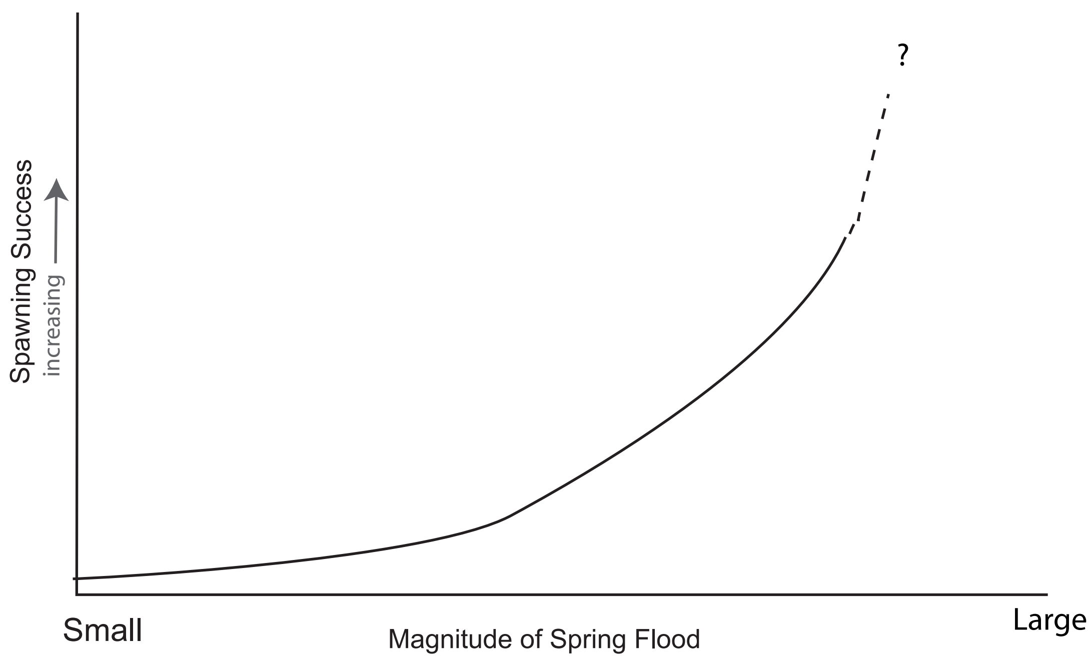

Figure 6-7. Hypothetical response of native fish spawning success to magnitude of spring flooding. Flooding depletes populations of predatory nonnative fish, which results in greater success for the native species.

Several other stream conditions important to fish will likely change with reductions in base flow. As flow rates decrease, water temperatures increase, algae multiply, and dissolved oxygen levels decline which can lead to fish mortality. Fish also get more crowded as the physical area of aquatic habitat is reduced, leading to increased predation, increased competition, and higher incidence of disease. With short-term reduced flow, longer-lived natives such as Sonora sucker and to a degree Roundtail Chub are better able to withstand it due to their longevity. Short-lived natives such as Speckled Dace

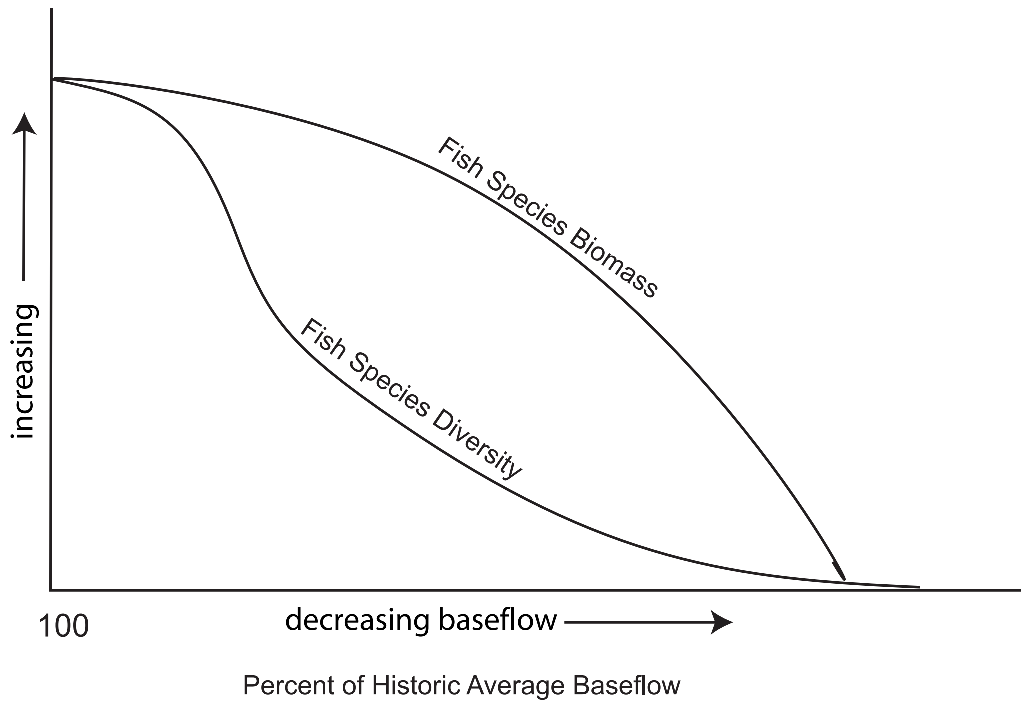

Figure 6-8. Hypothetical response of fish species richness and biomass to changes in base flow.

and Spikedace are not. Longer or permanent flow reductions will reduce all natives in the presence of predatory nonnative species. Natives are well equipped to withstand extended periods of low flow, but cannot compete long-term with nonnatives.

Reduced base flow would also work against the Verde River's value as a sport fishery. With extreme low flows, sport fish would suffer the same high temperature/low oxygen problems as the natives. But well before that, rainbow trout would likely disappear and smallmouth bass could be expected to overrun most other species with high numbers of sexually mature small (stunted) individuals. Water clarity also declines with reduced flow, which would affect bass feeding and catchability to anglers.

Amphibians

Lowland leopard frogs use a variety of aquatic and stream-side habitats, but several flow-related needs were identified. Thick cattail growth is not favorable habitat, so occasional floods form a useful disturbance. Pools or slow-moving runs are important for egg deposition, and provide over-wintering sites when they are deep enough to prevent freezing of the bottom sediments.

Reductions in base flow would concentrate aquatic predators in pools, while also exposing frogs to increased predation in the longer distances between pools. Thus a variable response would be increased loss to predation with decreased base flow (Figure 6-9). The response curve would likely be shaped by two inflection points: the flow level at which riffle size decreases, and at which riffles no longer function as escape routes. Partial reduction in Verde base flow (Scenario 1) would likely have negative effects, and major reduction (Scenario 2) would be worse.

Reptiles

Narrow-headed gartersnakes depend primarily on native fish for their diet, which they typically hunt in riffles or deeper pools. As riffle area decreases, narrow-headed gartersnakes may initially benefit due to the increased concentration of the prey species and the reduced escape routes (riffles) available to small-bodied fish. Eventually, reductions in fish populations would affect the snakes (Figure 6-5)(Nowak 2006).

Mexican gartersnakes depend on both native and non-native fish and frogs for their diet,

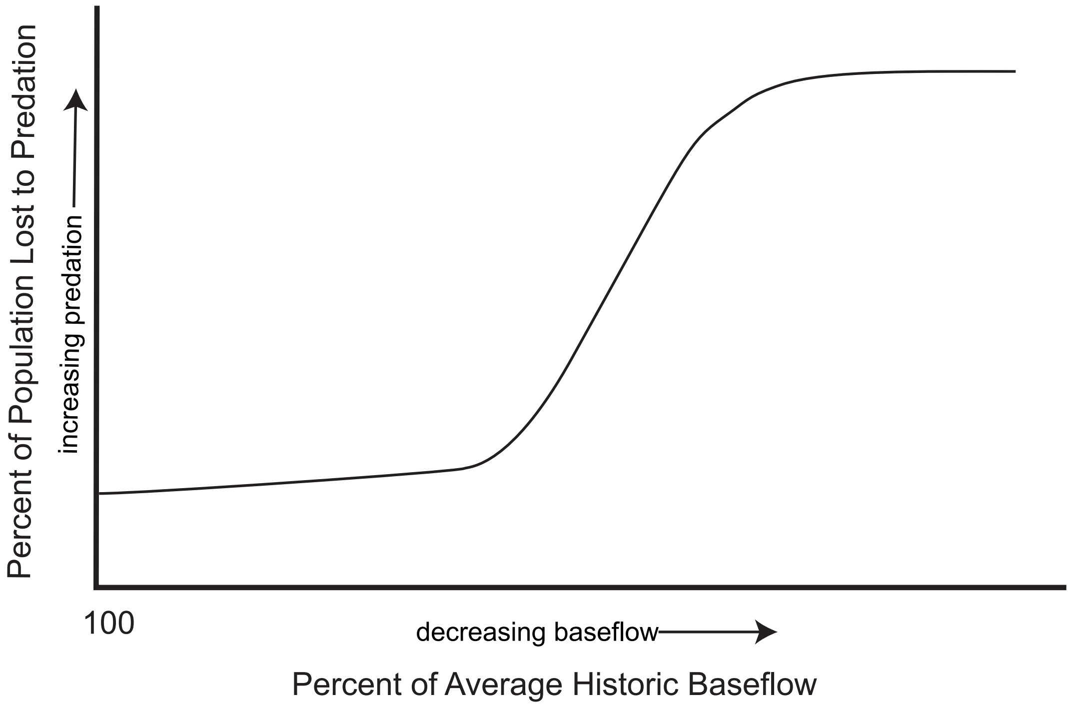

Figure 6-9. Hypothetical response of lowland leopard frog predation losses to changes in base flow.

and prefer shallow, marshy habitat for hunting. As marsh habitat decreases, they may have the ability to shift to deeper pool habitat for hunting. Due to their likely ability to switch between prey species and hunting habitats, they may be less affected by water drawdown than narrow-headed gartersnakes, and are likely to persist in low numbers until prey populations are gone (Holycross et al. 2006).

Both species will be more vulnerable to terrestrial avian and mammalian predators if in-stream and marsh vegetative cover decreases. Young snakes would be especially vulnerable to concentrations of predatory fish and large crayfish in pools.

Birds

Several large bird species are closely associated with cottonwood groves for portions of their life cycle, and their success may vary with that of the trees. These include common black hawk, Cooper's hawk, great blue heron, kingfisher, and bald eagle (Figure 6-1).

The Verde River ecosystem includes insectivorous bird species, such as several flycatchers and the Yellow warbler, which make significant use of Goodding willow stands. Major reductions in river base flow (Scenario 2), would likely reduce the relative abundance of willow, possibly leading to declines in the abundance of these birds (Figure 6-2).

Some birds such as common yellow-throat warbler, Virginia rail, Sora, and Least bittern, are closely associated with cattail marshes, and thus may be negatively affected if water levels drop enough to change the marshland communities (Figure 6-3).

Mammals

Beaver prefer cottonwood saplings as a food source, so their population success may be related to conditions that support cottonwood recruitment. That includes both regular spring flooding, to allow seedling establishment, and a shallow water table (Figure 6-1).

Muskrats are closely linked to marshland communities, using cattails for cover and food.

Table 6-2. Expected effects of two flow scenarios in two river reaches. Scenario details are provided in Box 6-1. Some species were considered for the scenarios of only one reach. Values range from extremely positive effect (++) through positive (+), neutral (0), and negative (-), to extremely negative (- -). Mixed effects (depending on other factors) or effects with uncertain magnitude are given two values.

	Canyon Reach		Valley Reach	
Species or Community	**Scenario 1**	**Scenario 2**	**Scenario 1**	**Scenario 2**
Marshland	+ / -	- -	0	-
Cottonwood seedling	-	- -	-	-
Cottonwood sapling	0 / -	-	0	-
Cottonwood mature	0	0	0	-
Goodding's willow sapling	0	-	0	-
Mesquite bosque	0	+	0	0
Tamarisk	0 / +	+	+	+ +
River otter	-	- -	0 / -	-
Beaver	0	- / - -		
Muskrat	0	- / - -		
Lowland leopard frog	-	- -	-	- -
Spikedace	-	- -	-	- -
Speckled dace	-	- -	-	- -
Desert sucker	0	- -	0	-
Roundtail chub	-	- -	-	-
Sonoran sucker	-	- -	0	-
Narrow-headed gartersnake	-	-		
Mexican gartersnake			0 / -	-
Invertebrates	0	-	0	-
Southwestern willow flycatcher	-	-	0 / -	-
Warblers	-	-	0	-
Bald eagle			0	0 / -
Fish eating birds			0	0 / -

Thus they can be expected to suffer declines with a significant drop in base flow which would cause declines in cattails (Figure 6-3).

Reach-specific effects

The workshop participants identified likely effects on particular flow-dependent species within two broadly defined geographic reaches, based on the two flow scenarios (Box 6-1) and a series of river channel cross-sections. Results are summarized as "scorecards" for each reach (Table 6-2) and reflect the collective input from the assembled experts. The "canyon" reach is generally delineated as the canyon-bound reach above Clarkdale and the "valley" reach as the Verde Valley. These reaches were selected due to the obvious differences in geomorphology, and thus ecological response to flow variation. Further reach delineation could be justified, given the Verde River's hydrologic and geomorphic variability; however, these two broad reaches were deemed sufficient delineation for the workshop purposes.

These "scorecards" serve to identify only general trends, from very positive (+ +) to neutral (0) to very negative (- -), and thus integrate a broader range of information than the flow-response curves. As discussed in Chapter 2, the river has a fairly constant base flow from the headwater springs to near Perkinsville. Downstream from Perkinsville, and through the Verde Valley, the river naturally gains base flow. Each major tributary contributes additional base flow. Thus, removing the same amount of base flow from each reach results in a greater percentage of water lost in the upper canyon reach than in the valley reach. Thus, results suggest that ecological impacts would be greater in the canyon reach than in the valley reach (Table 6-2). Also, because a larger volume of water is removed in Scenario 2 than in Scenario 1, impacts would be greater under Scenario 2 than Scenario 1.

Information needs

A major emphasis of the Verde River Ecological Flows workshop was identification of critical gaps in our knowledge, and development of a prioritized research agenda to fill those gaps. Participants shared an understanding that the flow-response curves developed by the group represent hypotheses that need to be tested with careful studies.

Recognizing the need for a coordinated approach, participants worked to outline a systematic, landscape-scale framework under which individual studies could be conducted in a coordinated, sequential manner. Such an approach would maximize the synergy among studies, researchers, and disciplines. No attempt was made to identify who would take responsibility for particular research projects, since that will be subject to interest, ability, and funding, but there was recognition that a shared research agenda and coordination among studies would lead to more useful outcomes, greater efficiency, and increased funding opportunities.

The framework recognizes that rivers are integrators, both across large expanses of geography and research disciplines. The framework also recognizes that the physical processes in large part drive the biological processes; thus, a well-grounded characterization of the physical system is the platform upon which biological studies can best be integrated. Although the focus here is on the river itself - how the riverine ecosystem responds to hydrologic variation and where response thresholds may exist – it is recognized that many factors, both proximal and distal, impact riverine ecosystems and watershed biodiversity. For ease of presentation, the research platform is divided into three tasks – additional background synthesis, physical characterization, and biological characterization; however, workshop participants recommended that research be integrated across disciplines and across spatial and temporal scales, and data be made publicly available in a reasonable amount of time.

Research Platform

<u>Task A. Develop Background Information</u>

1. Inventory existing data. While the effort reported in this volume included a compilation of published literature on the region, workshop participants knew of additional data sets, both physical and biological, that might be useful. These include extensive research by the US Forest Service Rocky Mountain Research Station, a possible Arizona Department of Environmental Quality database of aquatic invertebrate sampling, and vegetation data associated with early bird studies (e.g., Carothers et al. 1974).

2. Synthesize flow ecology literature. Conduct and synthesize results of an expanded search of flow ecology literature. This would allow learning from similar river systems elsewhere. A potential source is ecological models developed for the Lower Colorado River Multiple Species Habitat Conservation Plan.

3. Develop an information management system. This would include spatial information (Geographic Information System) and ecological flow information.

<u>Task B. Develop the Physical Characterization Platform</u>

1. Develop a river topographic and cross-section database. Conduct a LIDAR survey of topography and vegetation for the river corridor. Compile and evaluate existing river cross-section location and topography data.

2. Delineate river reaches and study sites.
Divide the river's length into reaches with similar characteristics, utilizing aerial photos and all available river cross-sections. Representative study units would be chosen within each reach, meant to become the locus of more detailed physical and ecological studies.

a) Analyze aerial photos followed by field reconnaissance to determine appropriate sites for new cross-sections.
b) Survey river cross-sections, including some that span the entire flood plain. Establish permanent markers for these cross sections and locate with accurate GPS. This would improve understanding of potential changes in aquatic habitat due to changing base flow. It would also allow better predictions of flood effects on downstream human structures.
c) Characterize flow regime at each cross-section location on a seasonal basis.
d) Develop stage/discharge relationships at cross-sections. This would allow understanding of how a specified drop in flow would affect the water surface elevation. This provides information about the area and character of aquatic habitat available, and allows inferences about depth to groundwater, which affects riparian vegetation.
e) Characterize sediment transport and bed and bank material. This would inform habitat analysis for native fish.
f) Install piezometers (water-level observation wells) and instrument some with continuous loggers. This would clarify relationships between groundwater and surface water, and inform the vegetation sampling. It would also clarify how seepage from irrigation ditches affects groundwater levels and the riparian plant community.
g) Conduct aquifer tests to obtain the hydrologic properties of the alluvial sediments.
h) Characterize the depth and width of alluvial sediments. This would improve understanding of the volume and distribution of groundwater.
i) Conduct repeat cross-section surveys over time. Scheduling for this could be both periodic and event-based (e.g. after big flood events). This would allow identification of major changes in the stream channel.

3. Characterize hydrologic elements of the irrigation ditch system.

a) Quantify flow rate for each ditch by month or season.
b) Identify locations and volumes of return flow.

<u>Task C. Develop the Biological Characterization Platform</u>
Biological research needs are extensive; tasks are listed below in roughly prioritized order. The order is based on a preferable sequence in the accumulation of related knowledge and urgency for natural resource management decisions.

1. Characterize biological conditions at river cross-section sites.

a) Sample vegetation along the cross-sections, including community attributes (cover, diversity, species composition), age classes of trees, and presence of water infrastructure (e.g., irrigation ditches). This would provide information for refining models of how riparian trees use different geomorphic surfaces and different depths to groundwater. It would also identify ways in which irrigation ditches affect the distribution of riparian vegetation.
b) Characterize macro- and micro-habitat and fish use, with research specifically focused to develop the quantitative information needed to refine flow-ecology response curves developed in the workshop.
c) Determine the influence of beaver dams on surface- and groundwater. This would inform use of beaver populations as a management tool.
d) Measure evapotranspiration rates for main riparian vegetation types.
e) Conduct repeat vegetation sampling over

time. Scheduling for this could be both periodic and event-based (e.g. after big flood events). This would allow assessment of recruitment and mortality.

2. **Characterize the status and ecology of sensitive riparian or aquatic wildlife species, with an emphasis on flow-ecology responses.**
   a) Important species for study include Southwestern willow flycatcher, Bald eagle, Yellow-billed cuckoo, Otter, Beaver, Muskrat, bats, Mexican garter snake, Narrow-headed garter snake, and Lowland leopard frog. This includes distribution, population size, habitat use, and response to changes in river flow. This should include refinement of flow ecology-response curves developed in the workshop.
   b) Identify groundwater-dependent riparian plant species. Quantify water sources and rooting depth for perennial plants believed to be obligate phreatophytes and for those believed to be facultative phreatophytes. This should include native and relevant invasive non-native species.
   c) Determine hydrologic thresholds, with respect to mean and maximum water table depth, standing water depth, or surface flow hydroperiod, for maintaining high cover of hydrologically-sensitive plant species including obligate phreatophytes and other wetland plants.
   d) Determine the effect of Otter dietary preferences on fish and crayfish populations.
   e) Develop a complete flora of the Verde River riparian corridor, ideally by river reach and for specialized habitats such as mainstem spring sites.
   f) Conduct a biotic inventory of spring systems. Existing data suggest that springs in the Verde watershed have an unusually high level of endemic species, but most springs have not been carefully studied.
   g) Characterize the composition, distribution, and water needs of riparian grassland communities. This would identify which grasses and forbs are obligate phreatophytes, and how their distribution is affected by water table depth.
   h) Determine the invertebrate productivity by aquatic and terrestrial habitat type, including use of the tree canopy. This has implications for bird diversity and abundance.
   i) Determine whether the Verde River marsh plant communities respond to changing water levels in ways that are similar to those on other rivers.
   j) Identify which plant species are most appropriate for restoring retired agricultural lands in the Verde watershed. This would improve the success of restoration efforts and reduce the spread of undesirable species.

3. **Characterize biological elements and social context of the irrigation ditch system.**
   a. Quantify extent and condition of riparian vegetation supported by ditch seepage.
   b. Characterize social context of irrigation ditch system.

<u>Task D. Scale up from cross-section to river reach</u>

a) Develop reach-wide ET estimates.
b) Develop estimates of changes in areal extent of particular vegetation types.
c) Develop estimates of changes in areal extent of aquatic macro-habitats.
d) Develop system-wide native fish and bird population estimates.
e) Determine role and value to wildlife of poorly-studied tree species, including recently introduced ones such as Tree of Heaven (*Ailanthus altissima*).
f) Determine effects of ditch seepage and irrigation use on riparian vegetation and native fish along the river channel.

Discussion

In developing flow-ecology response curves, there are dozens of hydrologic variables and hundreds of ecological variables that could be selected. The typical approach is to extract ecologically meaningful flow variables from the hydrograph that reflect natural flow variability (Arthington et al. 2006), thus focusing on a limited set of hydrologic parameters that captures ecologically important variability in flow. The hydrologic and ecological variables described above, while not an exhaustive list, were selected in open discussion by the workshop participants as representing some key elements of the ecosystem.

The response curves shown here represent hypotheses about the effects of changing river flow on the habitat required for plants and animals, with resulting effects on those species. These curves are all based on expert knowledge of the species, both through field observations and scientific literature. In some cases, the curves are also based on large bodies of scientific study, generally in other river systems. But in all cases, careful study of the Verde River ecosystem will be required to confirm the hypothesized relationships and to confirm or refine the shape of the curves with quantitative data. Such studies should form a central part of any research program on the Verde River ecosystem, and are incorporated into the Information Needs section above.

Despite those caveats, the overriding sense of these expert discussions was that a reduction in Verde River base flow will, at some point, cause decline or loss of some plant and animal species that depend on the river. That point varies by species and magnitude of flow decline, but can be predicted with reasonable confidence for some, based on existing data. We can say with confidence that populations of most native fish would decline, and with major flow reductions, disappear. Cottonwood and Goodding willow seedling recruitment would decline, and would be subject to greater losses from flood scour, leading to smaller cottonwood/willow groves. They would likely be replaced by expanded tamarisk groves. Birds that depend on cottonwood and willow would have population reductions, as would beaver. Marshland plants such as cattails would have smaller patches or be eliminated from some places, leading to reductions in marshland birds.

The ecological effects of reduced base flow would also differ according to the local hydrologic and geomorphic conditions. The river naturally gains base flow in the downstream direction. Base flow in the upper Verde River is smaller than in the Verde Valley (see Chapter 2), so the same volume of water removed from the river would remove a greater proportion of streamflow in the upper reach than in the Verde Valley. In addition to dependence of surface flow on discharge from the headwater springs, much of the upper reach is contained within narrow bedrock canyons and so has a limited storage capacity for floodwater recharge.

In contrast, the Verde Valley reach has multiple groundwater contributions to its base flow, but surface-water diversions already have strong localized effects. Effects in the Verde Valley are also complicated by alluvial deposits that store and release floodwaters, the locally elevated groundwater due to irrigation, and the multiple points of irrigation return flow entering the river channel. Until more detailed study characterizes the spatial distribution of water and habitat in the Verde Valley, it is difficult to predict how those effects will be exacerbated by reduced base flow.

The Verde River Ecological Flows workshop allowed an interdisciplinary group of experts to test the depths of our knowledge about an ecosystem, and to chart a path toward understanding the key flow-ecology relationships. The information to be gained from the research agenda described here will not, in itself, bring an end to conflicts between the needs of human and natural communities. But its absence will make wise decisions far more difficult as time moves on.

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Chapter 7. Synthesis: Verde River Flows and Ecosystem Water Needs

Jeanmarie A. Haney and Dale S. Turner

The goal of this study was to compile the available scientific data and expert knowledge about the consequences of various water-use scenarios on groundwater levels and Verde River flows; specifically, consequences to the riverine ecological system. Increasing population growth and water demand in the Verde watershed will capture groundwater that would otherwise discharge to the river ecosystem (Blasch et al. 2006), ultimately resulting in decreased base flow. In addition, predictions are for a warmer, drier climate in the Southwest with drought conditions becoming the climate norm (Seager et al. 2007).

The cumulative effects of increasing human water use and decreasing precipitation are bound to mean less water available for riparian and aquatic ecosystems, which suggests several large and difficult questions. Are there thresholds of human-induced hydrologic change, such as an allowable level of streamflow depletion, beyond which unacceptable ecological losses occur? Is it possible to manage water in the Verde River watershed such that human needs are met while also maintaining a healthy Verde River ecosystem?

To address these questions, a team of scientists reviewed and summarized the existing literature on physical and biological components of the Verde River ecosystem, looking primarily at those components that related to perennial streamflow (Chapters 2-5). Building on that foundation, the Verde River Ecological Flows workshop (Chapter 6) brought together experts from many disciplines to identify ecological responses to hydrologic variation through the development of flow-ecology response models. The workshop provided a forum for distilling various complex relationships into concise hypotheses, and for identifying key research needed to test those hypotheses.

The models developed in the workshop reflect the available data and expert opinion. This chapter identifies some key workshop outcomes, providing a roadmap of what we know with confidence and where additional research is needed. These include many of the major issues to be addressed in efforts to rationally manage the rich natural resources of the Verde River ecosystem.

<u>Changes in Physical Properties of the River Channel, Floodplain, and Aquifer</u>

A major finding of the ecological flows workshop and literature surveys was the strong influence of the physical systems on the plants and animals that live in and near the river. In many cases, the river's hydrology and geomorphology form the primary drivers of which species are present and how viable their populations appear. Thus, better understanding of the physical system will be critical to understanding and managing the ecosystem.

The period of record for continuous streamflow data on the upper and middle Verde River is relatively short, beginning in the mid-1960s. Extensive land-use alteration and diversion of surface water for irrigation and other uses had been on-going for over 70 years by that time. Thus, the pre-development hydrograph is not known based on measurement data, but could be simulated through watershed (rainfall-runoff) modeling. Because there are no large storage dams on the upper and middle Verde River, it follows that the flood and high flow regime has been minimally altered at a local level by human intervention. It is also apparent that the low flow regime (base flow) has been altered by surface-water diversions for irrigation and by capture of groundwater outflow to streams due to groundwater pumping. Additional capture of outflow, and resultant reduction of base flow, is expected to occur with increased groundwater extraction in the headwater aquifers and in the Verde Valley.

For ecological purposes, the complexity of the annual hydrograph is often divided into five major flow regimes – extreme low flow, low flow (e.g. base flow), high flow pulses, small floods, and large floods. These five flow categories have broad ecological significance (Appendix 3). To a degree that is unusual in Arizona rivers, base flow in the Verde River is relatively constant, reflecting hydrologic connection to large regional aquifers (Chapter 2). Base flow conditions provide various habitats for fish, including riffles, pools, and runs (which are sometimes also described as glides). Riffles consist of fast-moving, higher-gradient, shallower water over coarse sand/gravel/cobble substrate. Runs consist of moderate velocity, moderate depth water over coarse- to medium-sand substrate. Pools consist of slow-moving, deeper water over finer-grained substrates.

<u>River Channel</u>

Reduced base flow results in a smaller wetted perimeter in the river channel. This translates to reduced aquatic habitats, with the riffles dewatered first, followed by runs/glides and then pools, as flow continues to decline. With reduced base flow, riffles become narrower and shallower, leaving a large part of the riffle substrate above water. This restricts fish to a very narrow "trough" for feeding and moving through the riffle. Runs are also reduced in extent and depth with decreased base flow. With sufficient reduction in base flow, riffles become completely dewatered and runs suffer reduced velocity and depth and reduced extent. As reduction in base flow and dewatering of the river channel proceeds, habitat shrinks to isolated and disconnected pools. Species concentrate in the pools, where the smaller native fish, which generally are riffle specialists, fall prey to the larger pool-dwelling fish. The highly predatory non-native fish species typically win the competition game in such altered stream-flow conditions. Additional information on stage-discharge in relation to aquatic habitats for various reaches of the river is needed to better quantify this relationship.

The sediment transport regime has likely already been altered in the reach below Sullivan Dam in the headwaters region, although tributary sediment inputs probably reduce the impact in the downstream direction. With reduced base flow, sediment transport power in the river channel would be reduced, resulting in a substrate with increased fine-grained material. Several of the smaller native fish species, such as spikedace, are typically found over sand and/or gravel substrates (Propst et al. 1986); spawning occurs over gravel and sand substrates in moderate flow. Increased silting of the channel bottom, "smothering" the coarser substrates, would be detrimental to these species.

Water temperature in the Verde River is thought to be fairly constant, due to its groundwater origin and constant base flow rate. This has significance for fish populations, because elevated temperatures can affect their swimming ability, health, and behavior. Native fish have relatively wide temperature tolerance ranges, but will die at temperatures above 36-42° C, depending on the species (Carveth et al. 2006). Recent sampling found water temperatures in the upper Verde in the range of 7-28° C (Bonar et al. 2004). Reduced base flow would likely lead to increased water temperatures, especially if accompanied by reduced shading from riparian vegetation or by increased ambient air temperatures.

Nutrient retention and transformation are important ecosystem services provided by streams. General studies of nutrient cycling have indicated that streams and riparian systems have high nutrient (e.g. nitrogen, carbon) uptake rates relative to their spatial extent. The dynamics are complex and not yet fully understood; however, nutrient retention and transformation increases with increase in channel complexity (i.e. backwaters, hyporheic zones, lateral bars, and biotic patches such as beds of aquatic vascular plants or macroalgal mats). Reduced streamflow, including reduction in base flow, generally reduces channel complexity and thus would be expected to reduce nutrient retention.

The hyporheic zone is the region under and beside a stream channel or floodplain that contains water that is freely exchanged with the surface flow in the stream; i.e. the area where surface water and groundwater interacts. Aquatic ecologists have become aware of the importance of interactions of surface water and groundwater in the functioning of aquatic ecosystems (Hancock et al. 2005) and acknowledge that the hyporheic zone is a critical, but understudied, interface. Stream metabolic activity and nutrient cycling, including release and uptake of nitrate and carbon, appears to be strongly affected by processes in the hyporheic zone, including hydrologic exchange and hydraulic residence time. Studies elsewhere have suggested that connectivity in the hyporheic zone is important to the removal of nitrogen products in streams of the desert southwest and reduced surface flow results in reduced nitrogen removal (e.g., Crenshaw and Dahm undated).

The effects of reduced base flow would differ according to the local hydrologic and geomorphic conditions. The river naturally gains base flow in the downstream direction, so the same volume of water removed would result in a higher percentage reduction in flow in the upper reach than in the Verde Valley. Studies (see Chapter 2) have indicated that base flow in the upper 26 miles of the river - between its headwater springs and the springs below Perkinsville – is sustained chiefly by discharge from the headwater springs. Much of the upper reach is contained within narrow bedrock canyons and so has a limited storage capacity for floodwater recharge.

In contrast, the river through the Verde Valley has a larger volume of base flow with multiple groundwater contributions more extensive alluvial deposits. Until more detailed studies characterize the spatial distribution of water and habitat in the Verde Valley, it is difficult to predict how reduced base flow resulting from increased human groundwater use would affect the river ecosystem. Predicting the effects of reduced base flow in the Verde Valley is complicated by surface-water diversion dams, multiple points of irrigation return flow entering the river channel, multiple groundwater contributions, the presence of alluvial deposits that store and release floodwaters, complex land use adjacent to the floodplain, and the locally elevated groundwater level due to irrigation.

<u>Floodplain Riparian and Wetland Plant Communities</u>

Riparian forest response to streamflow regime and depth to groundwater fluctuations have been extensively studied in Southwestern rivers. Numerous studies have documented the close coupling of components of annual streamflow hydrographs and the germination and establishment of cottonwood trees (e.g., Stromberg 1993, Richter and Richter 2000). Key hydrograph components include timing and magnitude of flood peaks, the rate of decline of the recession limb, and magnitude of base flows. In developing a germination model for Fremont cottonwood, Goodding willow, seepwillow, and tamarisk in the Southwestern U.S., Shafroth and others (1998) combined discharge data, stage-discharge relationships, and seed-dispersal timing observations to develop a highly significant predictor of seedling establishment.

Lite and Stromberg (2005) examined shifts in community and population structure of Fremont cottonwood, Goodding willow, and tamarisk as a function of streamflow permanence, depth to groundwater, and annual groundwater level fluctuation. They identified hydrologic thresholds above which cottonwood-willow maintain tall dense stands with diverse age classes and are more abundant than tamarisk. Decreasing permanence of streamflow or declining groundwater levels below a certain depth or high inter-annual groundwater fluctuation will result in: 1) a decline in cottonwood/willow forest abundance; 2) increase in less structurally diverse shrubland communities comprised of species such as tamarisk or burrobrush; and 3) substantial loss of herbaceous streamside vegetation abundance and diversity.

Basic data on depth to groundwater and streamflow permanence do not exist for the Verde River. These data for the Verde, along with stage-discharge, river cross-sections and longitudinal profiles would allow for prediction of changes in the distribution and extent of riparian communities with changes in surface flow and groundwater levels. Obtaining stage-discharge data, habitat data, and groundwater data at representative study sites is the priority research platform identified during the ecological flows workshop.

Special-status Species

We can say with confidence that populations of most native fish would decline with base flow declines, and with major flow reductions, disappear, except at a few isolated springs with pools. This is due chiefly to the loss of habitat with reduction in streamflow. Habitat loss would affect spawning, juvenile, and adult life stages for all native fish species, but species-specific effects vary by the habitat needs and life cycles of the species. The extent of habitat loss coincident with a given reduction in base flow, and the probable effect on a given species life stage, would best be defined through delineating stage-discharge relationships, coupling that information with detailed habitat data at representative study sites, and utilizing those data to further quantify fish response to reduced base flow.

Spikedace depend on stream riffles – shallow reaches of relatively fast-moving water (Rinne 1991). Decreased streamflow would dewater riffles first, resulting in decreased water depth and decreased transport of fine-grained material. The result would be decreased area of riffle habitat and perhaps "smothering" of gravel-sand substrates with fine material. Less spawning habitat would mean less recruitment; less adult habitat would mean fewer individuals. With decreased streamflow, pools would persist longer than riffles, and spikedace would be concentrated in the pools with nonnative fish, resulting in increased predation.

Roundtail chub occupy pools adjacent to swifter riffles and runs. Spawning is often in association with submerged cover, such as fallen trees and brush. Fertilized eggs are randomly scattered over gravel substrates with no parental care involved (AGFD 2002). Data on microhabitat use and predator avoidance tactics, especially for fry and juveniles, are needed to better delineate response of roundtail chub to decreased base flow.

The key physical information that is needed to better delineate fish response to decreased streamflow is stage-discharge relationships for riffle and pool habitats, which would allow quantification of the amount of habitat loss for a given loss of streamflow.

Riparian birds would also likely be affected by changes in base flow. Southwestern willow flycatchers are riparian obligates, closely associated with shrub or tree species that depend on shallow groundwater. Nesting sites typically include high foliage density with nearby surface water (USFWS 2002). Minor reductions in the shallow groundwater elevation are known to affect the riparian plant community, with negative effects on flycatcher breeding success. Decreased base flow would be expected to result in higher mortality of cottonwood and willow tree seedlings (Chapter 6; Figure 6-1), thus limiting the density of cottonwood-willow stands or leading to replacement with tamarisk. Key data needs include models for the ways riparian trees use different geomorphic surfaces along the Verde River.

Yellow-billed cuckoos breed in riparian woodlands, nesting in trees or shrubs, often in areas with dense understory foliage. They are insectivorous, gleaning insects from leaves or catching them in the air. They typically require fairly large patches of mature riparian forest. Decreases in base flow would tend to affect the mature riparian forest only if accompanied by groundwater level declines that exceed the ability of root growth to keep pace. In addition, decreases in base flow may affect populations of insects that yellow-billed cuckoos prey upon. These relationships need to be better defined through additional research.

Both narrow-headed and Mexican gartersnakes are declining across their range in the US and both species have apparently suffered recent declines in the Verde River system (Holycross et al. 2006). Narrow-headed gartersnakes are found in cool, fast-flowing streams across the Mogollon highlands in Arizona. They depend primarily on native fish for their diet, and as a result spend much of the active season in the water or within several meters of the water's edge (Nowak 2006). Decreases in baseflow would affect the fish populations on which they feed, as well as affect snake hunting ability in riffles, ultimately leading to snake declines. Narrow-headed gartersnakes may be negatively affected by factors potentially created by decreased baseflow, such as increased water temperature, siltation, non-native spiny-rayed and predatory fish, crayfish densities, and water-borne bacterial or viral diseases (Nowak and Santana-Bendix 2002, Nowak 2006).

Mexican gartersnakes are typically found in more open, warmer, slower waters, and in particular are associated with marshy cienega habitat. They feed on both native and non-native fish and frogs, and thus may be more resilient to baseflow changes, unless marsh habitat area is decreased. They will likely be negatively affected by changes in baseflow that increase predator densities and water-borne diseases.

Both snake species will be more vulnerable to terrestrial avian and mammalian predators if in-stream and marsh vegetative cover decreases. Young snakes would be especially vulnerable to concentrations of predatory fish and large crayfish in pools.

Other Native Wildlife

Three obligate aquatic mammal species currently occur in the Verde Valley -beaver, muskrat, and river otter. Beavers utilize cottonwood and willow trees; when the abundance of these species declines past a certain point, it will negatively affect beaver. Otters benefit from pools created by beaver dams and would likely be negatively affected by a decrease in beaver. Maintaining permanent open water habitat of sufficient area is essential for maintaining populations of these three aquatic mammal species. These species are likely to respond negatively to reduced flow, flooding, and increased drawdown duration, frequency, magnitude, and timing. Beaver and muskrat are especially likely to be susceptible to summertime decreases in base flow, as they are less able to move long distances along ephemeral channels than are otters, and they are generally more susceptible to predators. However, insufficient information is available on these species' ecological roles to adequately predict population and trophic cascade effects.

Non-Native Invasive Species

Generally speaking, there are shifts in the composition of biotic communities when conditions are altered beyond the natural range of variation. In some cases, species that have been introduced to the region are better adapted to the new conditions. Tamarisk, for example, will benefit if groundwater levels decline along the Verde River, or if there are reductions in flood frequency or volume. When growing at wet sites, tamarisk abundance can be reduced by competitive interactions with cottonwood. Along the San Pedro River, saltcedar increased in abundance as groundwater deepened and fluctuated more, and as streamflows became more intermittent, the reverse of the pattern shown by cottonwood and willow (Chapter 4).

Some of the predatory non-native (sport) fish would benefit by partial reductions in base flow, as their prey fish are crowded into remaining pools. With additional declines in base flow, all fish species would suffer from loss of habitat and connectivity. However, even moderately reduced base flow would work against the Verde River's value as a sport fishery. With lower flows, smallmouth bass could be expected to overrun other species with high numbers of sexually-mature small individuals. Water clarity also declines with reduced flow, which would affect bass feeding and catchability to anglers.

Discussion

Identifying the physical parameters of greatest management concern for maintaining the desired ecological condition on the Verde River would provide direction for long-term management of the river ecosystem and maintenance of ecosystem services. It is clear that in southwestern river ecosystems, water availability is the most critical limiting component. Reduction in water available for the Verde River ecosystem has already occurred due to human consumptive use of water. Increasing population, drought, and climate change will only exacerbate the decline in water available for the environment. In addition to current and projected groundwater pumping, which "captures" water that would otherwise discharge to the river, reduced water availability for the riverine ecosystem also occurs due to surface-water diversions for irrigation, especially in the Verde Valley.

Thus, careful, proactive management of water is needed to get the most that we can out of every drop. In-depth understanding of the occurrence, movement, and connectivity of surface water and groundwater, combined with knowledge of the spatial and temporal elements of ecosystem water use, and the connections to human water use, is needed to meet human water needs while also maintaining functioning riparian and aquatic ecosystems.

Extensive research has occurred on other rivers in the Southwest to understand the occurrence and movement of groundwater and human and natural system utilization of groundwater and surface water. Results from this research are generally transferable to the Verde River, but specific quantified values must be confirmed and refined for the Verde River. This document presents known and presumed relationships between streamflow, groundwater level, and ecological response, thus beginning a process for determining how riparian and aquatic ecosystems function in the Verde River. It presents a prioritized research agenda for developing the additional information needed in order to meet ecosystem water requirements while also managing water in the most effective and efficient manner in the Verde River watershed.

Taking action on this research agenda will require cooperative efforts by the many communities, agencies, and organizations that place value on a living Verde River and the benefits it provides.

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Appendix 1
Ecological Flows Workshop Participants

Name	Organization
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Anne Brasher	US Geological Survey, Utah Water Science Center
Jean Calhoun	The Nature Conservancy, Arizona chapter
Dan Campbell	The Nature Conservancy, Arizona chapter
Andy Clark	Arizona Game & Fish Department
Susanna Eden	University of Arizona, Water Resources Research Center
Jeanmarie Haney	The Nature Conservancy, Arizona chapter
Andrea Hazelton	Arizona State University
Shaula Hedwall	US Fish & Wildlife Service
Kyle House	University of Nevada
Eloise Kendy	The Nature Conservancy, Global Freshwater Team
Greg Kornrumph	Salt River Project
Mike Leonard	US Forest Service, Prescott National Forest
Rob Marshall	The Nature Conservancy, Arizona chapter
Bill Meyer	retired hydrologist (US Geological Survey)
Dan Neary	US Forest Service, Rocky Mountain Research Station
Erika Nowak	US Geological Survey, Southwest Biological Science Center
Chuck Paradzick	Salt River Project
Rod Parnell	Northern Arizona University
Paul Polechla	University of New Mexico
Phil Pearthree	Arizona Geological Survey
Brian Richter	The Nature Conservancy, Global Freshwater Team
Anna Spitz	Arizona Water Institute
Abe Springer	Northern Arizona University
Larry Stevens	Museum of Northern Arizona
Tice Supplee	Audubon Arizona
Ellen Tejan	The Nature Conservancy, Oklahoma chapter
Blake Thomas	US Geological Survey, Arizona Water Science Center, Tucson
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Ruth Valencia	Salt River Project
Andy Warner	The Nature Conservancy, Global Freshwater Team
Dave Weedman	Arizona Game & Fish Department
Ed Wolfe	Verde River Basin Partnership

Appendix 2
Verde River Fish Habitat Needs

This Appendix contains information on habitat needs for native and non-native fish in the Verde River. Part of it duplicates material presented in Table 5-3.

Abbreviations:
Nativity: Na – native; Na-Extr – native but extirpated; NN – non-native.
Arizona Status: WSC – Wildlife of Special Concern.
US Status: LE – listed endangered, LT – listed threatened, SC – species of concern.

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U.S. Fish & Wildlife Service. 2002b. Razorback Sucker (*Xyrauchen texanus*) Recovery Goals: Amendment and Supplement to the Razorback Sucker Recovery Plan. Mountain-Prairie Region, Denver, CO.

Also consulted were species abstracts from the Heritage Data Management System, Arizona Game and Fish Department: http://www.gf.state.az.us/w_c/edits/hdms_abstracts_fish.shtml

Common Name	Family	Scientific Name	Nativity	AZ Status	US Status	Ecological Role	Spawning Habitat
Longfin Dace	Cyprinidae	*Agosia chrysogaster*	Na	---	SC	omnivorous and opportunistic in feeding behavior and diet	fine sand
Desert sucker	Catastomidae	*Catostomus clarki*	Na	---	SC	adults are largely herbivores, feeding on algae and organisms scraped from stones	riffles
Sonora Sucker	Catastomidae	*Catostomus insignis*	Na	---	SC	feed on larvae of aquatic insects	cleaned gravel bottoms
Roundtail Chub	Cyprinidae	*Gila robusta*	Na	WSC	SC,S	carnivorous, top predator in mid-elevation streams, also feed on inverts	gravel bottoms, preferring submerged cover
Spikedace	Cyprinidae	*Meda fulgida*	Na	WSC	LT,S	feed mainly on aquatic and terrestrial insects, some fish fry	shallow sandy bottoms
Gila Topminnow	Poeciliidae	*Poeciliopsis o. occidentalis*	Na	---	LE		
Colorado Pikeminnow	Cyprinidae	*Ptychocheilus lucius*	Na	---	LE	formerly the top carnivore of the Colorado River basin	adults run upstream to streams
Speckled Dace	Catastomidae	*Rhinichthys osculus*	Na	---	SC	omnivorous benthic feeders	swift water
Loach Minnow	Cyprinidae	*Tiaroga cobitis*	Na	---	LT	feed on larvae of riffle-dwelling insects	riffles; velocity 0-100 cm/sec, depth 6-40 cm (Gila R)
Razorback Sucker	Catastomidae	*Xyrauchen texanus*	Na	WSC	LE,S	feed on aquatic and terrestrial insects, filamentous algae, and other fish	along shorelines or in bays

Rearing Habitat	Adult Habitat	Spawning Period	Flow Needs	References
open high temperature waters	shaded, deep, high temperature waters	December- July or perhaps September	Usually in water less than 0.6 ft (0.2 m) deep with moderate velocities of around 1.1f/s (0.3m/s)	Minckley 1973; http://www.azgfd.gov; Bonar et al 2004
quiet pools near the banks	pools during day, riffles at night	late winter or early spring	rapids and flowing pools	Minckley 1973; http://www.azgfd.gov; http://www.co.pima.az.us/cmo/sdcp/species/fsheets/vuln/ds.html; Bonar et al 2004
stream margins	gravelly/rocky pools in relatively deep quiet waters		relatively deep, quiet waters	http://www.azgfd.gov; Bonar et al 2004; Minckley 1973
shallow margins and undercut banks	pools, eddys below rapids, low-gradient riffles	May- July in other systems	spawning triggered by rising water temp (14-24 C) during receding flow	Minckley 1973; http://www.azgfd.gov; Bonar et al 2004; Girmendonk & Young 1997
	riffles; moving water less than 1 meter deep; Verde mean depth 26.5 +/- 6.7 cm; Verde mean velocity 21.0 +/- 10.0 cm/s	May- June	Verde mean velocity 21.0 +/- 10.0 cm/s	Minckley 1973; http://www.azgfd.gov; Rinne 1991
	in moderate current below riffles and in margins	January- August	moderate current	Minckley 1973; http://www.rivers.gov/wsr-verde.html
warm, low-velocity backwaters	deep, low-velocity eddies, pools and runs	July to August in the Green River	adapted to large spring peak flows and low stable base flows; spawning triggered by rising water temp (18-23 C) after spring runoff peaks	Minckley 1973; http://www.fs.fed.us/r3/prescott/fishing/fishing_verde.htm; Bonar et al 2004; USFWS 2002a
gravel bottoms	less than .5m depth, congregated below riffes and eddies	2 spawns: spring and late summer	water less than 0.5 m (1.6 ft.) deep, with current averaging about 0.4m/sec (1.3ft/sec)	Minckley 1973; http://www.azgfd.gov; Schreiber and Minckley 1981
riffles; 33.0 +/- 23.2 cm/sec, 14.9 +/- 7.0 cm depth (Gila R)	on the bottom of gravelly riffles; 24-80 cm/sec, 12-27 cm deep (Gila R)	late winter- early spring	riffles maintained by flooding; spawning triggered by rising water temp (16-20 C); eggs need large gravel to cobbles, free of fine sediments, with flowing water	Minckley 1973; http://www.rivers.gov/wsr-verde.html; Propst and Bestgen 1991; (slightly different values in Rinne 1989)
quiet backwaters	1-15m depth; over sand, mud or gravel bottoms	February- early summer	adapted to large spring peak flows and low stable base flows; spawning triggered by rising water temp (9.5-22 C) after spring runoff peaks	Minckley 1973; http://www.azgfd.gov; Bonar et al 2004; USFWS 2002b

Common Name	Family	Scientific Name	Nativity	AZ Status	US Status	Ecological Role	Spawning Habitat
Common Carp	Cyprinidae	*Cyprinus carpio*	NN	---	---	important food resource for bald eagle, common black hawks and osprey (http://www.rivers.gov/wsr-verde.html)	shoreline
Threadfin Shad	Clupeidae	*Dorosoma petenense*	NN	---	---	introduced as a food soure for game fishes because they are relatively small, plankton-feeding with a high reproductive rate	water temps of 24-26, 2-3 m from shoreline in 1 m deep water
Mosquitofish	Poeciliidae	*Gambusia a. affinis*	NN	---	---		
Yellow Bullhead	Ictaluridae	*Ictalurus natalis*	NN	---	---		in cavities or other depressions
Channel Catfish	Ictaluridae	*Ictalurus punctatus*	NN	---	---		hole or other protected depression
Green Sunfish	Centrarchidae	*Lepomis cyanellus*	NN	---	---		hot shallow pools over sand, gravel or bedrock
Bluegill	Centrarchidae	*Lepomis macrochirus*	NN	---	---		males fan shallow depressions in sand, gravels, mud, or organic debris
Smallmouth Bass	Centrarchidae	*Micropterus d. dolomieui*	NN	---	---		sand or gravel nests below cut banks or near debris
Largemouth Bass	Centrarchidae	*Micropterus salmoides*	NN	---	---		roots, grasses, sandy or muddy bottoms, or bedrock
Yellow Bass	Percichthyidae	*Morone mississippiensis*	NN	---	---		
Red Shiner	Cyprinidae	*Notropis lutrensis*	NN	---	---		calm waters with natural features
Rainbow Trout	Salmonidae	*Oncorhynchus mykiss*	NN	---	---		gravel bottoms

Rearing Habitat	Adult Habitat	Spawning Period	Flow Needs	References
shoreline and then sheltered areas		late Feb to early July		Minckley 1973; Bonar et al 2004
	moderate current, congregating below swift riffles, in circular eddies, or in open flowing pools	spring and early summer		Minckley 1973; Bonar et al 2004
	all habitats			Minckley 1973; http://www.rivers.gov/wsr-verde.html; Bonar et al 2004
in cavities or other depressions	clear rocky bottom streams	spring- early summer		Minckley 1973; http://www.fs.fed.us/r3/prescott/fishing/fishing_verde.htm; Bonar et al 2004
hole or other protected depression		April - early June		Minckley 1973; http://www.fs.fed.us/r3/prescott/fishing/fishing_verde.htm; Bonar et al 2004
hot shallow pools over sand, gravel or bedrock	small, mud-bottomed low gradient streams near cover			Minckley 1973; http://www.rivers.gov/wsr-verde.html; Bonar et al 2004
in nests guarded by males	any waters below 2500 m, rarely in streams and rivers and most likely in ponds and reservoirs	April-May, usually in two peaks of activity		Minckley 1973; Bonar et al 2004
interstices of gravel	areas with current and hard stony bottoms	March- May		Minckley 1973; http://www.fs.fed.us/r3/prescott/fishing/fishing_verde.htm; Bonar et al 2004
roots, grasses, sandy or muddy bottoms, or bedrock	near debris or overhanging banks along rocky shorelines	April/May- June		Minckley 1973; http://www.fs.fed.us/r3/prescott/fishing/fishing_verde.htm; Bonar et al 2004
				Minckley 1973; Bonar et al 2004
		March- June		Minckley 1973; http://www.rivers.gov/wsr-verde.html; Bonar et al 2004
buried in gravel	cold waters	winter- early spring		Minckley 1973; http://www.fs.fed.us/r3/prescott/fishing/fishing_verde.htm; Bonar et al 2004

Common Name	Family	Scientific Name	Nativity	AZ Status	US Status	Ecological Role	Spawning Habitat
Flathead Catfish	Ictaluridae	*Pilodictis olivaris*	NN	---	---		mammal dens, depressions under stones, or caves
Fathead Minnow	Cyprinidae	*Pimephales promelas*	NN	---	---		
Sailfin Molly	Poeciliidae	*Poecilia latipinna*	NN	---	---		
Shortfin Molly	Poeciliidae	*Poecilia mexicana*	NN	---	---		
Black Crappie	Centrarchidae	*Pomoxis nigromaculatus*	NN	---	---		open water over mud, sand, or gravel bottoms
Tilapia	Cichlidae	*Tilapia sp.*	NN	---	---		

Rearing Habitat	Adult Habitat	Spawning Period	Flow Needs	References
mammal dens, depressions under stones, or caves	deep pools near cover	spring to early summer		Minckley 1973; http://www.fs.fed.us/r3/prescott/fishing/fishing_verde.htm; Bonar et al 2004
eggs attached to the undersides of an object above the substrate	quiet muddy streams			Minckley 1973; Bonar et al 2004
live bearers	shallow stream margins, avoiding currents and deeper waters	spring and summer		Minckley 1973; Bonar et al 2004
				Minckley 1973; Bonar et al 2004
nests in sediment a few centimeters deep by 25 cm wide, guareded by males	atrracted to submergent debris	spring to early summer		Minckley 1973; Bonar et al 2004
				Bonar et al 2004

Appendix 3
Ecological Significance of the Flow Regime Categories

These five environmental flow components have distinct ecological functions and are used in the Indicators of Hydrologic Alteration software (The Nature Conservancy 2005).

Low flows – This is the dominant flow condition in most rivers. In natural rivers, after a rainfall event or snowmelt period has passed and associated surface runoff from the catchment has subsided, the river returns to its base- or low-flow level. These low-flow levels are sustained by groundwater discharge into the river. The seasonally-varying low-flow levels in a river impose a fundamental constraint on a river's aquatic communities because it determines the amount of aquatic habitat available for most of the year. This has a strong influence on the diversity and number of organisms that can live in the river. The low-flow levels for a river can be estimated using standard hydrograph separation techniques.

Extreme low flows – During drought periods, rivers drop to very low levels that can be stressful for many organisms, but may provide necessary conditions for other species. Water chemistry, temperature, and dissolved oxygen availability can become highly stressful to many organisms during extreme low flows, to the point that these conditions can cause considerable mortality. On the other hand, extreme low flows may concentrate aquatic prey for some species, or may be necessary to dry out low-lying floodplain areas and enable certain species of plants to regenerate. The discharge levels associated with extreme low flows will need to be defined for each river. This can be accomplished either by using biological information to identify critical low flow thresholds, or by identifying a percentile level of flow (such as the 10^{th} percentile of all low flows) that occurs only during dry seasons or droughts.

High-flow pulses – During rainstorms or brief periods of snowmelt, a river will rise above its low-flow level. As defined here, high-flow pulses include any water rises that do not overtop the channel banks. These pulses provide important and necessary disruptions in low flows. Even a small or brief flush of fresh water can provide much-needed relief from higher water temperatures or low oxygen conditions that typify low-flow periods, and deliver a nourishing subsidy of organic material or other food to support the aquatic food web. High-flow pulses also provide fish and other mobile creatures with increased access to up- and downstream areas. Because these flows have the competence to move considerable amounts of sediment and occur fairly frequently, they play a very important role in shaping the geometry of the river channel and forming physical habitats such as riffles and pools.

Overbank flows – During floods, fish and other mobile organisms are able to move upstream, downstream, and out into floodplains or flooded wetlands to access additional habitats such as secondary channels, backwaters, sloughs, and shallow flooded areas. These usually inaccessible areas can provide substantial food resources. Shallow flooded areas are typically warmer than the main channel and full of nutrients and insects that fuel rapid growth in aquatic organisms. As used here, an "overbank flow" includes all river rises that overtop the main channel but does not include more extreme, and less frequent, floods. The distinction between these events and floodplain maintenance flows can be made on the basis of an ecologically-relevant threshold, such as the discharge level at which higher floodplain terraces are inundated, or they can be distinguished by their frequency of occurrence, such as designating anything larger than a 10-year flood as a "floodplain maintenance flow."

Floodplain maintenance flows – These events will typically re-arrange both the biological and physical structure of a river and its floodplain. These large floods can literally flush away many organisms, thereby depleting some populations but in many cases also creating new competitive advantages for some species. Floodplain maintenance flows may also be important in forming key habitats such as oxbow lakes and floodplain wetlands.

References

The Nature Conservancy. 2005. Indicators of Hydrologic Alteration, Version 7 User's Manual. http://www.nature.org/initiatives/freshwater/conservationtools/art17004.html Accessed January 23, 2008.

Appendix 4
Review Comments and Responses

AN OVERVIEW OF THE REVIEW PROCESS

A draft of this report was distributed to all participants of the Ecological Flows Workshop and several others, with a request for review comments. We received comments from 23 reviewers. Reviewers by affiliation included three federal agencies (USGS, USFS, USFWS), one state agency (AGFD), three universities (ASU, NAU, UNM), and two NGOs (TNC and VRBP). Reviewers by discipline included 10 physical scientists (with specialties including hydrology and geology), 12 biological scientists (with specialties including fish, reptiles/amphibians, mammals, riparian vegetation, and ecology), and a water policy specialist. All comments were fully considered and changes were made where appropriate.

Many of the comments related to grammatical and formatting aspects of the draft report, such as typographical errors, use of undefined abbreviations, consistent use of terms and place names, hyphenation, providing references for all citations, and table and map formatting. We made grammatical and formatting changes as suggested. Several comments raised non-technical issues that were beyond the scope of this report.

Substantive comments are summarized in this appendix. Those were comments that provided additional information, questioned technical aspects of the report, or requested additional clarification. A general summary of the nature of comments received and our general response is provided below. Specific comments and our responses follow.

Overall, reviewers commented favorably on the report and felt that the flow-ecology response curves were appropriate representations of the system, based on what is known at this time. Several reviewers suggested additional explanation of the flow-ecology response curves in the figure captions; captions were revised accordingly. Several reviewers suggested revisions to curves; revisions were made in one case.

Numerous reviewers provided comments and additional information on native fish and sport fish. Several reviewers asked for more detailed descriptions of historic and current distribution of fish species (in the mainstem and tributaries). We felt that level of detail was beyond the scope of the Phase I report; additional detail will be provided in the Phase II report. Many reviewers provided additional information on specific species' life histories and habitat use and on aspects of the physical system. We incorporated information received in the appropriate sections of the report.

Comments we received can be grouped into the following topic areas:

- Flow-Ecology Response Curves
  - Hypothetical nature
  - Suggested revisions
  - Basis for selection
- Native Fish
  - Flow relations
  - Habitat needs
  - Life cycles and relationship to flow regime
  - Distribution and occurrence (current and historic)
  - Importance of complex flow regime on life stages and feeding habits
  - Impact of non-native fish vs. impact of changed flows
  - Refinement of habitat and life history descriptions
- Sport Fish
  - Importance of sport fishery
  - Flow dependence
- Riparian vegetation
  - Importance of coyote willow and Nebraska sedge
  - Include non-native invasive plants other

than tamarisk and ailanthus
    - o Expand section on riparian ecosystem functions
- Birds
- Aquatic Mammals – additional information provided on river otters and beavers
- Herpetofauna - additional information provided on narrow-headed and Mexican gartersnakes and leopard frogs
- Physical System, Hypothetical flow scenarios, and Reach-specific effects
- Research Platform

SPECIFIC RESPONSES TO REVIEW COMMENTS

Topic: Flow Ecology Response Curves

Comment: Regarding the flow-ecology response curves, for data-less representations of expected responses, they are pretty good. We must keep in mind, that these may not include the potential interactions between incompatible species in a decreasing base flow scenario.
Response: We concur.

Comment: Provide citations in the figure captions for flow response curves, or at least make it clear in the figure captions whether what you are presenting is a hypothetical possibility or whether it is based on 'real' data.
Response: Figure captions revised to add citations and additional information and to clarify.

Comment: Suggest labeling flow-ecology response curve graphs as "hypothetical response curve of …."
Response: This change in graph label was made.

Comment: On the native fish spawning success response curve, it seems that the curve should reach a success threshold and flatten out, as at some point there are diminishing returns as flood power/ magnitude continues to increase.
Response: Although this suggestion seems reasonable, the flow ecology response curve was not revised. Because curves were developed with the significant involvement of all workshop participants, curve revisions were not made during the review process, except in the case where strong supporting data was provided.

Comment: On the lowland leopard frog losses to predation response curve - at high base flows, there be more predators and frogs in the system, thus more predation overall of populations. As base flow declines, might see less or more predation depending on species of predatory fish, and finally loss of habitat (high mortality) as base flow becomes intermittent.
Response: Although this suggestion seems reasonable, the flow ecology response curve was not revised. Because curves were developed with the significant involvement of all workshop participants, curve revisions were not made during the review process, except in the case where strong supporting data was provided by the species expert primarily responsible for the curve.

Comment: Contrary to the draft report and workshop discussions, there are two different scenarios with the gartersnakes: Narrow-headed gartersnakes are no longer in the Valley section, but they may be in the headwaters. So include both species, Narrow-heads in the headwaters and Mexican in the valley sections. They will have different response curves. Narrow-heads will follow that of the smallest native fish, due to feeding constraints on juveniles. Once those small fish are gone, narrow-head numbers will fall off due to failure of neonates to survive past birth, but it may take 2-3 years after the small fish go away to see population-level effects. Mexican gartersnakes, being more plastic in their diet, are our old top curve. They will hang in there until the bitter end, when there's no more water left, but even here the curve probably follows that of the fish more than its abrupt end as originally portrayed. Because adults can hang in there for a few years, the slope is likely more gradually negative (less precipitous) than we originally showed. I have attempted to show the new narrow-headed curve in a new chart by drawing over the old curve (I did not change the slope of the old curve). Based on discussions this summer with Phil

Rosen, these may reflect more of the situation we may be seeing in Oak Creek and Black River, where the populations may be compromised by failure of recruitment.
Response: A new curve was added to the existing graph (Figure 6-5). While our general intent was to not modify the results of the workshop after the fact, this was new information provided by one of the few experts on these species, and was supported by one of the other experts on these species and by literature that was provided for incorporation into Chapter 5.

Comment: Text in Chapter 6 states that workshop participants identified a "set of key relationships that could be displayed as flow-ecology response curves". Not sure these were the most critical - in some cases they were starting points, based on a reasonable judgment, or selected because certain people were in the room. The selected relationships were products of the meeting, but not ranked in terms of importance.
Response: No changes were made based on this comment. It is our understanding that workshop participants chose these particular relationships because they believed them to be the most critical. Otherwise, they would have chosen other relationship. The key point is that the relationships diagramed as curves in the workshop are not an exhaustive list.

Topic: Native Fish - Flow Relations, Habitat Needs, Life Cycles, Distribution and Occurrence

Comment: With short-term reduced flow, longer-lived natives such as Sonora sucker and to a degree roundtail chub are better able to withstand due to their longevity. Short-lived natives such as speckled dace and spikedace are not. Longer or permanent flow reductions will reduce all natives in the presence of non-native species. Natives are well equipped to withstand extended periods of low-flow, but cannot compete long-term with non-natives.
Response: Added to the text.

Comment: Wildlife Chapter, Fish Overview section - rather than focus on "management of flows" and "developing" ecologically supportive flows (which is not highly relevant in an unregulated river like the upper/middle Verde), instead revise and focus on the link between the components of the flow regime (high through low flows) to the various life stages of native fish. Emphasize importance of base flow - reduction in base flows could cause changes to wetted channel, habitat availability, water temperatures, inverts, greater competition for resources (including more nonnative fish interactions). Work to maintain base flows, and/or assessment of the smaller diversions and how they could be improved. Suggest rewording to state that protection and enhancement of native fishes is likely to require "conservation of the range of stream flows", including maintaining base flows.
Response: Text revised with this emphasis. Added greater emphasis on low flows, but kept discussion of flood flows to highlight importance of keeping a natural flood regime.

Comment: Wildlife Chapter, Fish Overview section - there is not much evidence that there has been a significant alteration from the "natural hydrograph" on the upper Verde River. The middle Verde River is affected by small mainstem and tributary diversions, but no evidence that flood pulses have been altered (although likely minimum base flows have been reduced from pre-settlement). John Rinne's work (USFS Rocky Mountain Research Station) indicates that overall human alteration of the system favors more nonnative species in the Verde Valley reach than in the upper canyon reach. This is likely due to more tributaries contributing nonnative species, irrigation diversions reducing minimum flows and creating small mid-channel impoundments favoring some nonnatives, and past wildlife agency efforts to manage for game species in this area. Main point is that hydrologically, while not absolutely natural, the ecosystem could support native species, but for the high numbers of nonnative species, and that native species are hanging on likely because the system is still for the most part functional. If base flows are further reduced, the effect of other anthropogenic stressors will be exacerbated and further threaten native fish.
Response: Clarified in text – changed from implying

that altered hydrology is affecting current conditions to potential for affecting future status. Also, revised the text to indicate that the altered hydrograph of the river includes the lower reach, with two large dams and reservoirs.

Comment: Young Roundtail Chub are also extremely tied to riffle habitat their first year. As we've seen in past trends, with extended years between high water events, chub recruitment is reduced or eliminated.
Response: The literature that we consulted does not mention a close association of juveniles to riffle habitat, though it does say they are sometimes found in low-gradient riffles. The correlation of recruitment with floods may be unrelated to riffle habitat.

Comment: Table 5-2, suggest adding a column that shows which species are found (and note historical) in the upper and middle reaches. Some of the species listed are headwater fish (headwater chub, Gila chub) or do not have self sustaining populations (e.g., white crappie, walleye, northern pike, yellow bass?, yellow perch, brown and brook trout). Request review of table from additional fish experts.
Response: Added text describing which species are common in mainstem Verde. To address this topic fully would require determination of current and historical distribution for each species, a non-trivial task that is peripheral to this study. Also, that topic is part of a current academic study, which we expect to be more definitive than what could be accomplished in the time available for this effort.

Comment: Roundtail chub spawning habitat info needs updating, per Voeltz 2002; Bryan and Robinson 2000.
Response: Text revised accordingly.

Comment: The draft report is informative, accurate and interesting. Found Chapter 5 Wildlife to be pretty accurate. It does recognize and state that the primary issue with native fishes is likely the co-occurrence of the non-native species and not the current and past changes in flow regime, although future flow changes will likely exacerbate the situation.
Response: We concur.

Comment: The amount of future research necessary to tie ecological flows to native fish maintenance and recovery will be substantial (not to mention all of the other flow/response curves). Future collaboration will be critical.
Response: We concur.

Comment: Table 5-3, Native Fish Habitat Needs in the Verde River. One reviewer provided suggestions and citations for refining habitat and life history descriptions.
Response: Incorporated into table

Comment: One reviewer provided citations and information for two fish not included on historical Verde River fish list (desert pupfish and woundfin) and a fish whose historical presence in the Verde is questioned (flannelmouth sucker).
Response: Additional species added to table. Text changed to clarify uncertainties.

Comment: One reviewer provided extensive comments and citations on native fish, number of species - 16 vs. 10 vs. 4 original/remaining - Verde mainstem vs. tributaries.
Response: The list now shows 13 native fish species known to have occurred in the Verde basin. The text mentions another 3 that may have been historically present, but for which there are no definite records.

Comment: Chapter 7, Threatened, Endangered, and Rare Species" section. Define the status of each species discussed - whether it is threatened, endangered, rare, or sensitive – and explain why only some of the listed, rare, and sensitive species that occur in the Verde are discussed. This is somewhat of an all-encompassing title that the text doesn't entirely support.
Response: Title of this section changed to "special-status species" to better reflect content and intent. The focus of this effort was not exclusively on federally protected species, but rather on the whole community of native plants and animals. Workshop discussions focused on those species that were expected to be most strongly affected by changes

in the flow regime, regardless of their protected status, with a bias toward those for which we have substantial information on habitat needs.

Topic: Sport Fishery - Flow Relations and Importance

Comment: Need to consider complexity of the sport fishery - public demand and economic benefit to state.
Response: Text added about the scale and value of sport fishing.

Comment: The value of the existing sport fishery would also be reduced with declines in base flow. Species such as smallmouth bass tend to overrun all other species with high numbers of sexually mature small (stunted) individuals. Water clarity also declines with reduced flow which affects bass feeding and catchability to anglers.
Response: Added this to the text in both Ch. 6 and 7.

Comment: Loss of water would also impact and likely reduce abundance of nonnative sport fish (e.g. lower flows = higher spring summer water temps which likely reduces recreational trout fishing).
Response: Added discussion of effects on sport fish to Ch. 5, 6 and 7.

Topic: Riparian Vegetation

Comment: The vegetation data is heavily skewed toward the San Pedro River.
Response: The San Pedro has received the most study of AZ's riparian systems, and shares most of the dominant species.

Comment: Coyote willow (arroyo, *Salix exigua*) and Nebraska sedge- two significant species that occur in the middle/upper Verde (but are limited or along the San Pedro River and lower Verde) – are worth watching if base flows decrease. Information on their preferred environment provided.
Response: Discussion of these species added to Chapter 4.

Comment: Invasive plant discussion needs to be expanded beyond saltcedar to include: *Ailanthus*; *Arundo donax*; water primrose; pampas grass, Russian olive(?); Siberian elm(?) etc – these species become more prolific as water becomes more limited in river channel. However, little information is available for these species pertaining to wildlife responses, ecological changes, ET rates, etc. in what might become the new vegetation community.
Response: Discussion of these species added to Ch. 4.

Comment: Need to expand section on riparian ecosystem functions in Chapter 4. Current text discusses only ET, which is far too limited.
Response: This section was significantly expanded to include a broader range of riparian ecosystem function relevant to the Verde River.

Comment: Expand list of invasive plants species needing additional study beyond just Tree of Heaven.
Response: Additional species and text added.

Comment: Mesquite is a later seral (successional) species that is not directly competing with cottonwood and willow, which are pioneer species. Mesquite is responding to a different suite of environmental controls.
Response: Text changes were made to reflect this observation.

Comment: Sedge and horsetail are associated with saturated soils- they are not in the mesic category.
Response: Text changes were made to reflect this observation.

Topic: Birds

Comment: Suggested additional text and citations to more-accurately describe habitat needs for southwestern willow flycatcher.
Response: Text inserted, with references

Comment: Table 6-2, future 1; Flycatcher – suggest that the effect should be characterized as 0/- or "-" based on research demonstrating that even slight reductions (and for this scenario we are assuming 32% base flow reduction) in shallow ground water elevation influences vegetation structure/vigor/or composition which can negatively affect breeding suitability.
Response: Revision made as suggested.

Comment: Not clear how bird species were selected for analyses and tables.
Response: Clarified in text.

Comment: Should specify in Table 5-5 which months instead of seasons have breeding activity by birds.
Response: Good idea, but not critical to main points of chapter. No revisions made based on this comment.

Topic: Aquatic Mammals

Comment: Chapter 5, page 69. Replace "drawdown" with "low flow". Consider stating that "reduced base flow would cause shallower pools and runs, and could disconnect habitats if the channel became intermittent, which would fragment and threaten populations of aquatic mammals".
Response: Changed "drawdown" to "low flow".

Comment: Is there really insufficient information to determine the effects of reducing flows on aquatic mammal species? Worst case is that the upper Verde goes dry which would greatly reduce the distribution and abundance of these species. Less water = less habitat.
Response: Reasonable speculation, but apparently not documented. That's part of the flow/ecology response curves that needs to be tested.

Comment: One reviewer provided a paragraph on otters, with citations, to add to text.
Response: The paragraph was added.

Topic: Herpetofauna

Comment: Two reviewers provided additional information, supporting literature, and proposed text on Mexican and narrow-headed gartersnake habitat and feeding needs, and relationship to flow.
Response: That text was incorporated in Chapters 5, 6, and 7.

Comment: Remaining populations of *Rana* (leopard frogs) are not at springs; *R. yavapaiensis* occur at springs and tributaries; *R. chiricahuensis* and *R. pipiens* are only at stock tanks; they no longer occur on mainstem or along the tributaries.
Response: Text clarified, with more specific information about the distribution of the four frog species present in the Verde watershed (including the bullfrog, *R. catesbeiana*).

Topic: Physical System, Hypothetical Flow Scenarios, and Reach-Specific Effects

Comment: The hypothetical flow scenario description is confusing. Estimates of 32 and 66% reduction in base flow at Camp Verde need explanation. Presumably these estimates reflect base flow during periods when there are upstream irrigation diversions, but you need to be explicit about how these estimates were determined. (i.e., what value did you use for current Camp Verde base flow and how was that determined?) Are the 10,000 and 20,000 acre-feet of capture of base flow passing the Camp Verde gage above and beyond the loss of Paulden base flow plus capture in the Verde Valley beyond that which currently occurs? Estimates that are not supported by understandable reasoning could damage the credibility of the ecological flows effort.
Response: This section was re-written to clarify and better explain the terms of the scenarios.

Comment: One reviewer took issue with phrasing pertaining to reach-specific effects of reduction in base flow, specifically the statement that the upper reach is most susceptible to loss of base flow and impacts would be greater in the canyon reach than in the valley reach.

Response: Following detailed dialogue with this reviewer, all sections with this language were rewritten in terms of percentage loss of flow in the upper reach compared to the middle reach, and associated proportional impacts to habitat. Given a volume of base flow removed from the river, the upper 25 miles would suffer the largest percentage loss of flow, because of its smaller base flow compared to the middle reach.

Comment: Chapter 6, *"The workshop discussions focused on potential consequences of reductions in the river's base flow. This was based on analyses by USGS personnel, anticipated pumping levels, and the historic loss of flow from Del Rio Springs (Springer and Haney, this volume)."* Why is the loss of flow from Del Rio Springs is mentioned here? Certainly there has been a loss of flow (64% reduction in flow between 1940 and 2005) and approximately 50% loss in groundwater underflow from the Little Chino to the Big Chino/Verde. But, there has been no ecological work that has tried to describe the impacts of this flow decline (which is what this section seems to be implying).
Response: The point about Del Rio springs is that documented base flow loss has already occurred. The sentence was deleted here, but the description of that loss was retained in Chapter 2.

Comment: Chino Wash, Williamson Valley Wash, and Walnut Creek are certainly worth mentioning as major tributaries to the Verde River and are in the study area as defined by fig. 1-1.
Response: Mention of those tributaries was added to the text.

Comment: One reviewer provided text to clarify source of groundwater contributions to the river from Perkinsville downstream, and to improve the use of aquifer name nomenclature.
Response: These changes were made in the text.

Topic: Research Platform

Comment: In "Research Platform", add two sentences: 1) Public agencies will make their data available to all agencies in a reasonable amount of time; and 2) Conduct aquifer tests to obtain the hydrologic properties of the alluvial sediments.
Response: These sentences were added.

Comment: In "Research Platform", rather than focusing exclusively on *Ailanthus*, need to research all important non-native species - wildlife responses, ecological changes, ET rates, and other ecologically important attributes.
Response: Additional text added to address additional species.

Comment: Add "aquifer tests" to research platform
Response: Text added.