Defining Ecosystem Flow Requirements for the Bill Williams River, Arizona

Edited by Patrick B. Shafroth and Vanessa B. Beauchamp

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Cover photograph courtesy of Patrick Shafroth, U.S. Geological Survey

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	0.4047	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
cubic foot (ft^3)	0.02832	cubic meter (m^3)
Flow rate		
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Chapter 1. Background and Introduction

By Andrew Hautzinger[1], Patrick B. Shafroth[2], Vanessa B. Beauchamp[2], and Andrew Warner[3]

Alteration of natural river flows resulting from the construction and operation of dams can result in substantial changes to downstream aquatic and bottomland ecosystems and undermine the long-term health of native species and communities (for general reviews, cf. Ward and Stanford, 1995; Baron and others, 2002; Nilsson and Svedmark, 2002). Increasingly, land and water managers are seeking ways to manage reservoir releases to produce flow regimes that simultaneously meet human needs and maintain the health and sustainability of downstream biota (e.g., Poff and others, 1997; Patten and Stevens, 2001; Hughes and Rood, 2003; Postel and Richter, 2003; Richter and others, 2003; Rood and others, 2003; Rood and others, 2005; Arthington and others, 2006).

The Nature Conservancy (TNC) has developed an approach for defining “environmental flows” and is applying this approach to several rivers in the United States as a part of a collaboration with the U.S. Army Corps of Engineers (USACE) known as the Sustainable Rivers Project (Richter and others, 2006). The Sustainable Rivers Project is designed to evaluate and, if necessary, recommend changes to dam operations to restore and protect the health of rivers and surrounding natural areas while continuing to meet human needs for services such as flood control and power generation. The definition of ecological flow requirements is the first step in a methodology, known as ecologically sustainable water management, which guides decisionmaking at those USACE dam sites across the country that participate in the Sustainable Rivers Project (see *http://nature.org/success/dams.html* for more details regarding the Sustainable Rivers Project).

Ecosystem Flows

An ecosystem flow is the flow of water in a river or lake that sustains healthy ecosystems and the goods and services that humans derive from them. Effective quantification of these flows includes the ecologically important range of flow magnitudes (low flows, high flow pulses, and floods), as well as the timing, duration, frequency, and rate of change of these flow conditions. Globally, these flows are most commonly referred to as “environmental flows”. In this report, “ecosystem flow requirements” are the specific quantified flows defined during the Bill Williams River Ecosystem Flow Workshop and considered necessary for sustaining the health of the Bill Williams River ecosystem.

This document is part of an effort to define a set of ecosystem flow requirements (see box at right) for the Bill Williams River (BWR) downstream of Alamo Dam in western Arizona (fig. 1), one of the USACE/TNC focus rivers. In addition to USACE and TNC involvement, the BWR effort is being undertaken by a multiagency/entity group (the Bill Williams River Corridor Steering Committee) that meets on an approximately quarterly basis to coordinate resource management and prioritize research needs associated with the BWR. In the context of the BWR and Alamo Dam, the focus of both the steering committee and the technical and resource support made possible by the USACE–TNC agreement is to use the definition of flow requirements as a means to (1) assess current dam operations and their effect on the downstream aquatic and

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riparian ecosystems and (2) identify changes in reservoir management that will restore and protect downstream ecosystems. By design, this work to define ecosystem flow requirements will also advance the steering committee's firm commitment to develop and implement an adaptive management and monitoring plan. This plan will be used to evaluate ecosystem response to current and future management of Alamo Dam.

The current effort to articulate ecosystem flow requirements for the BWR builds upon reoperation analyses that date back to the early 1990s. This earlier work came about through recognition by many interested parties that conflicts regarding Alamo Dam operations between stakeholders were probable and that any approach to reoperating Alamo Dam had to provide a means to resolve these likely conflicts. This effort culminated in the 1994 endorsement of a new approach to managing Alamo Dam (as embodied by the Bill Williams River Corridor Technical Committee's (1994) water management plan) and the issuance of a new water control manual by the USACE in December of 2003. By the end of the 1990s, it had become clear that improvements could be made to existing models of reservoir release routing and that a comprehensive adaptive management and monitoring plan to assess dam operations had not been developed and implemented. These factors, coupled with advancements made in river science over the past decade, have served as motivators to engage in the current approach to generate ecosystem flow requirements.

Much of the content of this document was originally used as background material on various aspects of the BWR by participants in a workshop, the Bill Williams River Ecosystem Flow Workshop, held in Tempe, Ariz., March 16 to 18, 2005. The purpose of the workshop was to define a set of flow requirements for sustaining the long-term ecological health of the BWR corridor with the overall goal of maximizing native biodiversity within the BWR flood plain. Specific topics covered in this document include surfacewater and groundwater hydrology, channel structure and geomorphology, and the ecology of the riverine and riparian systems including vegetation, aquatic organisms, small mammals, reptiles, amphibians, avifauna, and ecosystem function. The document draws on information that pertains directly to the BWR, as well as on relevant publications from other river systems in the Southwest or from around the world. The Bill Williams River Ecosystem Flow Workshop was attended by over 50 scientists and water and natural resource managers representing over 20 agencies and institutions. Workshop participants included experts with a broad array of relevant expertise. The flow requirements defined during the workshop built on over 15 years of flow-related work on the river system and are designed to support adaptive management of Alamo Dam. The final chapter (chapter 8) of this document summarizes the process, discussions, and results of the workshop.

Study Area Description

The BWR drains more than 13,000 km^2 (5,200 mi^2) of rugged, mountainous terrain in west-central Arizona. It is the largest tributary of the Colorado River between the Virgin and Gila Rivers. The name "Bill Williams River" is applied to the river segment extending from the confluence of the Big Sandy and Santa Maria Rivers to the Colorado River confluence at Lake Havasu (fig. 1). The watershed of the BWR spans diverse physiography ranging from high-elevation forested mountains along the western margin of the central highlands province to low-lying, rugged desert mountains and intervening alluvial valleys in the basin and range province. The course of the Big Sandy River approximates the boundary between these two provinces. Average annual precipitation in the watershed ranges from approximately 45 cm (17.7 in.) in the headwaters to 22.5 cm (8.86 in.) near Alamo Dam (National Climatic Data Center station Alamo

Dam) to 12.1 cm (4.76 in.) near the Colorado River (National Climatic Data Center station Parker 6NE).

The BWR extends about 65 km (40.4 mi), its upstreammost 6.5 km (4.0 mi) now consisting of water impounded behind Alamo Dam, a flood-control structure which was completed in 1968 and has a reservoir storage capacity of approximately 1,233 m^3 x 10^6 (43,540 ft^3 x 10^6). Downstream of the dam, the BWR flows 58.5 km (36.4 mi) with an average gradient of 0.003 (range of 0.001–0.009) to its confluence with the Colorado River (at Lake Havasu) at an elevation of 137 m (449 ft) (fig. 1). The BWR passes through canyons (fig. 2) interspersed with alluvial valleys, including the 10.6-km-long (6.6 mi-long) Planet Valley, a significant hydrological control on flows in the 14.5 km (9.0 mi) of river between the basin and the confluence with the Colorado River (fig. 3). Different investigators have divided the BWR into reaches, based primarily on differences in valley width, reliability of surface flow, and distance downstream of Alamo Dam (House and others, 1999; TetraTech. Inc., 2002; Shafroth and others, 2004) (fig. 4). No perennial tributaries enter the BWR downstream of Alamo Dam. Channel bed and floodplain sediments are dominated by coarse particles (81 percent), primarily sand (67 percent), and are generally low in electrical conductivity (ca. 1.0 dS/m). Flows of 35.1 m^3/s (1,240 ft^3/s) and larger readily transport the poorly consolidated sand.

Human use is minimal along the BWR corridor. Although extensive alfalfa (*Medicago sativa*) farming and associated groundwater pumping occurred within the Planet Valley Basin historically and as recently as the early 1990s, agriculture is currently limited to a single cotton (*Gossypium* spp.) farm along a 2.6-km (1.6-mi) reach of the BWR (within Reid Valley; see fig. 4). Along the BWR, cattle legally graze only a small area within Planet Valley, though trespassing cattle occasionally utilize reaches of the river upstream of Planet Valley. Feral burros are present throughout the study area, but their grazing and browsing impacts appear to be relatively minor. Four-wheel-drive vehicles commonly drive through a stretch of county road (and occasionally on unroaded portions of the flood plain) in the bottomland within the Bill Williams River National Wildlife Refuge and also within the flood plain on State of Arizona land, private land, and some Bureau of Land Management (BLM) land upstream of Planet Valley.

Flow-Biota Relations

After a chapter on the BWR's hydrology and geomorphology (chapter 2), the next five chapters (chapters 3–7) of this report contain discussions of relationships between streamflow and various physical and biological aspects of the BWR. These chapters were provided to workshop participants as background material. Some of these discussions are general, but throughout the document we also refer to several categories of streamflow (described below). These categories were used during the ecosystem flow workshop to help structure discussions related to flow requirements of different parts of the river system. Flows are discussed in terms of flow timing or seasonality and flow magnitude (floodflows and baseflows). Discussions of flow-biota connections are presented both in terms of broad relationships and also in the context of key taxa or guilds about which there was a relatively substantial base of information available.

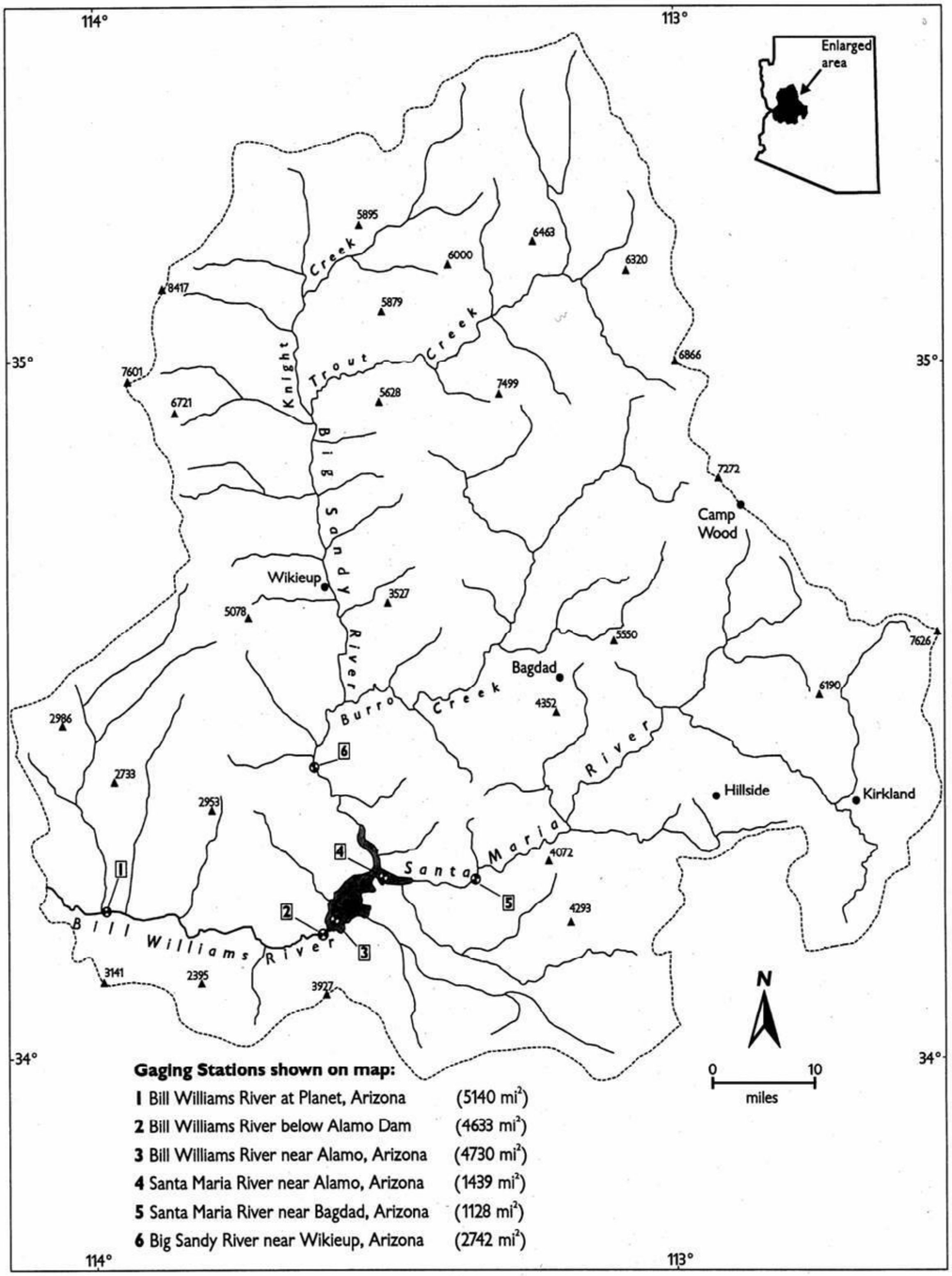

Figure 1. Map of the Bill Williams River Basin, Ariz.

Figure 2. Canyon reach of the Bill Williams River, Ariz. Photograph by Patrick Shafroth, U.S. Geological Survey.

Figure 3. Alluvial valley reach of the Bill Williams River, Ariz. Photograph by Patrick Shafroth, U.S. Geological Survey.

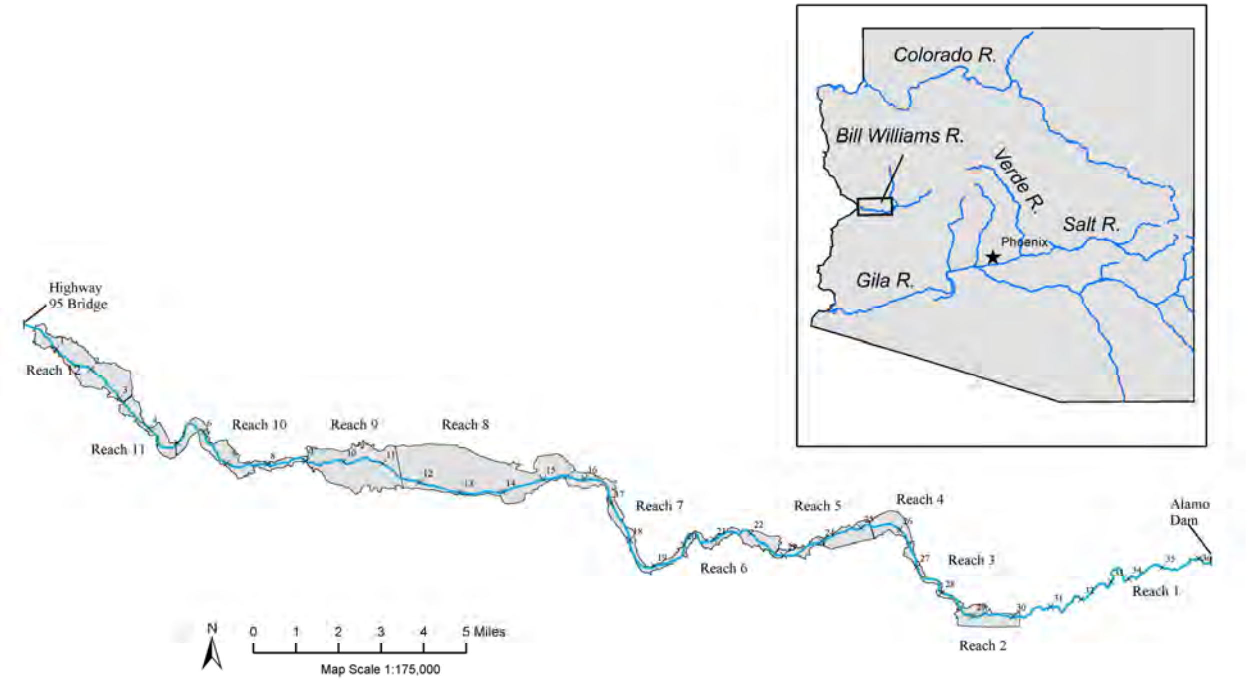

Figure 4. Map of the Bill Williams River, Ariz. Showing river miles upstream from the Highway 95 bridge crossing and twelve reaches. Reach boundaries were based on a combination of valley width and alluvial groundwater dynamics (Shafroth and others, 2004).

Flow Categories

Flow Timing

We have defined four seasons and the precipitation events and flow conditions that may occur within each season. These are September 15–November 15: tropical storms; November 15–April 30: winter-spring frontal storms; May 1–June 30: dry; July 1–September 15: monsoons.

Flow Magnitude

We distinguish two flow magnitude groups: floodflows and baseflows. Floodflows include flood magnitude, frequency, duration, and rates of flow recession or drawdown following the flood. Flood peaks can be flows greater than or equal to 28.3 m^3/s (1,000 ft^3/s). Flow recessions or drawdowns extend from the flood peak down to baseflow levels, which we define here as less than or equal to 2.8 m^3/s (100 ft^3/s). Within both the floodflow and baseflow groups, we have identified three magnitude classes and estimated various associated physical effects (table 1a, b). Direct and indirect effects on particular biota are discussed in more detail within each section below.

Table 1a. Estimated physical and biological effects of different magnitude floods on the Bill Williams River, Ariz.

[CPOM = Coarse particulate organic matter; FPOM = fine particulate organic matter]

	Large flood	Moderate flood[1]	Small flood
Flow range	30,000 ft^3/s or greater	5,000–30,000 ft^3/s	100–5,000 ft^3/s
Channel geomorphology	Channel avulsion. Channel geometry change and formation of new channels. Channel widening and deepening.	Some channel migration, widening, local deepening (magnitude and duration dependent).	No significant changes to channel geomorphology.
Sediment	Extensive sediment erosion and deposition, including channel bed sediment, tributary fans, and channel banks in incised reaches. Complete turnover of instream sediments.	Some bare substrate generated via sediment mobilization (erosion and deposition).	Turnover of some sediments.
Beaver	Removal of essentially all beaver dams.	Removal of most beaver dams.	Removal of few beaver dams, damage to some.
Vegetation	Removal of mature trees in some floodplain locations. Removal of most herbaceous vegetation.	Mechanical damage or removal of smaller woody plants in broad floodplain reaches; large woody plants damaged or removed in narrow reaches. Some herbaceous vegetation scoured.	Some mechanical damage to near-channel riparian vegetation.
Flood plain	Creation of new off-channel aquatic habitats such as pools, destruction or filling of old off-channel habitats. Wetting of entire flood plain.	Refresh and/or rescour existing off-channel aquatic habitats. Some creation of new off-channel aquatic habitats such as pools, and some destruction or filling of old off-channel habitats (magnitude dependent). Most of flood plain wetted.	Refilling of some (lower lying) existing off-channel habitats without major scouring. Some of floodplain wetted.
Organic matter	CPOM and FPOM removed.	Some CPOM and FPOM removed.	Little CPOM or FPOM removed.
Groundwater	Alluvial groundwater and soil moisture recharge.	Alluvial groundwater and soil moisture recharge.	Partial recharge of alluvial groundwater and soil moisture.

[1] A wide range of effects is possible within this flow range, representing a gradient between responses associated with large and small floods.

Table 1b. Estimated effects of different magnitude baseflows on surface and ground water of the Bill Williams River, Ariz.

	High baseflow	**Moderate baseflow**	**Low baseflow**
Flow range	50–100 ft^3/s	10–50 ft^3/s	0–10 ft^3/s
Surface flow	Surface flow maintained throughout the year in all reaches except east end of Planet Valley.	Surface flow maintained in winter months in all reaches except east end of Planet Valley. Surface flow may be absent during some or all of the spring, summer and fall months from several river reaches (e.g., upstream end of Rankin Valley, from near Swansea to west end of Planet Valley, and from Kohen Ranch downstream on refuge).	Surface flow absent throughout the year from several river reaches (e.g., upstream end of Rankin Valley, from near Swansea to west end of Planet Valley, and from Kohen Ranch downstream on refuge). During some/all of the spring, summer and fall months, surface flow also may be absent through more of the river's length (e.g., above reaches plus more of Rankin Valley, from gas pipeline crossing down to near Swansea, and on refuge from Mohave Wash down to Kohen Ranch).
Ground water	Alluvial water tables fully charged and relatively stable.	Dynamic alluvial water tables, with summertime declines of 1–3 m (3–10 ft) in intermittent flow reaches.	Relatively deep alluvial water tables, including 1–4 m (3–13 ft) summertime declines in intermittent reaches.

Chapter 2. Hydrology and Fluvial Geomorphology

By P. Kyle House[1], Patrick B. Shafroth[2], and Vanessa B. Beauchamp[2]

Regional Hydroclimatology

Streamflow in most large rivers in Arizona corresponds to a distinct regional hydroclimatologic pattern with a mixture of regional and local storms. Streamflow in rivers draining the central highlands of Arizona is primarily controlled by precipitation from dissipating tropical cyclones in the late summer and fall and by regional-scale winter frontal storms in the late fall, winter, and early spring (Webb and Betancourt, 1992; Ely and others, 1994; House and Hirschboeck, 1997). Isolated summer and fall monsoonal thunderstorms rarely result in significant runoff in large river basins, but they can have an important local impact on smaller tributaries and can contribute to the system's overall discontinuous nature of sediment input and channel response (e.g., House and Pearthree, 1995; House and Baker, 2001). Interestingly, flow regulation on the BWR is such that flashfloods from some tributaries can equal or even exceed the peak discharge of maximum flow releases from Alamo Dam (e.g., scenarios described in Gatewood and others, 1946; Hansen and Schwartz, 1981).

The most significant types of flow-generating storms in the BWR Basin and similar basins in the Lower Colorado River drainage are demonstrably linked to El Niño or positive El Niño Southern Oscillation (ENSO) conditions that vary over decadal and centennial time scales. These storms influence the probability of higher than average regional precipitation and, hence, streamflow on most rivers in the Southwest (Hirschboeck, 1985; Andrade and Sellers, 1988; Redmond and Koch, 1991; Webb and Betancourt, 1992; Ely, 1997; House and Hirschboeck, 1997). La Niña (or negative ENSO) conditions have an opposite effect and are more likely to be associated with below average precipitation and runoff (Redmond and others, 2002). These relations are relatively strong for most rivers in the historical record, and some studies indicate that they have had similar influence during the last 3,500–5,000 years on rivers in the Southwest (Ely, 1997), including the BWR.

Surfacewater Hydrology

At the site of Alamo Dam, the contributing drainage area to the BWR is approximately 11,200 km^2 (4,330 mi^2). The Big Sandy River Basin constitutes 65 percent (ca. 7,280 km^2 (2,810 mi^2)) of this area and contributes the majority of streamflow to the BWR. The Santa Maria River Basin constitutes the remaining 35 percent (ca. 3,940 km^2 (1,520mi^2)). At its mouth, the BWR drains an estimated 13,470 km^2 (5,200 mi^2), making it the third largest drainage basin that lies completely in Arizona. Despite the smaller watershed area, several of the largest reported historical peaks on the BWR are comparable to or even larger than corresponding peaks on the Salt (16,140 km^2 (6,232 mi^2)) and Verde (16,190 km^2 (6,250 mi^2)) Rivers. Low flows on the BWR were typically lower than those on the Salt and Verde Rivers, both of which receive perennial flow from tributaries along the margin of the Colorado Plateau. The unregulated BWR flow regime was more variable and lower magnitude overall and showed a slightly greater response to storms in the late summer and fall than did the Salt and Verde Rivers. Since 1969,

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the hydrologic regime of the BWR has been significantly altered by flow regulation through Alamo Dam, which is located below the Big Sandy-Santa Maria confluence and is now the de facto head of the BWR.

Stream gaging records in the BWR Basin are limited in spatial and temporal scope, but adequate data exist to characterize the predam and postdam flow regimes. Each station is shown on the map in fig. 1, and the corresponding annual flood series are shown in fig 5. For this report, we evaluated the period of record up to and including water year 2003.

Big Sandy and Santa Maria Rivers

The only stream gage on the Big Sandy River (near Wikieup, Ariz., USGS #9424450) is located near Signal, Ariz. about 48 km (30 mi) south of Wikieup and approximately 24 km (15 mi) upstream of the Big Sandy River-Santa Maria River confluence. The Big Sandy River drains 7,280 km^2 (2,810 mi^2) at the gage site. The official period of record is 1966–2003. There have been two gaging stations on the Santa Maria River , and the composite period of record is 1939 to the present. The station "Santa Maria River near Alamo" (USGS #9425500) was moved upstream to the station "Santa Maria River near Bagdad" (USGS #9424900) in 1967 to eliminate the influence of inundation and backwater effects from Alamo Lake. The resultant decrease in the contributing drainage area was 806 km^2 (311 mi^2).

Peak Flows

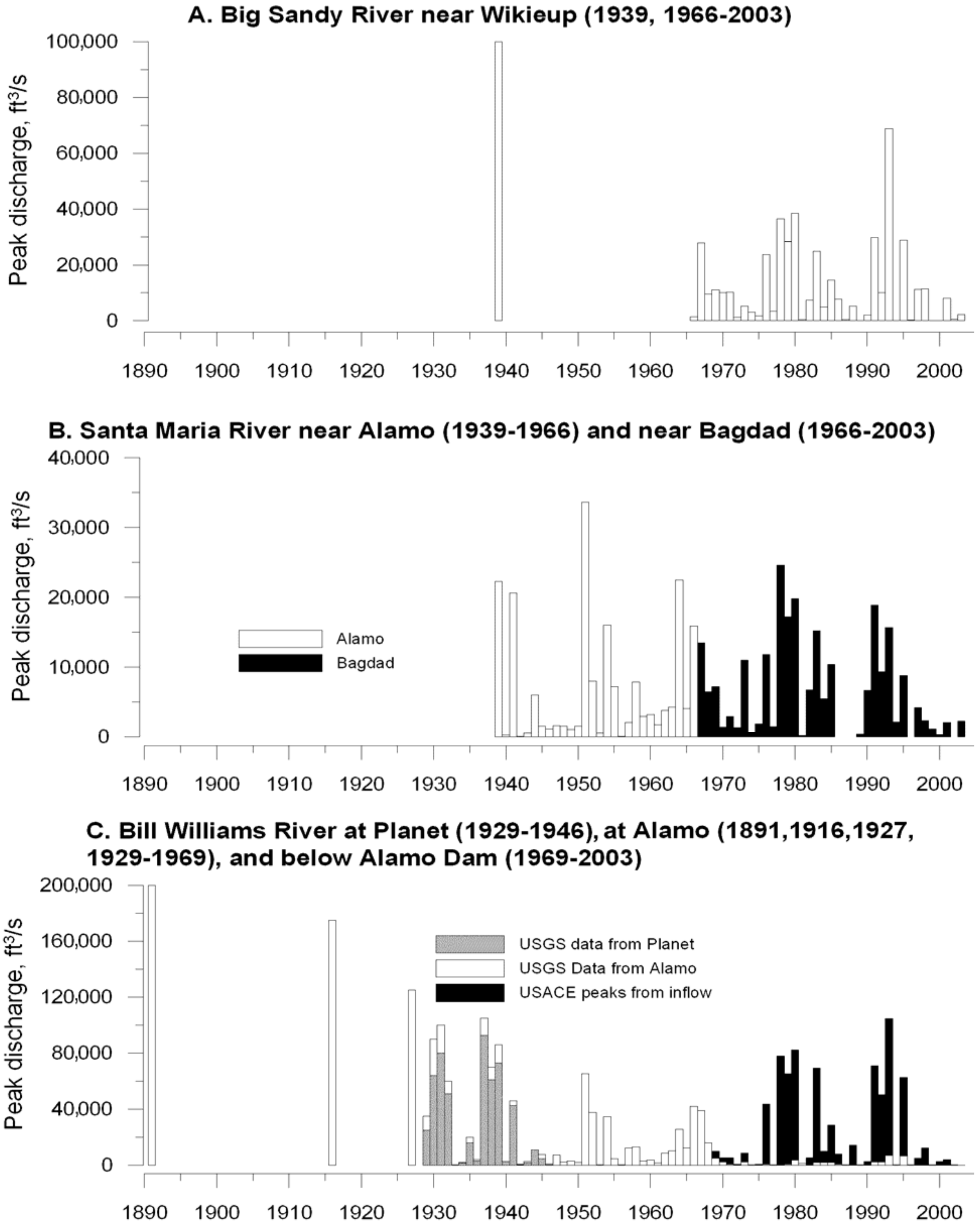
On the Big Sandy River, the flood of record of 1,945.4 m^3/s (68,700 ft^3/s) was recorded on February 9, 1993. Most of the peak flow in this event came from Burro Creek, a major tributary that joins the Big Sandy River 7 mi. upstream of the gage. Burro Creek recorded a peak discharge of 1,565.9 m^3/s (55,300 ft^3/s) 3 hours before the peak on the Big Sandy River (fig. 5a). The notable historical discharge estimate of 2,831.7 m^3/s (100,000 ft^3/s) was reported from near the gage site in September 1939 (Gatewood and others, 1946). This event resulted from a series of tropical storms that flooded large parts of southern California and western Arizona. On the Santa Maria River, the flood of record is 951.5 m^3/s (33,600 ft^3/s) (at the gage near Alamo), which occurred in August 1951 (fig. 5b).

Average Daily Flows

Some descriptive statistics of the daily streamflow records from each BWR tributary site are summarized in table 2 (from House and others, 1999). On the Santa Maria River, the change in the gaging station location in 1967 affected daily flow values. The station near Alamo Dam has a 27-year record (1939–66) and recorded no days of zero flow. Over a comparable period of time, the record station near Bagdad, Ariz. (after 1967), recorded 6,474 days of zero flow. Thus, for approximately 65 percent of the 9,662 days in the record, there was no streamflow at the gage. Average monthly flows in the post-Alamo Dam era are illustrated in figure 6.

Bill Williams River

There have been two primary gaging stations on the BWR. The earliest stations were "Bill Williams River near Swansea" (1910–12), followed by "Williams River near Swansea" (1913–15), "Williams River at Planet" (1928–43), and finally "Bill Williams River at Planet" (1943–1946). Examination of historical surfacewater records indicates that each of these corresponds to the same station located about 1.6 km (1 mi) downstream from the site of Planet, Ariz.



A. Big Sandy River near Wikieup (1939, 1966-2003)

B. Santa Maria River near Alamo (1939-1966) and near Bagdad (1966-2003)

C. Bill Williams River at Planet (1929-1946), at Alamo (1891,1916,1927, 1929-1969), and below Alamo Dam (1969-2003)

Figure 5. Annual flood series for the Big Sandy, Santa Maria, and Bill Williams Rivers, Ariz.

Table 2. Daily streamflow characteristics of the two principal tributaries of the Bill Williams River, Ariz.

[Discharges are in cubic feet per second (ft^3/s)]

Parameter	Big Sandy River near Wikieup	Santa Maria River near Alamo	Santa Maria River near Bagdad
Period of record	1966–2003	1939–1966	1967–2003 (missing 1986–1988)
Mean	80	34	56
Median	6	3	0
Mode	8	2	0
Standard deviation	646	325	324
Coefficient of variation	8.1	9.6	6.1
Count	13,700	9,648	12,584
Zero values	0	0	8,774
Missing values	0	0	1,096
Minimum	1.3	0.1	0.0
Maximum	26,100	15,500	8,410

In 1939, a second gage on the BWR was established near Alamo, Ariz. In April 1968, the gage was moved 2.7 km (1.7 mi) downstream to a point below Alamo Dam, which was completed in that year. The annual flood series for the BWR at Planet and Alamo are both shown in the lower graph on figure 5. In the interval 1929–1939 (except for 1937), the most recently compiled data in Pope and others (1998) for the Alamo site are extrapolated from the Planet site (discharges slightly lower). Each data set is provided in figure 5c for reference and comparison. Postdam annual peaks are values reconstructed from reservoir inflow (United States Army Corps of Engineers, 2003).

Effects of Alamo Dam Operation on the Bill Williams River Flow Regime

Peak Flows

Three large historical floods in 1891, 1916, and 1927 are listed in the records for the gage at Planet and the gage at Alamo (fig. 5c). According to Patterson and Somers (1966), these values are estimates made by using floodmarks in "Striped Canyon," about 37 km (23 mi) upstream from Planet. This site is near the present location of Alamo Dam, and the reported discharges, though likely maximum estimates (House and others, 1999), are most appropriately related to the record from the gage sites nearer to Alamo. The effect of the dam on annual peak discharges is extreme. The largest postdam instantaneous peak discharge is 197.6 m^3/s (6,980 ft^3/s), which occurred in March of 1993. This value is less than 11 percent of the maximum instantaneous peak in the official period of record and less than 5 percent of the largest reported historical peak discharge. The postdam maximum discharges are limited by the capacity of the dam outlet structures.

To quantify the effects of the dam on peak flow frequency, we analyzed the predam and postdam peak flows from the Alamo site data sets by using FLDFRQ3, a Bayesian statistical model developed by the U.S. Bureau of Reclamation (described in O'Connell and others, 2002). The results are shown in table 3 and figure 7. Weibull plotting positions for both data sets were fitted to the log-Pearson 3 distribution, and the values in the table are from the fitted curve. The tremendous difference between the two data sets reflects the magnitude of peak flow reduction

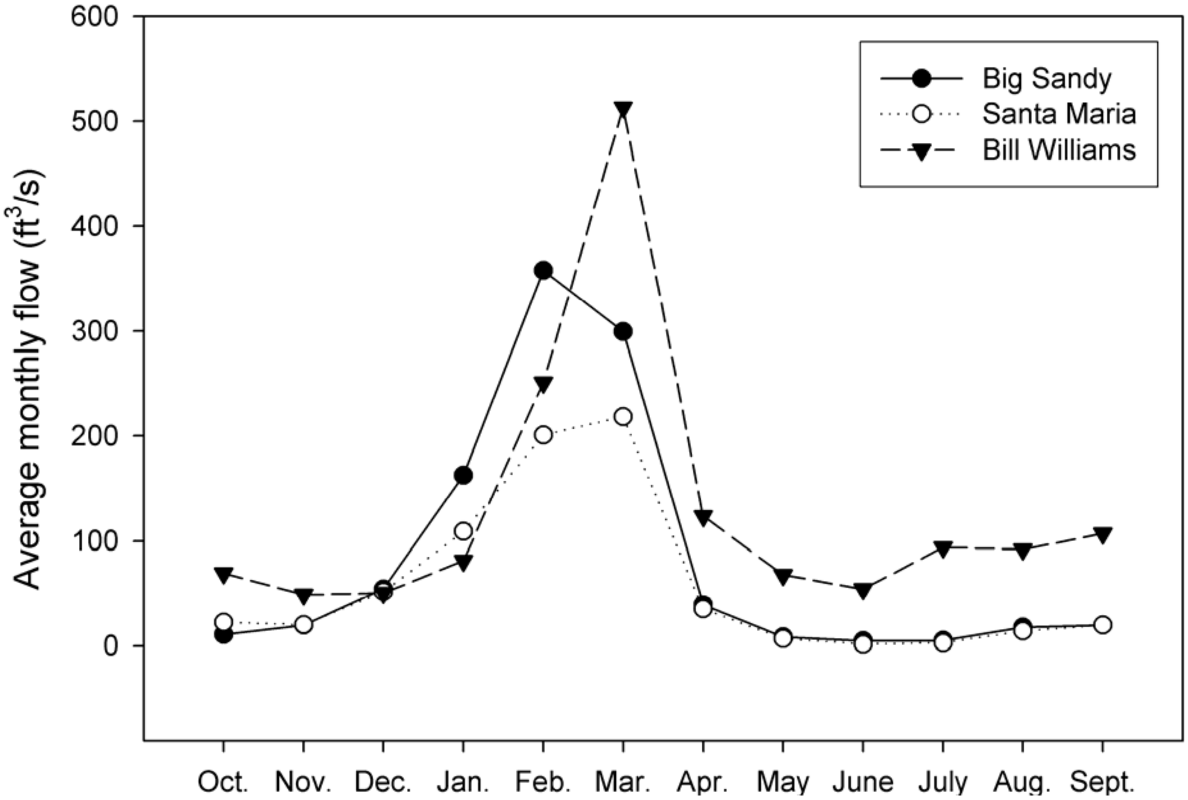


Figure 6. Average monthly flow for the postdam period on the Bill Williams, Santa Maria, and Big Sandy Rivers, Ariz (1969–2003).

Table 3. Summary statistics of predam and postdam peak flood series for the Bill Williams River, Ariz.

[RI = Return interval for the specified flow magnitude]

R.I.	Predam	Postdam	Change
1.33	2,920	159	95%
10	63,945	3,949	94%
20	87,239	5,224	94%
50	11,4721	6,580	94%
100	13,2427	7,364	94%
200	14,7459	7,970	95%
500	16,3582	8,556	95%

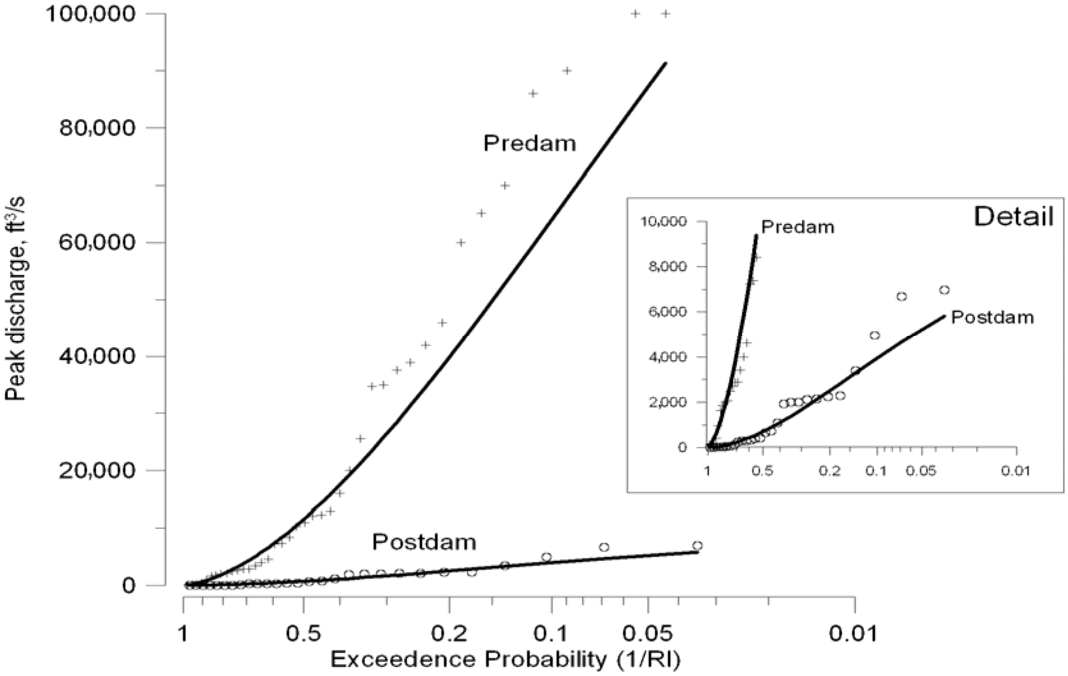


Figure 7. Log-Pearson analysis of annual peak flows for the Bill Williams River, Ariz. RI = Return interval; Predam values are shown with plus symbols, post dam values are shown with open circles.

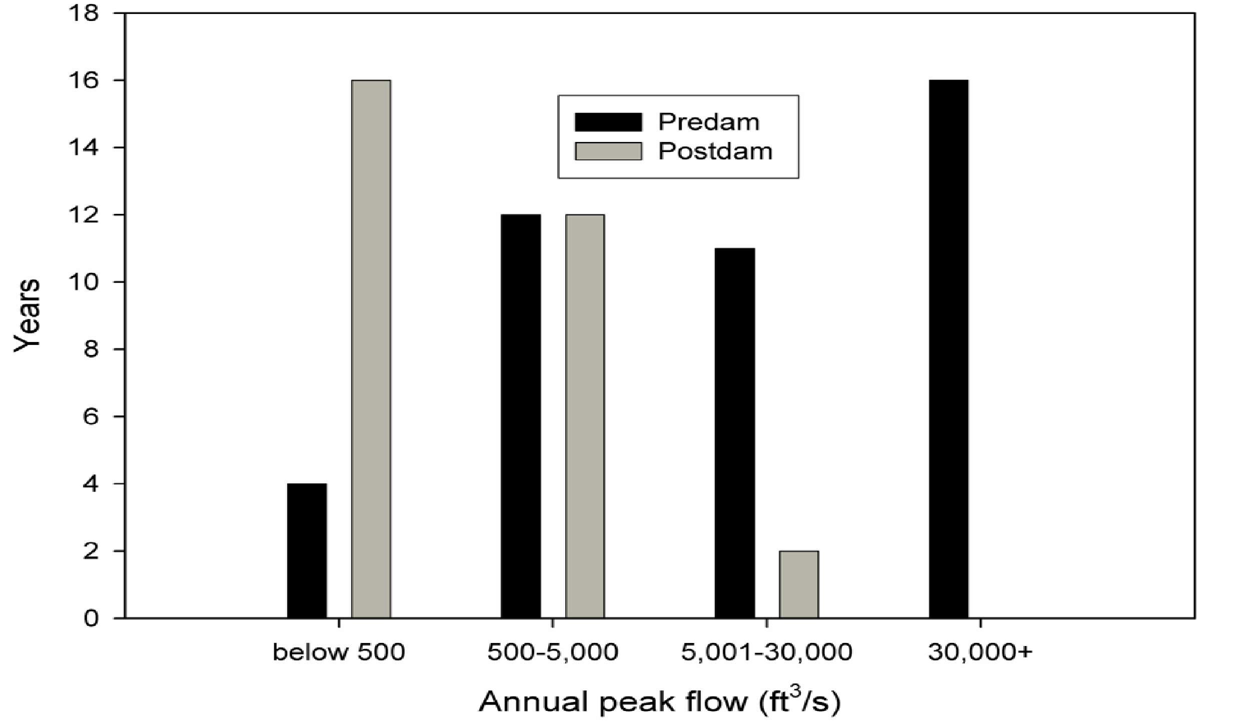


Figure 8. Frequency distribution of annual instantaneous peak flows in the high flow categories for the predam (43 years) and postdam (30 years) periods at Bill Williams River below Alamo Dam, Ariz.

associated with Alamo Dam. Although the regulated flow regime violates most assumptions of the statistical analysis, the comparison serves an important purpose by clearly showing the magnitude of the change. The steep predam curve represents a highly variable flood regime in which the difference between average flows and flood flows is very large, typical of an arid-region river. The flat postdam curve indicates extremely low variability and small differences between average and extreme flood conditions. For example, the maximum postdam peak discharge corresponds to a 1- to 2-year flood in the predam era. The frequency distribution of annual peak flows in the floodflow categories presented above is illustrated in figure 8.

Average Daily Flows

Descriptive statistics of the predam and postdam average daily streamflow values in Table 4 (House and others, 1999) summarize striking hydrological changes on the BWR associated with flow regulation through Alamo Dam. Because Alamo Reservoir serves the primary purpose of storage and flood control, it is not depleted by consumptive use, and thus the annual flow volume has not been much affected by the existence of the dam, except for the effect of evaporation from the reservoir surface, which can be significant under certain conditions (United States Army Corps of Engineers, 2003). Climatic factors have resulted in some predam versus postdam flow differences. For example, the mean flow in the postdam era (3.6 m^3/s (128 ft^3/s)) was considerably higher than that in predam era (2.6 m^3/s (93 ft^3/s)). Median annual flows however, were more similar (predam median = 0.27 m^3/s (9.4 ft^3/s), postdam median = 0.42 m^3/s (15 ft^3/s)), reflecting the strong effect of a few particularly wet years in the late 1970s and early 1990s on average values. Average monthly flows show some effect of dam operations. First, in the postdam era, high flows were less likely to occur in December or January (fig. 9). Second, on the BWR, flows from May through October were substantially higher in the postdam era than predam (fig. 9). The frequency of average daily flows in several categories, including the three baseflow categories used in this report (see “Flow Categories” in chapter 1, above), is illustrated in figure 10. Baseflows in the 1.4–2.8 m^3/s (51–100 ft^3/s) range were relatively uncommon both before and after the construction of Alamo Dam (fig. 10). Flows in the range of 0.31–1.4 m^3/s (11–50 ft^3/s) have been more frequent in the postdam era, while flows in the 0.003–0.28 m^3/s (0.1–10 ft^3/s) range were more common in the predam era (fig. 10). Flow regulation by Alamo Dam resulted in some zero flow days, which did not occur on the upper BWR prior to the construction of the dam. Most of these zero flow days occurred in the first several years following dam construction.

Table 4. Comparison of predam and postdam characteristics of daily streamflow on the Bill Williams River near Alamo and below Alamo Dam, Ariz., (modified from House and others, 1999).

[Discharges are in cubic feet per second(ft^3/s)]

Parameter	Predam	Postdam	Difference
Mean	93	128	38%
Standard deviation	692.3	468.7	-38%
Median	9.4	15	60%
Mode	11	11	0%
Coefficient of variation	7.4	3.7	-50%
Count	10,471	12,844	2,373
Zero values	0	699	699
Minimum	0.05	0	0.05
Maximum	25,200	6,980	-72%

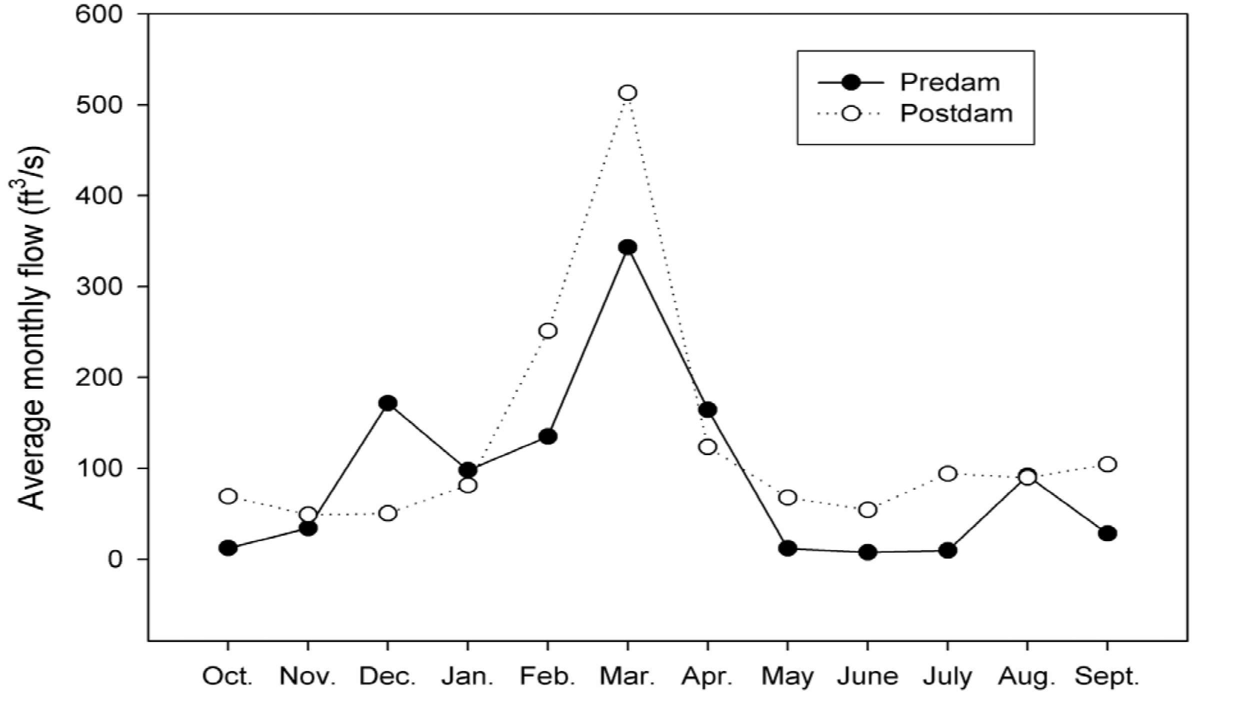


Figure 9. Average monthly flows for the predam (1940–1968) and postdam (1969–2003) periods at Bill Williams River below Alamo Dam, Ariz.

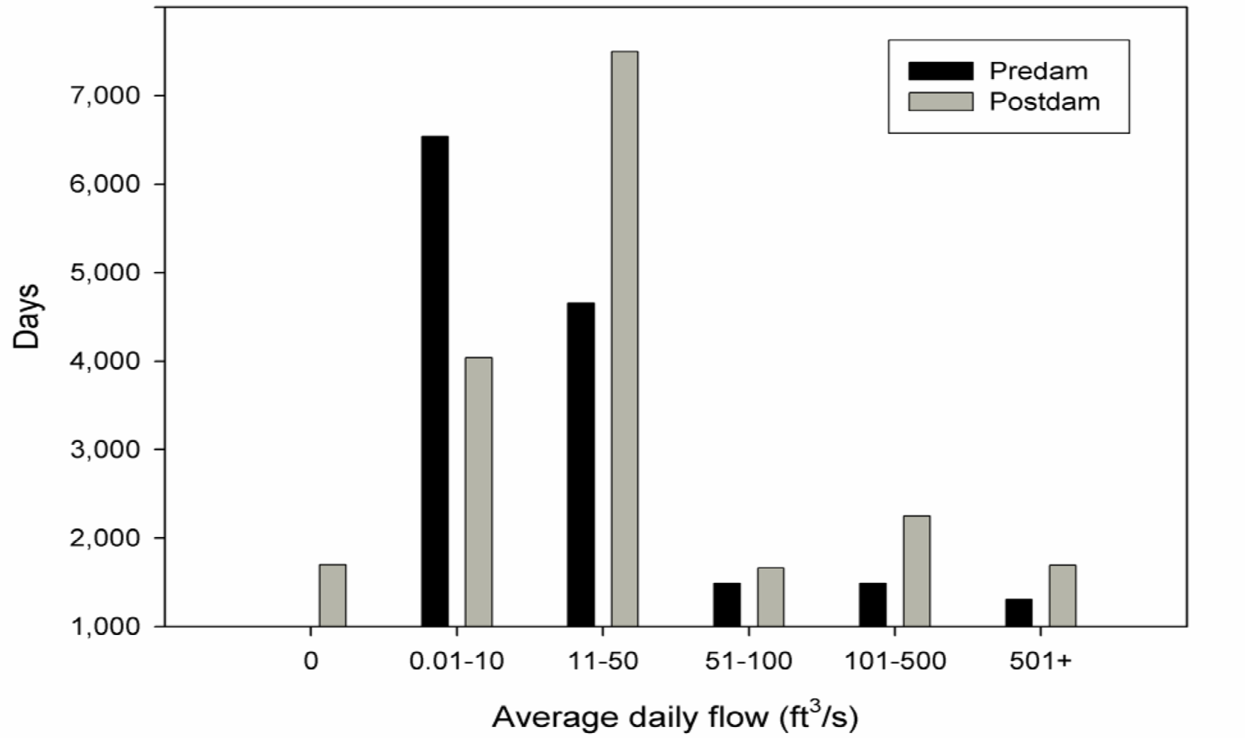


Figure 10. Distribution of average daily flows for the predam (10471 days) and postdam (12844 days) periods at Bill Williams River below Alamo Dam, Ariz.

Representative Crosssections and Stage-Discharge Curves

The topography of eight crosssections along the BWR was surveyed in January and February 1996. Crosssections were perpendicular to the low flow channel and extended from valley wall to valley wall. Four crosssections were located in a segment of the river between Alamo Dam and Planet Valley, and four were located downstream of Planet Valley (appendix A, table A1). Transects were selected to represent different reaches and hence exhibit variation in geomorphologic and hydrologic characteristics.

We used Manning's equation to estimate stage-discharge relationships at each of the crosssections, based on inputs of slope and surface roughness values (Manning's n; WEST Consultants Inc., 1998). We estimated slope from topographic maps (1:24,000) and Manning's n values from published sources (Arcement and Schneider, 1989). These results should be considered rough approximations only, as there are several sources of error associated with our estimates (e.g., poor calibration, mobile sand bed channel, coarse estimate of slope from topographic maps, two dimensional flow, effects of conditions upstream and downstream of the crosssections, etc.). Hydraulic modeling results are presented in appendix A (figs. A1–A8). For each crosssection, we have displayed estimates of the river stage (elevation), velocity, and wetted perimeter associated with flows ranging from 0 to 1,415.8 m^3/s (0 to 50,000 ft^3/s). In addition, a schematic of the cross-sectional topography and areas inundated at 14.2, 141.6, and 849.5 m^3/s (500, 5,000, and 30,000 ft^3/s) is presented to illustrate the approximate distribution of flow during floods at the low end of each of the three floodflow categories. Comparisons of results at the eight sites help to illustrate some of the variation in flood effects across a range of crosssections.

Fluvial Geomorphology

The BWR channel is characterized by a series of relatively narrow bedrock gorges separated by wider, alluvial reaches. Photographic and field evidence indicates that the bed of the river is filled with alluvium virtually throughout the length of the river. Bedrock is shallow and occasionally exposed in the narrow gorge downstream from the dam, and it may be shallow in other narrow canyon reaches. Minimal data exist to evaluate bedrock depth in detail, however. At low flows, the river follows a braided pattern characterized by relatively low sinuosity channels separated by medial braid bars composed of sand and gravel. During high flows (prior to the dam) the channel apparently occupied nearly all of the late Holocene flood plain, even in alluvial valleys that are nearly 3.2 km (2 mi) wide (i.e., Planet Valley). During low flow periods, streamflow in the river is intermittent, with surface flow only typical of narrow canyon reaches and subsurface flow in the wider valley reaches. In general, the upper ends of the valleys are losing reaches, and the lower ends are gaining reaches where throughflow resurfaces.

Longitudinal Profile

The longitudinal profile of the BWR was determined from available 7.5-minute topographic maps and digital orthophoto quadrangles (fig. 11). The channel length was determined by digitizing the thalweg and calculating cumulative distance from point to point beginning at the Highway 95 Bridge at Lake Havasu and ending at the stream gage below Alamo Dam. Elevations were simply taken from points where the thalweg crossed contour lines on the maps.

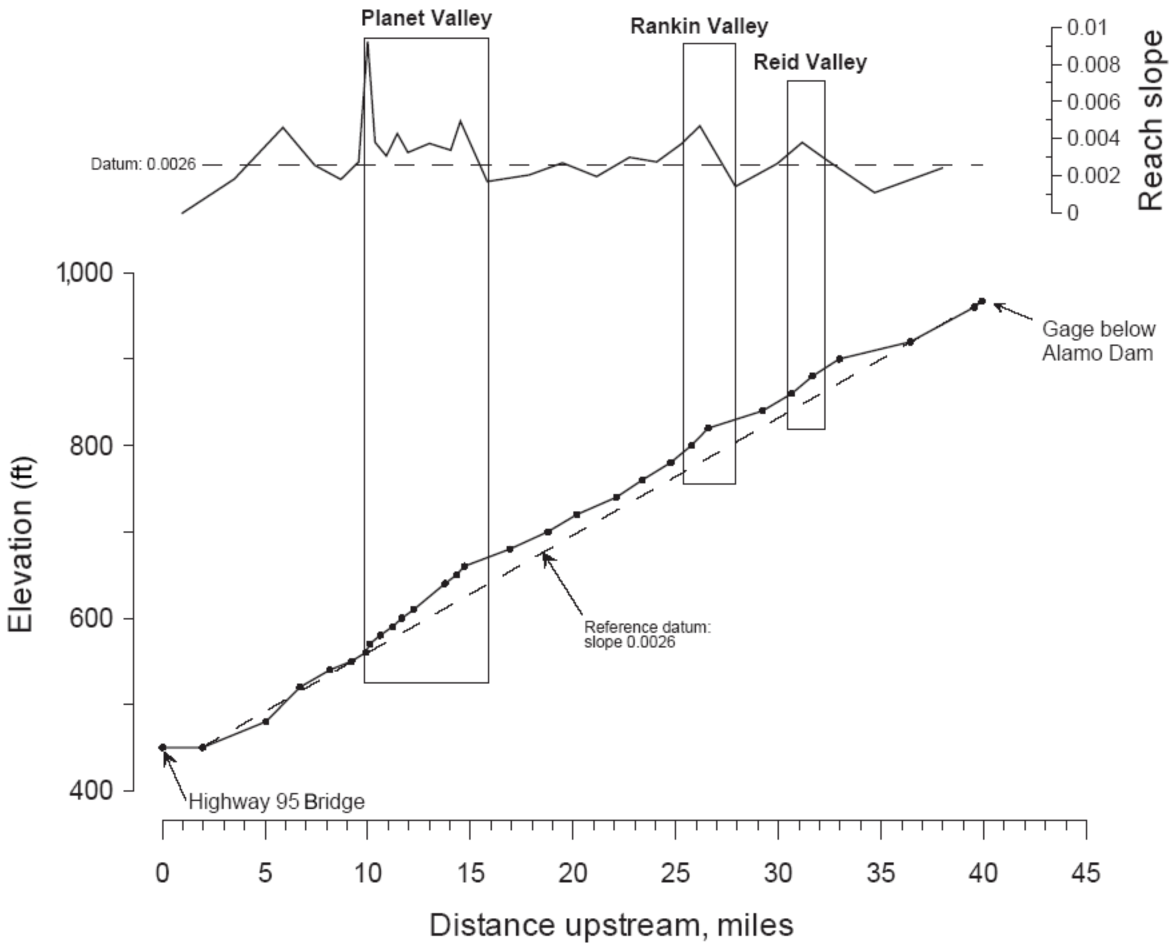


Figure 11. Longitudinal profile of the Bill Williams River, Ariz., from Alamo Dam to the Highway 95 Bridge.

The patterns evident from the longitudinal profile likely reflect the discontinuous nature of the channel morphology and (likely) its predam mode of sediment transport and storage. Distinct increases in the channel gradient occur in close proximity to entrances to the alluvial valleys, and rapid decreases in gradient occur below or near the downstream end of the valleys. In the predam condition, sediment conveyed through the canyons was deposited in broad (sometimes valleywide) areas of flow expansion below the head of each valley. This sediment deposition pattern is an inevitable consequence of the alternating gorge and valley morphology, and large-scale flow expansion in the valleys is clearly evident in predam aerial photography (House and others, 1999). Aggradation of sediment increases the channel gradient, and incision into alluvial fill decreases channel gradient. At the downstream end of each valley, changes in channel gradient from steep to gentle reflect incision into the valley fill. In each flood event, a wave of sediment liberated from the valley fill is passed into the next gorge and deposited in the next area of flow expansion. Over time, the overall morphology is maintained, but waves or slugs of sediment have moved farther down the system. In the postdam era, this process is maintained but is occurring at a different spatiotemporal scale and subject to some different controls, including net decrease in sediment, attenuation of peak discharge, and sustained low and moderate flows.

The sediment trapping above Alamo Dam will have inevitable and likely irreversible effects on the process of sediment movement through the system, as the available external sediment is progressively reduced at the expense of sediment resources in the valley bottom. The upper reaches of the BWR will be more heavily impacted by sediment depletion than will lower reaches because sediment flushed from the upper part of the BWR is stored in the middle and lower reaches, but the zone separating net storage from net loss is expected to move downstream over time.

The vast amount of sediment storage is taking place in the lower reaches of the river (below Planet Valley). Channel roughness in the lower reaches is associated with dense vegetation cover is conducive to sedimentation by retarding flow velocities and enhancing infiltration. The river terminates with a delta in Lake Havasu, and sedimentation is greatly enhanced by the interaction of the river with a standing body of water. Base-level rise in Lake Havasu can increase sedimentation, but this effect is likely to be restricted to a short reach upstream. The effect of base-level fall in Lake Havasu during periods of BWR input (though likely rare) would have much more significant geomorphic consequences by enhancing river incision into the zones currently receiving a net input of sediment.

Tributaries can also be important sources of sediment, particularly in arid-land systems. According to paleoflood studies and comparison of historical aerial photographs reported in House and Baker (2001), however, the relative sediment input by tributaries in the BWR watershed is extremely discontinuous in space and time. The reliability of sediment input by tributaries is low and the ability of regulated flows to move the higher caliber portion of this sediment is also questionable. Photographic comparisons show that the last flow to obliterate tributary fans occurred in the 1960s and was definitely larger than the maximum dam releases in the modern regime. Furthermore, the tributaries with the largest drainage areas that contribute the most sediment most frequently (e.g., Mohave Wash, Castaneda Wash, and Centennial Wash) enter the BWR in the lower reaches beginning near Planet Valley, where sediment depletion is currently less of a problem.

Predam Condition

The predam geomorphology of the BWR has been characterized through analysis of predam aerial photographs (House and others, 1999; Shafroth and others, 2002). House and others (1999) used aerial photographs from 1953 to map the predam baseline geomorphology of the BWR channel at a 1:24,000 scale. The maps indicate that the predam channel morphology was dominated by the effects of relatively high-magnitude floods. The 1953 photographs were taken after a relatively large flood, which occurred in August 1951 (1,843.4 m^3/s (65,100 ft^3/s) and a smaller flood in water year 1952 (1,064.7 m^3/s (37,600 ft^3/s)), so the specific effects of these events are well preserved on the photographs (fig. 12). The predam BWR channel was conspicuous in the broad extent of active braided channels and flanking alluvial surfaces. Throughout most of the channel length from the present base of Alamo Dam to the downstream end of Planet Valley, active alluvial surfaces cover most of the available valley bottom, except in Reid Valley, where agricultural activities were constraining the width of the channel somewhat. Remarkably, the entire width of Planet Valley was subject to inundation during large predam floods, which is evident in the 1953 photographs and in General Land Office survey maps compiled after the large flood in 1916 (fig. 13).

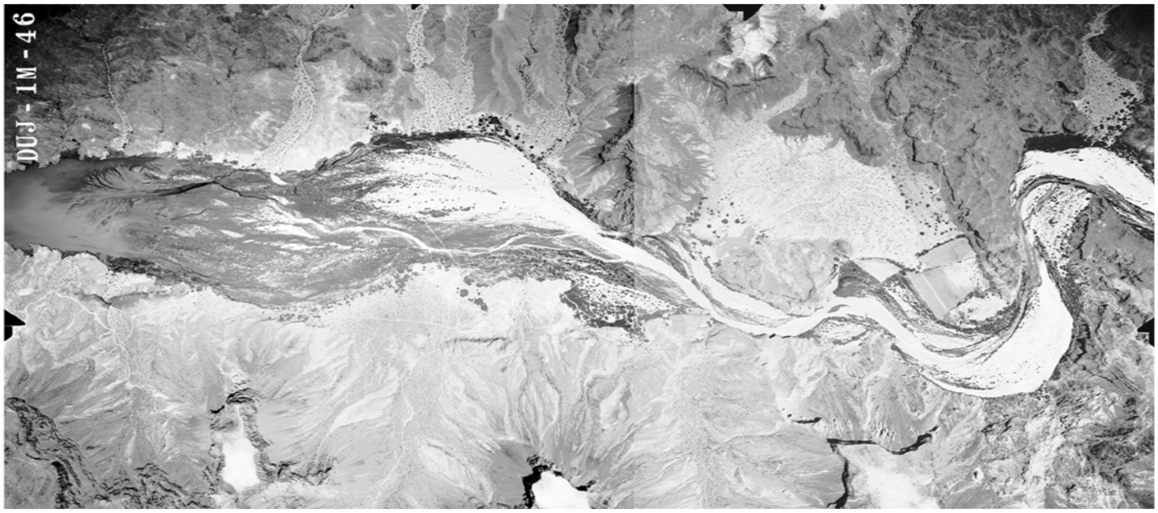


Figure 12. Lake Havasu Delta and reach upstream in 1953, showing the resulting broad, active channel after extensive flooding in 1951.

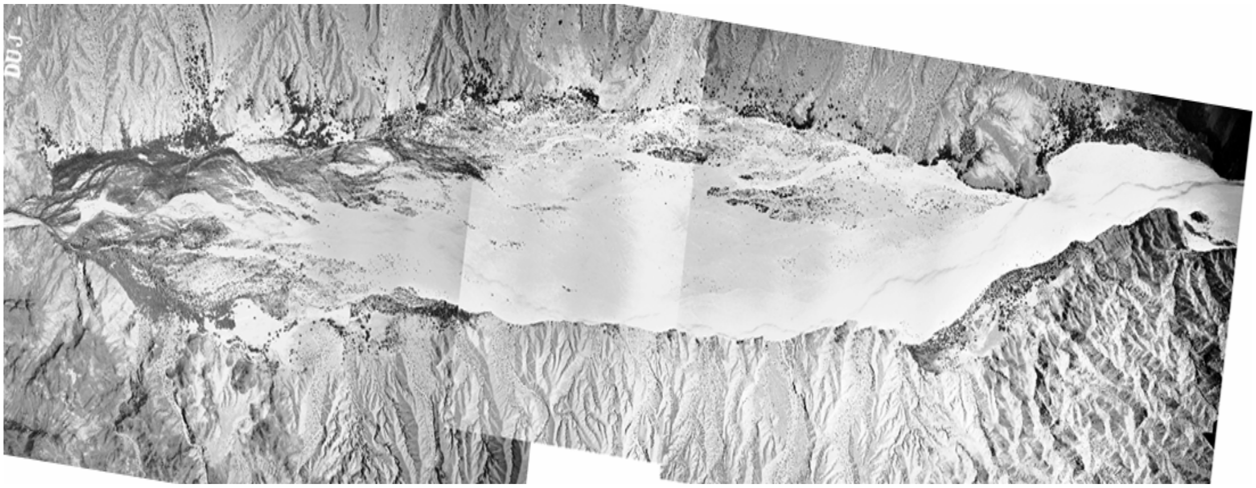


Figure 13. Planet Valley in 1953, showing the resulting broad, active channel after extensive flooding in 1951.

Another study (Shafroth and others, 2002) evaluated changes in channel width as a function of streamflow by using a time series of aerial photographs along eight reaches of the BWR, including 2 predam years (1953 and 1964), and 4 postdam years (1976, 1987, 1996, and 2002). Channel width was found to be significantly related to the maximum flood power and the average summer flow during the 5 years preceding a photograph year, as well as to whether a river reach had perennial or seasonally intermittent flow. Channels narrowed during intervals with relatively low flood magnitudes and/or relatively high summer flows (fig. 14). As mentioned above, aerial photographs from 1953 reveal large areas with bare, wide channels, the likely result of large magnitude floods in both 1951 and 1952 (fig. 13). Between 1959 and 1964, flood magnitudes were smaller, and summer flows were larger. As a result, channels were considerably narrower in the 1964 photographs (fig. 15).

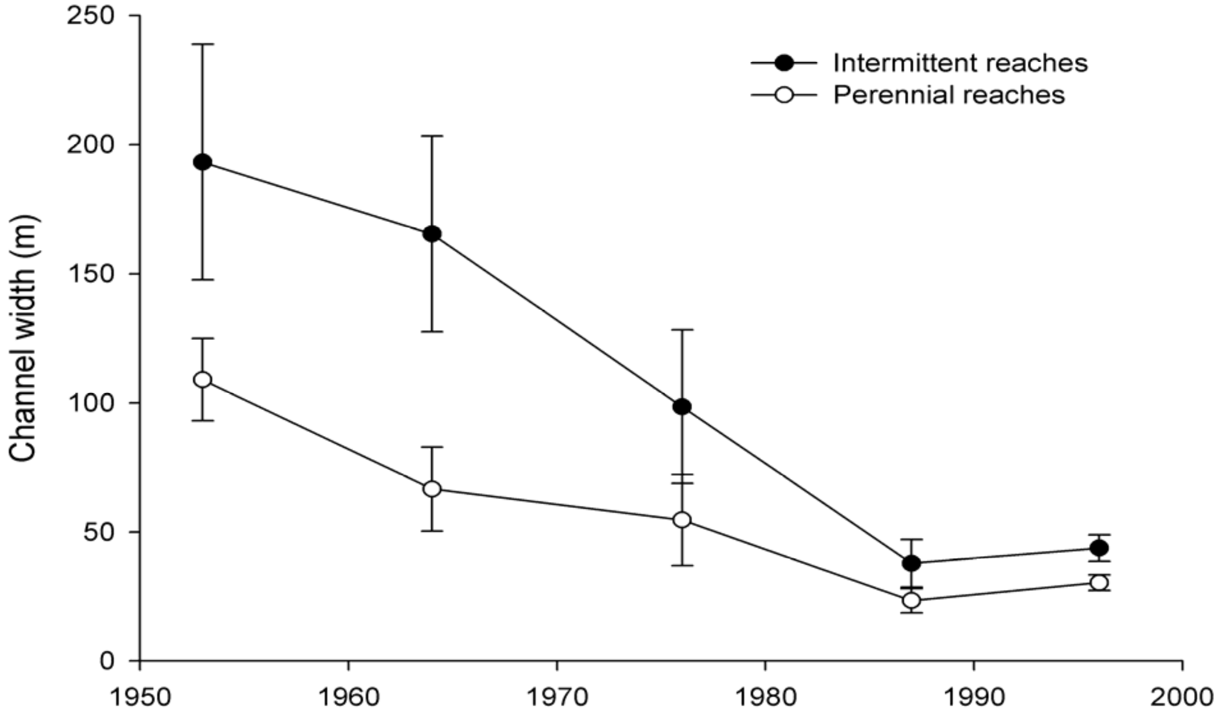


Figure 14. Changes in channel width, 1953–1996, Bill Williams River, Ariz. Channel width as measured on five sets of aerial photography within eight reaches of the river: four perennial and four intermittent. Values are means; error bars are one standard error. (See Shafroth and Patten, 1998; and Shafroth and others, 2002, for more details.)

It is common for the morphology of large rivers in arid and semiarid settings to be dominated by the effects of floods (Schumm and Lichty, 1963; Burkham, 1972; Baker, 1977; Wolman and Gerson, 1978). Rivers that undergo large flood-related morphologic changes require time to "recover" (i.e., retain preflood channel conditions that are commensurate with average or dominant flow conditions) (Wolman and Miller, 1960; Andrews, 1980). In situations where the recovery time is longer than the average recurrence interval of channel-modifying floods, the floods become the controlling influence on channel and valley bottom morphology. This characteristic describes the morphologic evolution of the BWR channel in the 20th century and, presumably, for past millennia.

Postdam Geomorphology

Flow regulation and trapping of bedload sediment associated with Alamo Dam has resulted in a flow and sediment transport regime that is tremendously different from the predam condition. Prolonged low flows and periodic prolonged moderate flows coupled with extreme attenuation of flood peaks have completely altered the nature of the river, leading to rapid and widespread expansion of riparian vegetation, channel narrowing, and channel incision (Shafroth and others 2002). Narrowing in the early 1970s was not very dramatic, likely because of the very low volumes of water released during the filling of the reservoir, including many days of zero flow. By the late 1980s and 1990s, however, channels had narrowed dramatically after many years with relatively high baseflows and a continued lack of large floods (Shafroth and others, 2002) (fig. 16).

Figure 15. Lake Havasu Delta and reach upstream in 1964 showing vegetation growth and channel narrowing resulting from smaller spring floods and higher summer flows between 1959 and 1964.

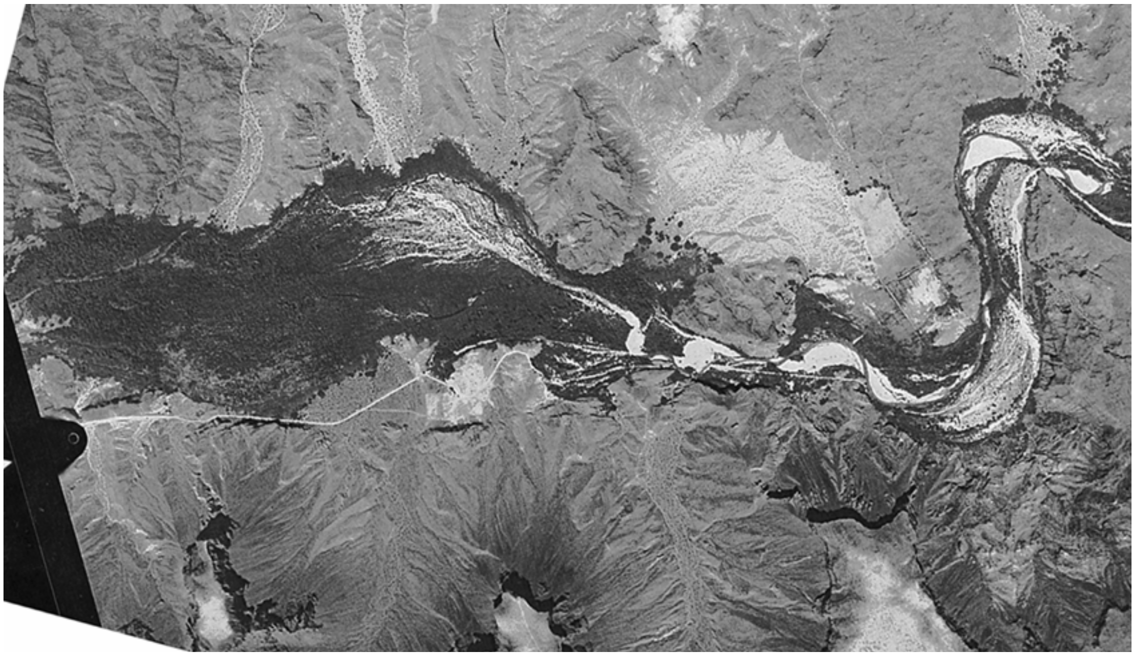


Figure 16. Lake Havasu Delta in 1995 showing vegetation growth and continued channel narrowing resulting from smaller spring floods and higher summer baseflows caused by the presence of Alamo Dam.

In addition to the extreme attenuation of flood peaks, the effect of the dam has been, of course, to trap sediment. In the case of the BWR, this effect is particularly acute because few large tributaries enter the river below the dam. The BWR, because of its short mainstem length through an arid region of moderate relief, receives only sporadic, local sediment input from tributaries. The progressive depletion of sediment from the upper reaches of the BWR is an inevitable consequence of bedload loss to the reservoir; however, large amounts of fluvial sediment are stored in the alluvial valleys and in the channel bed in canyon reaches along the middle and lower stretches of the river. It is uncertain what the long-term geomorphic consequences will be of the progressive depletion of valley bottom sediment. Ultimately, most liberated sediment will be deposited at the river's terminus at Lake Havasu and in the delta upstream. For example, a crosssection about 4.8 km (3 mi) upstream of the Highway 95 Bridge that was surveyed before and after moderate reservoir releases in April 1995 shows considerable deposition following this event (fig. 17).

The occurrence of predam-scale flood peaks in the postdam valley condition would likely lead to substantial geomorphic changes, including locally significant erosion and corresponding proximate (downstream) deposition. Because the dam traps the vast majority of sediment transported to the BWR corridor, the cumulative effect of large flows would be increasingly erosive as the largely unreplenished fluvial sediments are transported through the system. Thus, attempts to restore predam flows without augmenting the corresponding sediment load will impart significant changes to the morphology of the valley bottom that will likely increase in scale over time. It may be more appropriate to consider altering flows in a way that is more consistent with the scale of the existing river corridor (i.e., a system with a drainage area that is ca. 1,300 km^2 (500 mi^2)). In this sense, the river can be thought of as an "underfit stream," that is, one that occupies a valley bottom with morphological and sedimentological characteristics that are related to throughflows of water and sediment of a much larger scale than those associated with the present condition. In any case, once an acceptable flow regime is established, the river will have to go through a transitional period of uncertain duration, involving redistribution of valley bottom sediment and channel realignment.

Conceptual Framework for Assessing Postdam Geomorphic Change on the Bill Williams River: Spikes and Bricks

Predam hydrographs of typical floods on the BWR are characterized by steep, rapidly rising limbs and only slightly less steep falling limbs, thus resembling "spikes." Flood durations were relatively short. Winter floods were often characterized by multiple peaks associated with relatively prolonged frontal storm conditions, whereas summer and fall floods were characterized by single peaks. In contrast, postdam flood hydrographs have abrupt rises followed by prolonged, flat crests and then by abrupt drops, thus resembling "bricks." Examples of representative hydrographs are provided in figure 18.

In a simple sense, the hydrographs can be viewed as measures of cumulative energy expenditure in the valley bottom (Costa and O'Connor, 1995). The sharply spiking hydrograph exerts tremendous amounts of energy over a very short period of time, whereas the brick-shaped flow exerts a nearly constant rate of low or moderate energy expenditure over a long period of time. There are various possible morphologic consequences associated with each type of hydrograph that relate to distinct differences in associated erosion and deposition (e.g., Huckleberry, 1994; Costa and O'Connor, 1995). Resulting effects on floodplain sedimentation, channel migration (rates and processes), and sediment transport are likely to be considerably different in each scenario.

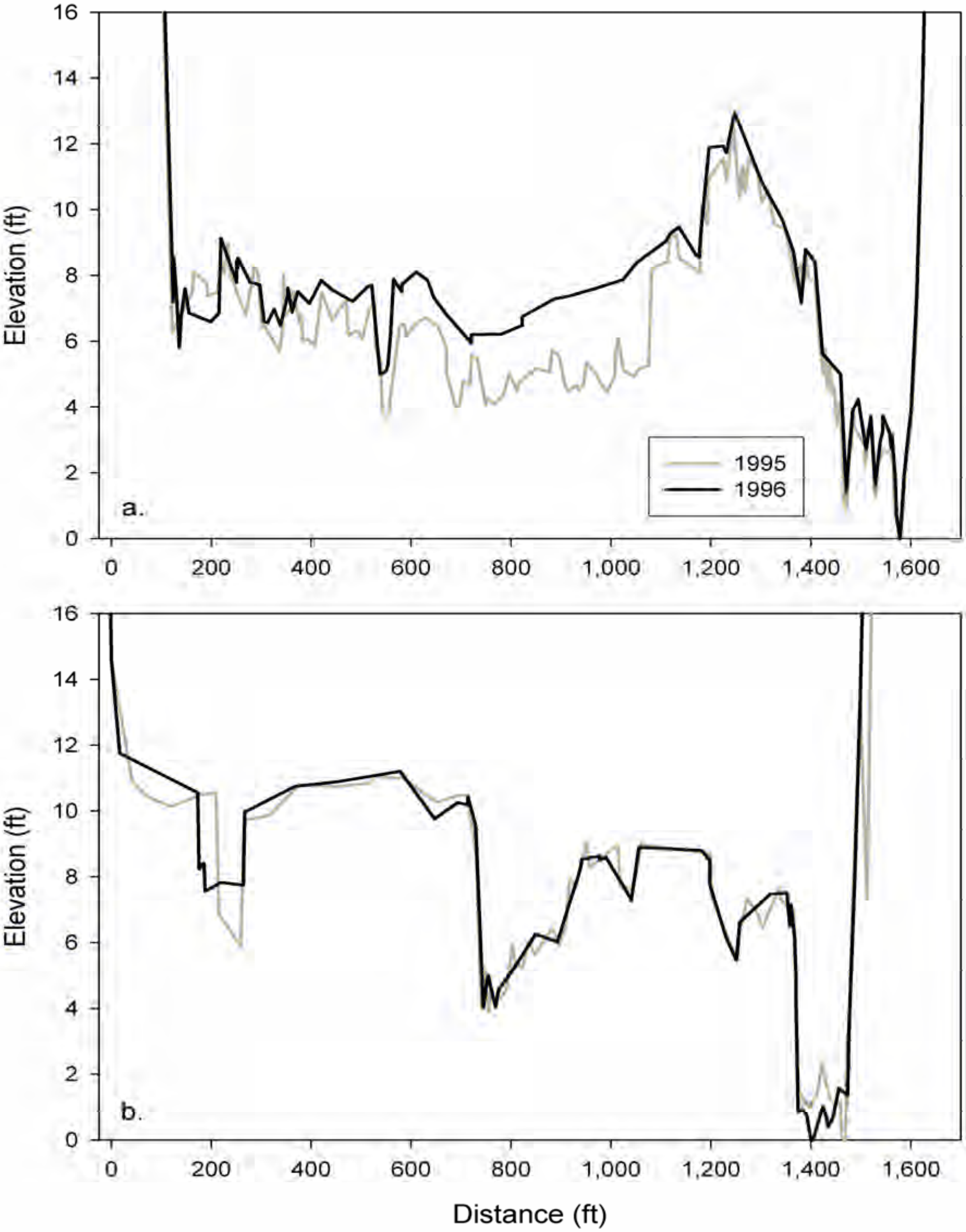


Figure 17. Changes in cross-section topography between 1995 and 1996 following a high flow event in April 1995. Upper panel (a) shows elevation change in reach 11 (river mile 3). Lower panel (b) shows elevation change in reach 10 (river mile 5.4).

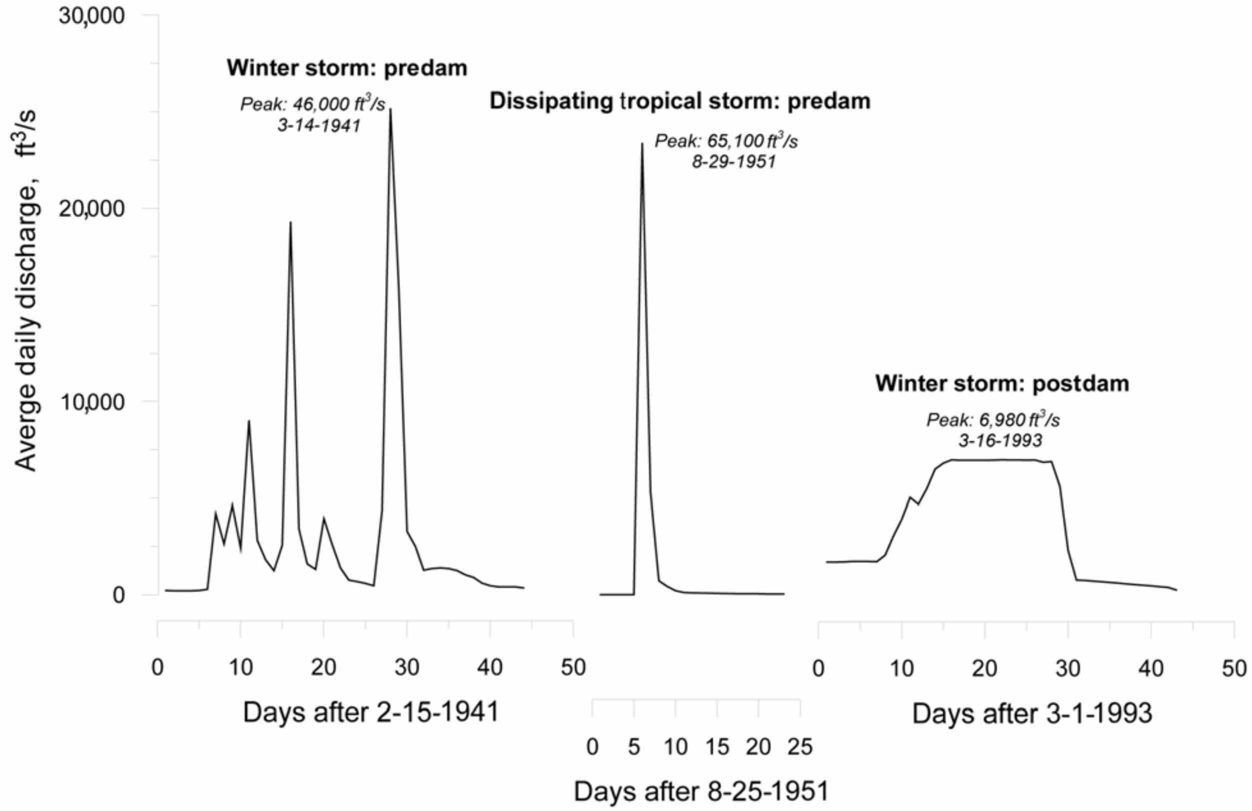


Figure 18. Representative predam and postdam storm hydrographs, Bill Williams River, Ariz. Data are daily values for the gaging station "Below Alamo Dam."

Differences in the effects of spikes versus bricks relate also to the associated depth of inundation of the channel and adjacent flood plain. The brick, because of its duration and relatively low magnitude, may be more conducive to channel migration and mobilization of fluvial sediment (except maybe for the largest particles) because of prolonged stress applied to channel banks. The predam spike involved significant overbank flow, broad expansive flow, floodplain scour and deposition, and mobilization of the coarsest fractions of bedload (in the case of the largest floods). The predam spike may also have had a more significant effect on riparian vegetation through bending, snapping, and uprooting of plants over a larger range of sizes (Phillips and others, 1998). The brick hydrograph may have a locally similar net effect with respect to progressive undercutting of riparian plants during protracted flow at constant rates and lateral erosion, but outcomes are difficult to predict with confidence without field investigation and experimentation with different flow types. The persistence of much of the riparian vegetation following a series of protracted releases in 1993 and 1995 indicates that these types of flows have a relatively minor influence on the overall abundance of riparian plants (Shafroth and others, 2002).

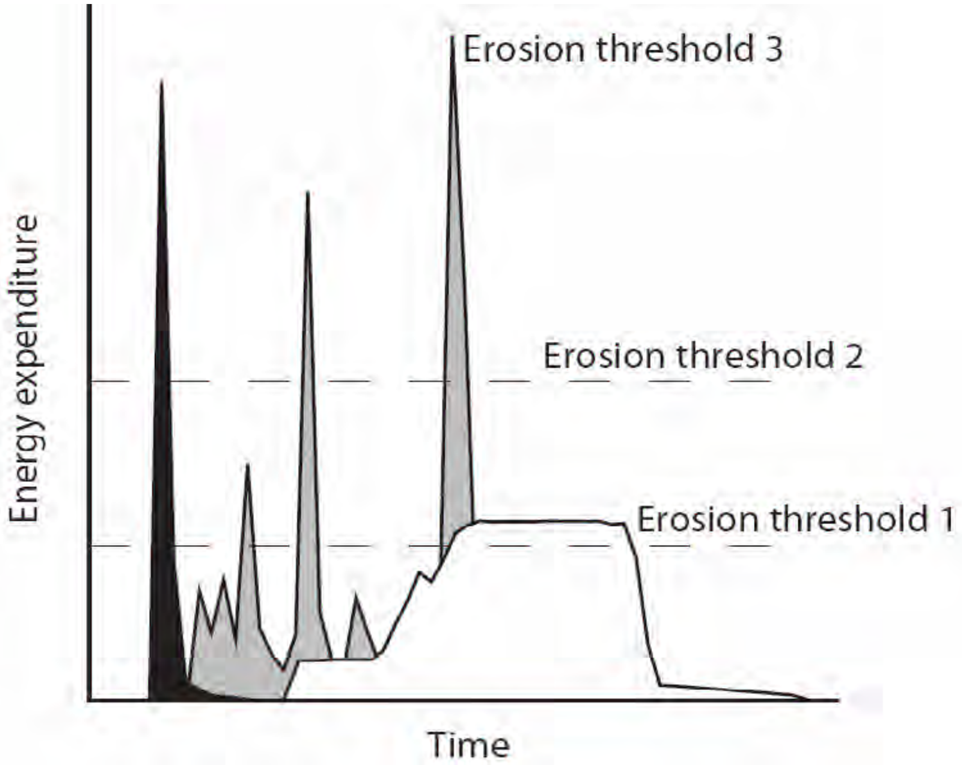


Figure 19. Conceptual model of the erosion potential of different types of flood hydrographs on the Bill Williams River, Ariz.

A conceptual model of spike and brick hydrographs in relation to erosion thresholds is provided in figure 19. There, each of the hydrographs presented in figure 18 is shown in relation to a series of postulated erosion thresholds, or levels of flow/energy expenditure that must be exceeded in order to produce some type of morphologic change in the valley bottom (figure based on Costa and O'Connor, 1995, fig. 10 therein). The three different erosion thresholds (1, 2, and 3 on the figure) are shown to indicate that some changes require larger amounts of energy. The three levels could represent, for example, alluvial bank erosion, tributary debris fan erosion, and destruction of mature riparian trees, respectively (fig. 19). Developing a quantitative basis for such a diagram and an understanding of how the thresholds may vary over time in relation to sequential changes during floods and between floods could be achieved by evaluating the effects of different flow levels and durations on relevant physical parameters derived from photointerpretation, mapping, and focused field studies.

Beaver Dams

Beavers can have a surprisingly significant impact on stream channel morphology and attendant ecological phenomena (for thorough overviews, see Butler, 1995; Gurnell, 1998; Baker and Hill, 2003; see also chapter 6, this report). Between 1995 and 2005, a series of beaver dams appeared along most of the length of the BWR. The persistence of beaver dams on the BWR reflects their overall durability relative to the erosive power of the flows to which they have been exposed. Beaver dams can include an intricate, interlocking array of woody and herbaceous vegetation, mud, and rocks (Gurnell, 1998). Over time, dams trap flotsam and sediment, therefore increasing in bulk and strength. Additional strength may be provided by vegetation growing in the bulk of the dam and penetrating it with a root network. We know of no studies that evaluate the strength of beaver dams and document the flow parameters required to induce beaver dam failure. Several studies, however, do document the occurrence of "catastrophic" beaver dam failure and describe significant impacts on downstream channel morphology (Butler, 1989; Kondolf and others, 1991; Butler and Malanson, 2005). Most studies of the geomorphologic effect of beaver dams have focused on their role in influencing channel morphology. Beaver dams are efficient sediment traps (Butler and Malanson, 1995) and, in series, create a stepped profile along affected rivers and streams. Hydrologically, beaver dams act as buffers on flow magnitudes and may contribute to sustained low flows and higher local water tables (Gurnell, 1998). Westbrook and others (2006) documented significant effects on groundwater flow patterns and hydrologic processes downstream of dams. It is also likely that the failure of a beaver dam that has been particularly effective at trapping sediment could initiate local incision that could migrate some distance upstream; however, the response to the failure would vary depending on local conditions (e.g., valley and channel gradient, size of beaver dam and related sediment reservoir, etc.).

Groundwater Dynamics

Most investigators agree that the BWR groundwater flow system is a variation on a two-layer aquifer (Vionnet, 1995; Wilson, 2001). The system has two types of reaches: (1)canyon reaches in which relatively young and permeable (Quaternary) alluvium overlies fractured bedrock and (2)valley reaches in which young and permeable alluvium overlies a set of older, somewhat less permeable alluvial deposits that overlie fractured bedrock. The upper unit is the Bill Williams alluvial aquifer. It is composed of unconsolidated to loosely consolidated stream alluvium and interlayered tributary deposits. The lower unit, the basin fill aquifer, is predominantly weakly to moderately consolidated tributary alluvium, but it likely contains some mainstem alluvium as well, depending on its age in relation to the history of the river's development. Both of these units overlie a presumptive, highly fractured and faulted, regional bedrock aquifer. Previous investigations indicate (assume) that little water is lost to the regional aquifer. Canyon reaches along the BWR, thus, are overlaid by relatively thin veneers of the alluvial aquifer overlying the regional bedrock aquifer. Wider valley reaches, most importantly Planet Valley, are underlaid by a greater thickness of the alluvial aquifer and, likely, the basin fill aquifer (fig. 20).

The most significant groundwater repository along the river occurs in Planet Valley, which has the deepest, most highly permeable aquifer downstream from the dam (Harshman and Maddock, 1993). Elsewhere, a shallower aquifer persists in sandy alluvium below most of the length of the river (except for immediately below the dam where, locally, much alluvial cover has been removed or isolated through incision by dam-released flows, and bedrock outcrops in the streambed are visible in some sections immediately downstream from Alamo Dam (P.K. House, personal observation, 1995–98)). The Planet Valley aquifer serves as a major hydrologic buffer on the BWR system and is a critical component of maintaining a reliable baseflow in the lower reaches of the BWR (Turner, 1962; Jackson and Summers, 1988; Harshman and Maddock, 1993; Vionnet, 1995).

The buffering effect of Planet Valley on low and moderate flows is to reduce their magnitude and attenuate their variability markedly. These effects are a function of the scale of the alluvial aquifer, its permeability, and, presumably, underlying bedrock structural control at the entrance to the canyon at the west end of the valley (Jackson and Summers, 1988). Thus, despite variation in timing and size of low and moderate flows at the head of Planet Valley, the

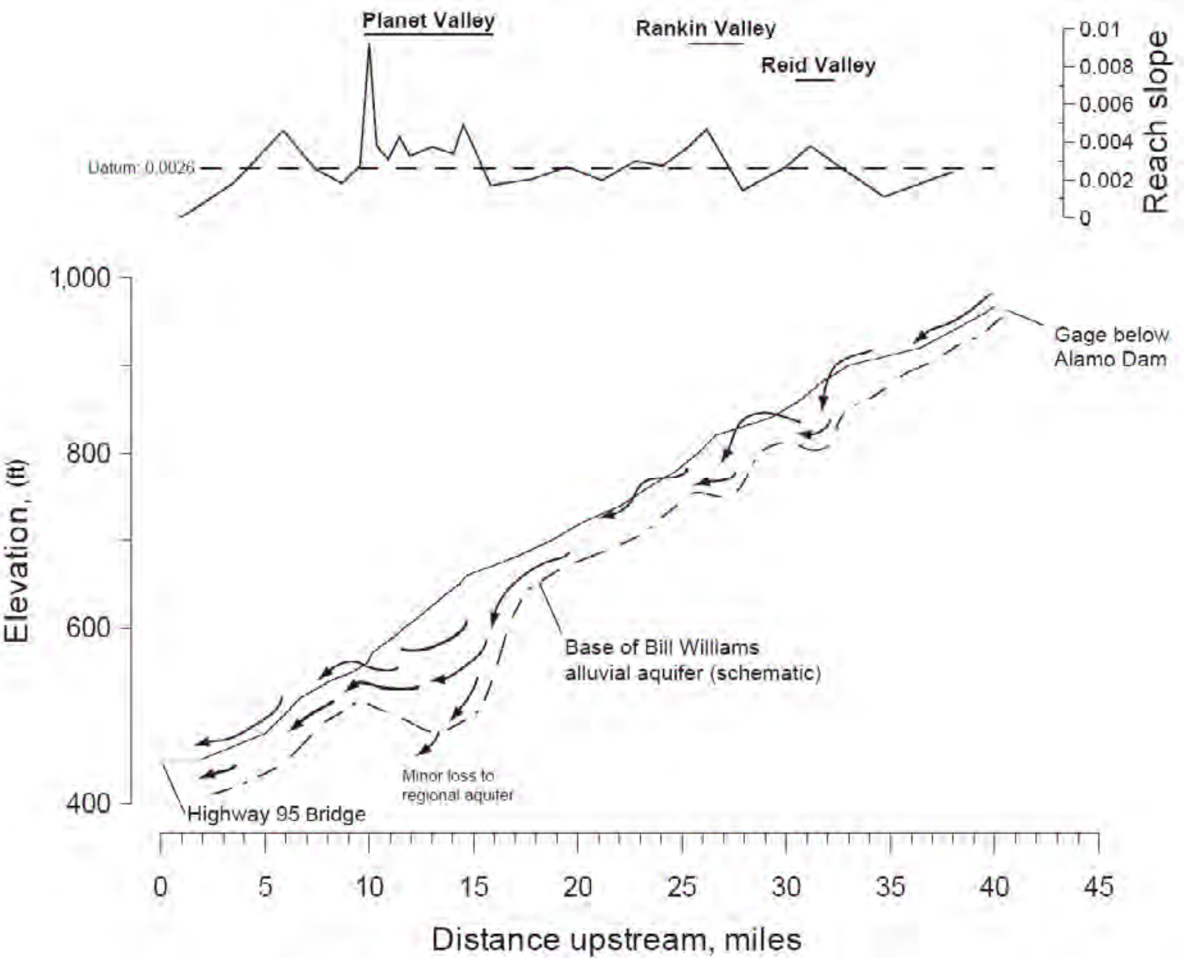


Figure 20. Surfacewater and groundwater flowpaths for the Bill Williams River, Ariz.

output at the downstream end typically averages about 0.28–0.31 m^3/s (10–11 ft^3/s). During large flows, the effects of the groundwater system are overwhelmed by the surface discharge (surface discharge greatly exceeds the infiltration capacity of the aquifer). The buffering effect is apparent during and following the recession of the flood wave.

Surface and subsurface flow in the BWR channel contributes to the dynamics of shallow alluvial ground water. The alluvial water table levels are influenced by the depth of alluvium that overlies the bedrock and the volume of water in the system. On the BWR, in reaches with relatively deep alluvium (e.g., Reid Valley, Rankin Valley, and Planet Valley), surface flow commonly disappears during much of the year, resurfacing in areas where bedrock is closer to the surface and valley widths are narrower. Thus, a given low flow release results in different groundwater dynamics in different reaches of the river (fig. 21). Another factor affecting groundwater levels is evapotranspiration, particularly during the warmer months of the growing season. Finally, alluvial ground water apparently responds to a combination of antecedent conditions and current conditions, resulting in different water levels in different years or seasons that have the same discharge rate (fig. 21).

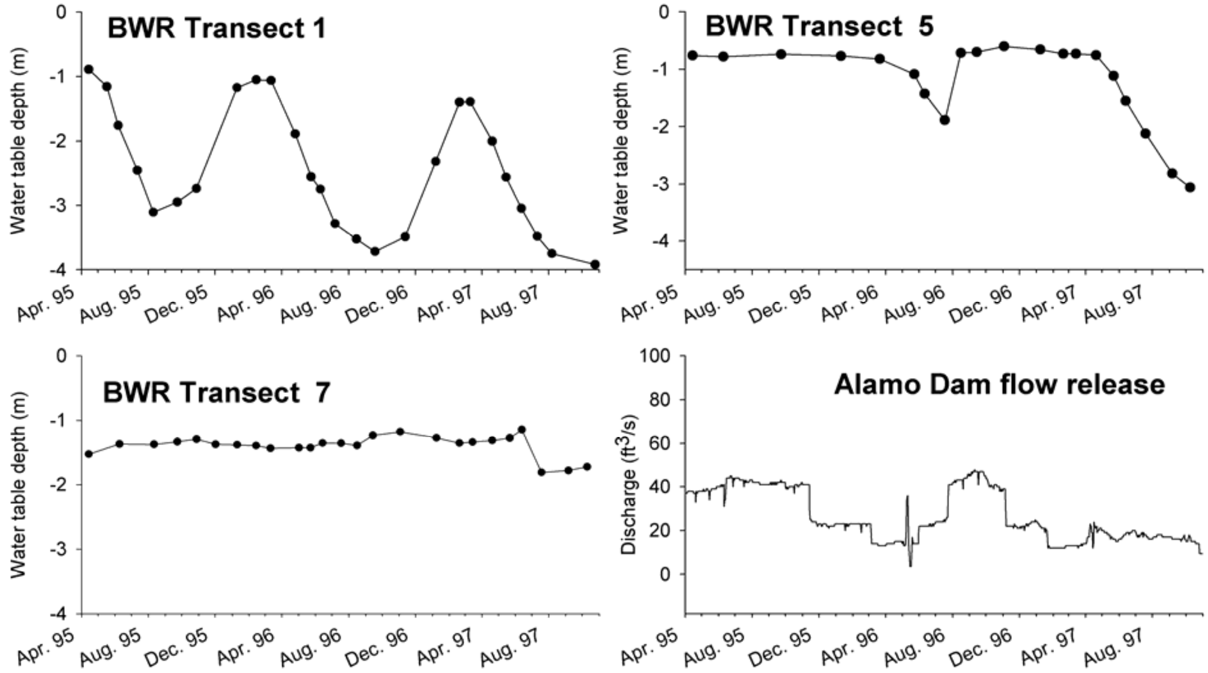


Figure 21. Variation in alluvial groundwater levels at three sites along the Bill Williams River (BWR Transect 1, BWR Transect 5, BWR Transect 7), during a period of varying low flow releases from Alamo Dam, Ariz., from April 1995 to August 1997.

Water Quality

Only sporadic data exist pertaining to historical trends in water quality in the BWR. Reports available on the Environmental Protection Agency STORET Legacy Web site (http://www.epa.gov/storpubl/ legacy/gateway.htm) describe the results of measurements made near the dam in 1983. A report from 1996 (Ashby and others, 1996) describes problems with excessive concentrations of hydrogen sulfide gas in the discharge from Alamo Lake that resulted in degradation of concrete in the outlet works, corrosion of electrical components, and obnoxious odors below the outlet. The United Sates Army Corps of Engineers (2003) referred to this problem in relation to corrosion of electrical components and in restricting access to the outlet works for routine inspections(United Sates Army Corps of Engineers, 2003). The buildup of hydrogen sulfide is associated with strongly anaerobic conditions that develop from intense thermal stratification and associated isolation of hypolimnetic waters (Ashby and others, 1996).

Water quality downstream from Alamo Dam is not well documented. The USACE stated that the principal concern was the effect of anaerobic conditions in the reservoir and that the downstream impact of Alamo Lake's water quality on the BWR was negligible because of the small releases typical of the dam (United Sates Army Corps of Engineers, 2003). Harshman and Maddock (1993) summarize the results of water quality measurements below Planet Valley by the Arizona Department of Water Resources (dating to 1995). Overall, water quality in the reported measurement period 1975-91 was good. Seasonal spikes in overall low levels of nitrates and fecal coliform occurred in some years during low flow periods. The late 1970s and early 1980s data show the most variability (Harshman and Maddock, 1993). Harshman and Maddock

(1993) also reported that the groundwater and surfacewater chemistries were nearly identical in during this time.

There may be two other potential impacts to water quality: (1) irrigation return flows from Lincoln Ranch, which might contain higher levels of nutrients and possibly some herbicide or pesticide residues, and (2) mine tailings and perhaps other byproducts of mining operations that can be transported down washes (e.g., the old Planet Mine and mines in Mineral Wash and the Swansea area) and into the BWR. We are not aware, however, of any data quantifying any effects of these potential sources.

Chapter 3. Streamflow-Biota Relations: Riparian Vegetation

By Patrick B. Shafroth[1] and Vanessa B. Beauchamp[1]

It is widely accepted among riparian ecologists that the composition and dynamics of riparian (streamside) vegetation reflect direct and indirect effects of streamflow (e.g., Hughes, 1997; Friedman and Auble, 2000; Stromberg, 2001). The flow regime is often the driving variable in these systems, strongly affecting other aspects of the riverine environment such as fluvial processes (e.g., channel widening, meandering) and alluvial groundwater dynamics. These factors, overlaid on the geologic and climatic setting, form the physical "stage" on which vegetation dynamics play out.

Aspects of the life history of many riparian plants are associated with different flow components (e.g., Mahoney and Rood, 1998; Karrenberg and others, 2002), and much of the research on relationships between streamflow and riparian vegetation has been conducted in the southwestern United States (Stromberg and others, in press), including studies on the BWR (Shafroth and others, 1998, 2000, 2002). Most research to date has focused on cottonwood species (*Populus* spp.; often the dominant floodplain tree), for which relationships between flow and the establishment, growth, and survival of vegetation have been well quantified. Literature on relationships between flow components and herbaceous species on southwestern systems is beginning to emerge (e.g., Bagstad and others, 2005). In this chapter, we summarize some of the general connections between flow and riparian vegetation, as well as some details for species that have been the subject of more intensive study.

Floodflows

Floodflows influence riparian vegetation in various ways. Large floods may have sufficient energy to remove or damage woody vegetation from significant portions of the flood plain, whereas small floods may only remove or damage vegetation within the highest energy flow paths. Floodflows entrain and transport sediment, leading to erosion, deposition (and perhaps associated burial of vegetation), and consequent changes to fluvial surfaces. Floods often drive dominant fluvial processes (e.g., channel meandering, widening, sediment deposition), which in turn determine the nature of substrates upon which riparian vegetation becomes established and grows (Scott and others, 1996). Infrequent, large-magnitude flood events can result in the establishment of new cohorts of woody vegetation throughout a river system ("general replenishment model" sensu Hughes, 1994). Smaller magnitude floods can result in more spatially limited establishment of new cohorts ("incremental replenishment model" sensu Hughes, 1994). Sediment deposition associated with floods can also elevate flood plains, making plants there less susceptible to future flooding and leading to an increased importance of autogenic (successional) processes in determining vegetation change on the highest surfaces. Changes in elevation above the stream channel or water table can alter water availability, perhaps affecting plant growth.

Floodflows also wet flood plain areas, replenishing soil moisture that riparian plants utilize, often depositing fine-textured substrates and promoting decomposition of forest floor litter (Ellis and others, 1999). Floods can also play a role in dispersing the seeds of riparian

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species ("hydrochory"; see Merritt and Wohl, 2002). Flood regimes include flows that differ in their timing (e.g., winter versus summer or fall), magnitude, frequency, and duration, contributing to the high dynamism associated with riparian plant communities on unregulated rivers. Over decades, floods of different magnitudes, timing, etc., create a mosaic of sites and vegetation patches along rivers (Stromberg, 1998; Lytle and Merritt, 2004). The flow regime interacts with the geologic and geomorphic setting so that the same flows may influence vegetation differently in different reaches of the same river (Shafroth and others, 1998; Cooper and others, 2003; Stromberg and others, in press).

Baseflows and Alluvial Groundwater Conditions

Low flows are typically important for maintaining the relatively high water availability on which riparian plants depend for growth and survival. Low flows replenish ground water through infiltration and percolation. On southwestern U.S. flood plains, differences among species in tolerance of low or high soil moisture result in somewhat predictable variation in the abundance of dominant species along gradients of water availability (Stromberg and others, 1996). Saltcedar or tamarisk (*Tamarix* spp.) is more drought tolerant than is cottonwood or willow (*Salix* spp.) (Busch and Smith, 1995; Horton and others, 2001a, b; Rood and others, 2003) and thus can dominate river reaches where flows are typically lower and ground water is deeper (Stromberg, 1998; Shafroth and others, 2000; Lite and Stromberg, 2005).

Bill Williams River Vegetation Dynamics

Riparian vegetation along the BWR is dominated by several woody species common to low-elevation southwestern riparian ecosystems, including Fremont cottonwood (*Populus fremontii*) and Goodding's willow (*Salix gooddingii*) (figs. 22 and 23), tamarisk *(Tamarix ramosissima*) (fig. 24), seep willow (*Baccharis salicifolia*), and mesquite (*Prosopis* spp.). Woody vegetation abundance (cover, density, basal area) varies largely as a result of water availability, with perennial reaches supporting the most abundant vegetation. Herbaceous vegetation tends to be quite sparse, except adjacent to perennial channels where water and light availability are high.

Research on the BWR revealed that periodic floods and summer baseflows are key flow components that influence riparian vegetation abundance (Shafroth and others, 2002). Large-magnitude floods can remove vegetation and produce bare sites for new growth, and they likely did on a fairly regular basis historically. Riparian vegetation growth and survival can be limited by periods of very low flow that do not provide sufficient moisture or replenish alluvial ground water sufficiently for the water-demanding riparian plants, especially during typically hot and dry parts of the growing season (i.e., May–September; Shafroth and others, 2000). Conversely, periods with higher low flows during the growing season, or occasional pulses that replenish soil and ground water, can enable relatively high growth and survival of riparian vegetation. Vegetation at a particular point in time or space often reflects the sequence of flow events over previous years and decades, particularly with respect to the magnitude of floodflows and summer flows.

Vegetation patterns can also be influenced by local geomorphology, which influences the effects of flood flows and the availability of ground water. Along the BWR, river reaches differ in the distribution and nature of surfaces where vegetation typically grows. For example, canyon reaches tend to have narrower flood plains and a less complex arrangement of channels than do wider valley reaches, which may have multiple channels and a broad flood plain. Along the BWR, there are three significant alluvial basins, in each of these, there are important

Figure 22. Riparian vegetation growing along the Bill Williams River, Ariz.. Fremont cottonwood and Goodding's willow dominate the upper canopy level with tamarisk present in the lower canopy. Photograph by Patrick Shafroth, U.S. Geological Survey.

Figure 23. A canyon reach of the Bill Williams River, Ariz., filled primarily with Fremont cottonwood. Photograph by Patrick Shafroth, U.S. Geological Survey.

Figure 24. A floodplain area along the Bill Williams River, Ariz., dominated by shrubby tamarisk, with smaller patches of cottonwood and willow trees. Photograph by Patrick Shafroth, U.S. Geological Survey.

differences between the upstream and downstream portions of the basins. Notably, the upstream portions of the basins are influent or "losing" reaches, where much of the surface flow infiltrates into relatively deep alluvium, resulting in lower alluvial water tables, especially during times of low flow and high evapotranspiration. At the downstream end of the basins, bedrock is closer to the surface again, and ground water in the basin rises concomitantly, resulting in higher water tables and the presence of surface flow during times of the year that surface flow may be absent in the upstream reaches. (See chapter 2, this report, for additional discussion.)

Relationships Between Flow Components and Cottonwood Life History

A substantial body of research has elucidated relationships between streamflow and the germination and establishment of cottonwood species throughout semiarid and arid Western North America (for reviews, cf. Braatne and others, 1996; Mahoney and Rood, 1998; Karrenberg and others, 2002). Flood timing, elevation of seedling establishment, and flood recession rates or availability of soil moisture during the first growing season are all important components of cottonwood recruitment and have been synthesized into a "Recruitment Box" model which uses aspects of the annual hydrograph to estimate areas of potential woody riparian seedling establishment (Mahoney and Rood, 1998) (fig. 25).

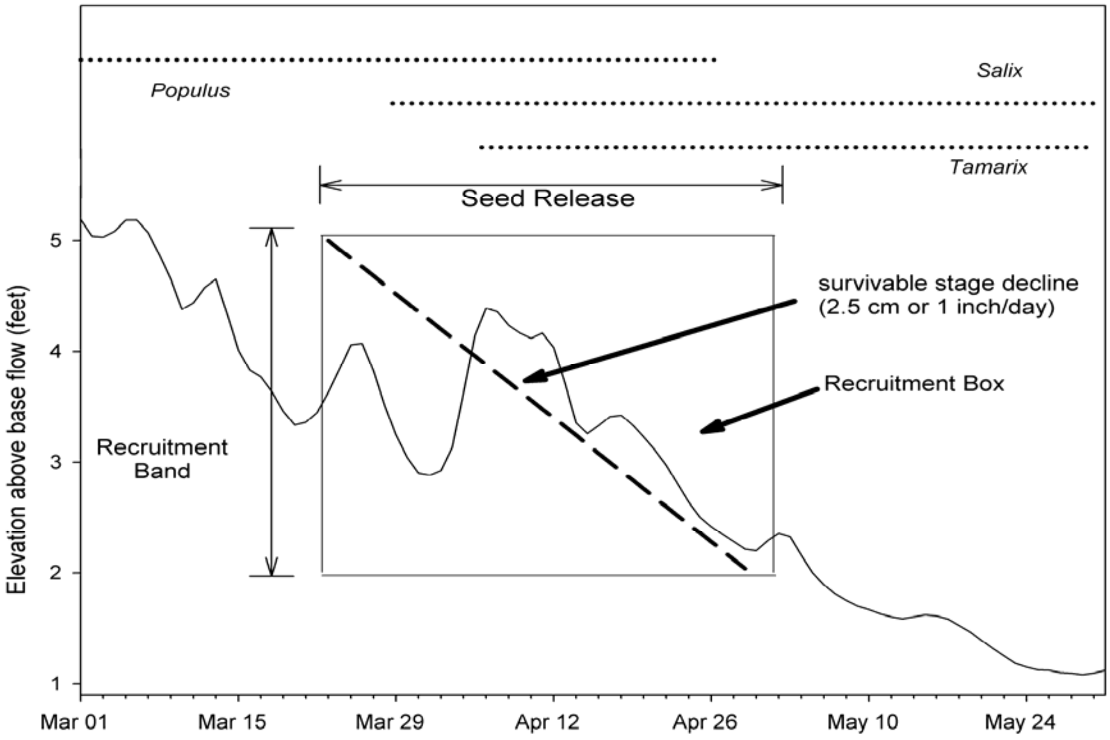

Figure 25. The "Recruitment Box" which defines a zone of floodplain elevation and time in which cottonwood seedlings can become established if streamflow conditions are favorable (modified from Mahoney and Rood, 1998).

Key aspects of cottonwood germination and establishment requirements are as follows:

- **Seed germination.** Successful germination requires the presence of moist mineral substrate during the period of cottonwood seed release.
- **Early seedling survival: adequate soil moisture.** Continued, sufficient soil moisture is needed during the first year to enable young seedlings to survive and to promote root growth. This moisture may result from water stored in the soil following the flood event, from gradually receding floodwaters, from precipitation, or from a combination of the above. In the recruitment box model, Mahoney and Rood (1998) estimate 2.5 cm/d (1 in./d) as a generalized maximum rate of water table decline.
- **Later seedling survival: protection from scour, desiccation.** Seedlings need to establish at an elevation (relative to base level), the low end of which is high enough to be protected from high flows that can scour seedlings, and the high end of which is low enough to avoid desiccation. Based on a synthesis of previous cottonwood studies, the Recruitment Box model includes a successful seedling recruitment zone of 60–150 cm (24–59 in.) above the annual low water level (Mahoney and Rood, 1998).

Application of the Recruitment Box to the Bill Williams River

Seed Germination

Shafroth and others (1998) examined woody riparian seedling establishment along the BWR in the context of the above hydrologic variables following high flow releases from Alamo Dam in 1993 and 1995 (fig. 26). One aspect of this study was a germination model, which combined water surface levels and seed dispersal phenology to predict which sites supported or did not support seedling establishment. This germination model is similar to one component of the recruitment box model in that germination locations are determined largely by the coincidence of the availability of seed and the availability of moist soil. Seed dispersal phenology of Freemont cottonwood and other common, woody, pioneer plants on the BWR is presented in figure 27.

Early Seedling Survival

Shafroth and others (1998) observed maximum rates of surface water decline at sites where seedlings survived for both the 1993 (average 1.2–4.4 cm/d (0.47–1.73 in./d)) and 1995 cohorts (average 2.8–4.2 cm/d (1.1–1.6 in./d)) on the BWR that were similar to the 2.5 cm/d (1 in./d) generalized rate of Mahoney and Rood (1998). In experimental studies of cottonwood species, growth was reduced, but plants survived declines of up to 10 cm/d (3.9 in./d) (Mahoney and Rood, 1991, 1992). Comparisons of drawdown rates across studies can be confounded because different reported drawdown values may have been averaged over different periods of time, affecting different cottonwood species growing in different soils under different climatic conditions (cf. Cooper and others, 1999). Although precipitation during a period of rapid drawdown may enhance seedling survival, rainfall is typically very sparse along the BWR during the months following seed germination.

Later Seedling Survival

Removal of germinants or seedlings by high flow events subsequent to germination or establishment can be an important cause of seedling mortality in western riparian ecosystems (Stromberg and others, 1991, and 1993; Johnson, 1994; Auble and Scott, 1998; Friedman and Auble, 2000). On the BWR, removal of seedlings and saplings established in 1993 by high flows late in the same year (ca. 28 m^3/s (990 ft^3/s)) and in early 1995 (ca. 188.9 m^3/s (6,670 ft^3/s)) was not a primary cause of mortality at the quadrat scale (Shafroth and others, 1998). The apparent inability of flows up to 188.9 m^3/s (6,670 ft^3/s) to remove substantial numbers of seedlings and saplings illustrates an impact of Alamo Dam, as unregulated flows would have been much larger and more destructive to young plants. The absence of high flows from 1995 to 2004 allowed the continued survival and growth of woody vegetation which became established in 1995 at floodplain elevations generally considered too low to allow long-term survival. High flows in fall 2004 and winter 2005 removed many of these plants (P.B. Shafroth, personal observation).

Extension of Cottonwood Flow Models to Other Woody Riparian Species

Most of the work relating aspects of flood hydrographs to the establishment of riparian vegetation has focused on cottonwood species; however, a few studies have looked at applying these models to other species (Shafroth and others, 1998; Amlin and Rood, 2002; Horton and Clark, 2001). It stands to reason that other pioneer plants, which, like cottonwood, typically require bare, moist substrates for successful seed germination and seedling establishment, would

Figure 26. Fremont cottonwood seedlings along the Bill Williams River, Ariz. Photograph by Patrick Shafroth, U.S. Geological Survey.

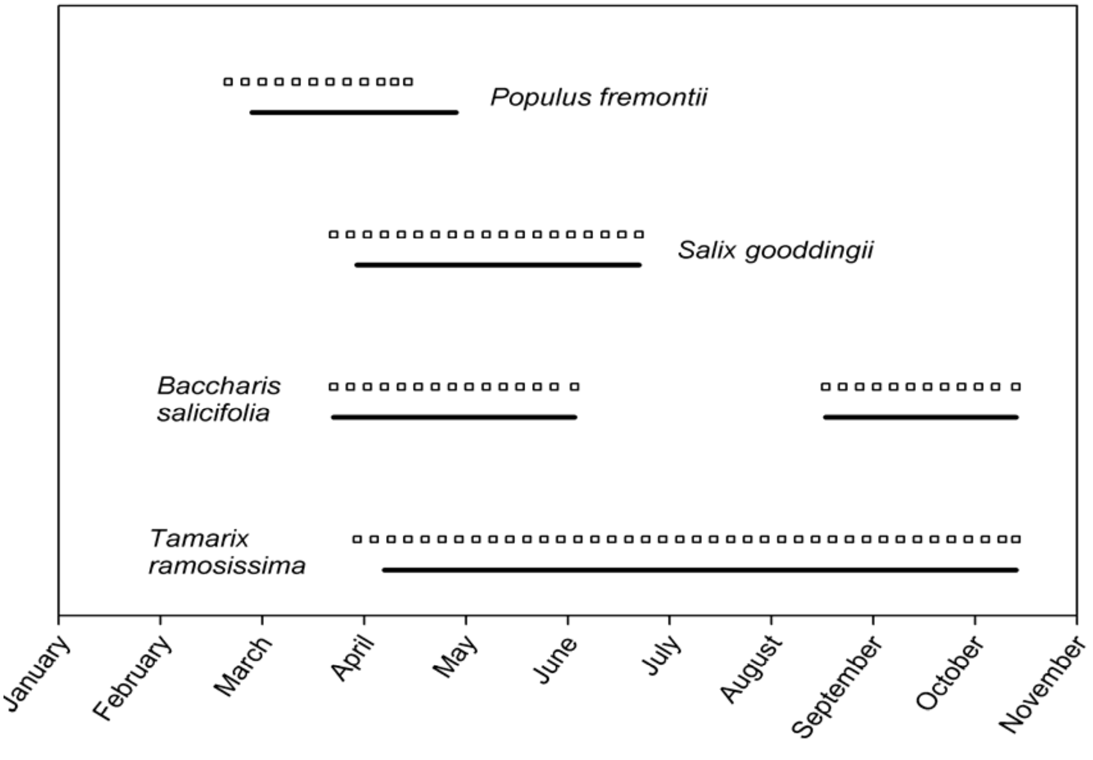

Figure 27. Seed release periods of four woody riparian pioneer species at upstream and downstream areas of the Bill Williams River, Ariz. Dispersal at the downstream site (140 m above sea level) is represented by a solid line and dispersal at the upstream site (230 m above sea level) is represented by open squares.

have similar requirements. The most common other woody pioneer taxa on the BWR are Goodding's willow, tamarisk, and seep willow. Each of these species has a unique period of seed dispersal, though they may be overlapping at times (fig. 27). Goodding's willow disperses seed later than does Fremont cottonwood on the BWR and thus tends to germinate either in response to later floods or to a later period of the flood recession limb. In the second case, Goodding's willow would generally become established at a lower elevational position within the bottomland than would Fremont cottonwood (closer to ground water but more vulnerable to scour from future high flows). Seed dispersal of the nonnative tamarisk species (Gaskin and Schaal, 2002) begins later than that of Fremont cottonwood on the BWR (Shafroth and others, 1998—though not all rivers in Western North America—e.g., Cooper and others, 1999) and continues throughout the growing season and into fall months. Thus, tamarisk is not nearly as dependent as cottonwood or willow on precisely timed floods for establishment.

Flow Connections to Taxa with Warm Season Phenology

Less is known about the importance of floodflows that occur during the summer or fall months, although flows in these seasons historically made up approximately one-half of the largest magnitude floods in a given year on the BWR. Some effects that are understood relate to the reproduction of species whose phenology is tied to these later precipitation events. For example, the seeds of mesquite trees germinate in response to late summer moisture, whether from precipitation or flooding (Stromberg and others, 1991). Floods may help promote mesquite seed germination by scarifying seeds and by providing moisture. The growth of mesquite trees is also somewhat tied to these summer storms, and floodwaters at this time of year can promote more vigorous growth by providing a supplement of soil moisture and maintaining relatively high water tables. Mesquite growth and productivity are strongly influenced by the availability of ground water, with maximum growth occurring in floodplain settings where water tables are typically 5–6 m (16.4–19.7 ft) below the surface (Stromberg and others, 1992, 1993).

Flow Connections to Herbaceous Plants

The distribution and abundance of herbaceous riparian species are also linked to streamflow. Both the disturbance created by flood flows and the elevated base flows which follow flood events are important in regulating the distribution and abundance of herbaceous species in the riparian zone (fig. 28). The bare, moist sites that are favorable for pioneer woody species establishment are also favorable for a large number of annual or biennial herbaceous taxa adapted to these environments ("ruderals" sensu Grime, 1979). Annual species typically have a rapid and positive response to flooding because disturbance clears suitable germination sites. Many riparian perennial species have the capacity for clonal spread and can also respond positively to flooding, even after scouring floods have damaged vegetation. After the flood pulse passes, elevated baseflows allow for increased survival and growth of many herbaceous riparian species. Generally, the superposition of the effects of various floods over decades results in a complex set of microsites, with niches for a variety of plant taxa.

A recent study of herbaceous vegetation response to flooding and rainfall on the San Pedro River Ariz., found that flooding had a positive effect on herbaceous richness and cover through a combination of disturbance and water availability effects (Bagstad and others, 2005). Annual species had a strong positive response to flooding, presumably because of removal of litter and existing understory vegetation and increases in light availability. Perennials responded less strongly than did annuals to flood disturbance. Scouring forces locally reduced richness of perennial vegetation, but the clonal habit of many of these species allowed for survivorship and vegetative spread after burial and fragmentation caused by flood disturbance. Alluvial water

Figure 28. Herbaceous vegetation along the Bill Williams River, Ariz. Photograph by Patrick Shafroth, U.S. Geological Survey.

tables and stream flows remained elevated for several months after the flood, which greatly benefited hydric (wet site) annual and perennial species through increased flow permanence and increased dispersal (hydrochory) of seeds and vegetative propagules. Mesic (moist site) species (both annual and perennial) responded to a combination of flood soil wetting, groundwater recharge, and rainfall, while xeric (dry site) species responded primarily to increased rainfall.

Dewatering of streams through flow regulation, water diversion, or groundwater pumping can lower baseflows and increase the frequency and extent of intermittent flows, causing shifts in the abundance and composition of herbaceous vegetation. Stromberg and others (1996) found that many herbaceous riparian species had a narrow tolerance range for depth to ground water, and in particular, the abundance of obligate wetland herbaceous species (such as bulrush (*Scirpus* spp.)) declined sharply at groundwater depths below 0.25 m (0.82 ft). Along the San Pedro River, cover and richness of herbaceous vegetation declined continuously across a gradient of permanent to intermittent flow. Hydric species were the most negatively affected by increases in flow intermittency, while mesic perennials (such as bermuda grass (*Cynodon dactylon*) increased at sites with intermittent flow (Stromberg and others, 2005).

Summaries of flow-biota relationships for woody plant establishment, plant growth, and plant diversity are presented in table 5.

Table 5. Summary of flow-biota relationships for riparian vegetation in the Bill Williams River Corridor, Ariz.

Process	Moderate to large floods	Small floods	High to moderate baseflows	Low baseflows
Woody plant establishment	Winter-spring floods and associated drawdowns create conditions suitable for recruitment of woody pioneer vegetation and may result in extensive areas of new establishment. The frequency of flows that result in successful establishment largely determine mix of age classes present along the river. (5–10 years between successful establishment events is common along southwestern rivers.) Monsoon and tropical season floods stimulate reproduction of a suite of species with phenology tied to these seasons, such as mesquite.	Small-magnitude floods may result in limited areas of new establishment, often adjacent to the main channel.	High baseflows, particularly during the summer months after a recruitment event, will promote seeding survival and growth.	Low baseflows during the establishment phase may drop the water table below the rooting zone of woody seedlings, leading to increased desiccation and mortality.
Plant growth	Floods during all seasons replenish soil moisture and alluvial ground water, enhancing growth of riparian plants. Floods during dormant season (ca. November–January) are least effective in this regard.	Small floods replenish nutrients and fine sediments on the flood plain, which promotes growth of woody overstory and herbaceous understory species without widespread destruction of existing vegetation.	Stable, high baseflows enable rapid growth of riparian vegetation.	Lower baseflows and dynamic water tables may kill some riparian plants, but they also promote broader root distribution on woody plants, better preparing them to survive future dry periods.
Plant diversity	Floods during all seasons create a diversity of sites suitable for a diverse mix of herbaceous and woody plant species.	Small floods create a mosaic of patches on the flood plain which differ in time since disturbance and support vegetation in a range of successional stages.	High baseflows allow for the presence of obligate wetland species and generally higher species richness.	Low baseflows and highly dynamic water tables may kill some riparian plants (for example, obligate wetland species).

Chapter 4. Streamflow-Biota Relations: Birds

By Charles van Riper III[1] and Charles E. Paradzick[2]

Riparian ecosystems, and particularly the BWR corridor, provide critical resources such as water, vegetation, and abundant food for resident and migrating birds in the xeric environment of the southwestern United States (Grinnell, 1914; Rosenberg and others, 1991). Riparian habitat makes up less than 1 percent of the landscape in the Southwest yet supports more migrating and breeding birds than do all other western habitat types combined, with approximately half of the breeding species being riparian obligates (Anderson and Ohmart, 1977; Johnson and others, 1977; Knopf and others, 1988). Riparian areas also serve as critical stopover habitat for neotropical migratory birds, supporting 10 times more birds than do surrounding uplands during migration (Stevens and others, 1977). Aspects of the life history and habitat relationships of many southwestern birds are tied to both floristic composition and structural characteristics of the riparian plant community. Thus, the spatial and temporal distribution and abundance of riparian birds along the BWR are largely a function of interrelationships between streamflow, fluvial processes, and the riparian plant community (vegetation dynamics are discussed in detail in chapter 3, this report; see also Scott and others, 2003).

General Responses of Major Bird Groups to Flood Flows and Low Flows

This chapter discusses different bird groups and how they are generally influenced over the annual cycle by flow components of the BWR. Over 300 bird species have been recorded along the BWR corridor, these species are listed in appendix B. This list is stratified first by taxonomic group and then broken down by general bird-habitat affiliation. By placing birds within general habitat affiliations, we are better able to summarize relationships between streamflow and avian life histories across multiple species. The general habitat affiliations that we utilized were (1) deepwater birds, (2) shallowwater birds, (3) predators/scavengers, (4) gamebirds, and (5) small forestbirds (see appendix B). Streamflow-biota relationships for bird species found along the BWR are summarized in table 6 at the end of this section.

Deepwater and Shallowwater Birds

Many of the bird species and much of the avian biomass along the BWR corridor are concentrated in the delta region. The two bird groups most greatly influenced in this stretch of the river corridor are the deepwater and shallowwater birds. Riverflows work in concert with Lake Havasu water levels to influence numbers and distributions of birds within these two groups.

The deepwater birds respond primarily to resources either transported down the BWR or deepwater resources influenced by river and delta nutrient upwelling. These birds also respond, in a secondary fashion, to deeper water regions along the river behind beaver dams and in deep scoured pools. During high flood events, water levels and turbidity increase in the stream and especially in the delta. The turbidity particularly influences deepwater birds because underwater prey is hidden. For example, the numbers of western grebes (*Aechmophorus occidentalis*)

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decrease during high flow events because fish prey become more difficult to find. This effect of high flow events also occurs for mergansers (*Mergus* spp.) and other diving deepwater birds.

The shallowwater birds respond to variable flow regimes principally through the addition (or deletion) of available foraging habitat provided by exposed sandbars along the BWR. There is some use of shallowwater areas and exposed sandbars along the entire river, but the majority of shallowwater birds are found in the delta region. Low flows in the BWR and lower lake levels would proximately enhance the use of the river and delta region by shallowwater birds through the exposure of more sandbar habitat; however, higher flows and flood events that are ultimately needed to bring sediment for sandbar building negatively influence shallowwater bird numbers on the BWR. These higher flow events remove some of the dense stands of cattail (*Typha* spp.), bring outside nutrients for the shallowwater birds' prey base, and create shallow pools and backwater marshes along the entire river corridor, thus ultimately enhancing shallowwater-bird habitat.

Predators and Scavengers

The avian group that is most greatly influenced by variable flows of the BWR is the predators and scavengers group. These birds respond directly to the large biomass of resources along the entire river drainage and especially in the delta. Avian predator numbers increase as available prey (birds, herps, mammals) biomass increases, and their numbers decline as prey biomass is reduced or disappears from the BWR. Thus, avian prey numbers and biomass along the entire riparian corridor of the BWR corridor directly influence avian predator densities. Any positive relationships between flow components and bird numbers will enhance numbers of predator and scavengers. Large flood events that cause numbers of bird, herp, and mammal deaths will enhance resources for scavengers along the entire drainage. Potential prey that is not killed but that is negatively influenced by large flood events will be easier for avian predators to capture. Prey that is killed during the high flows will increase food resources for scavenger birds (e.g., turkey vultures (*Cathartes aura*)).

Gamebirds

Of the remaining two avian groups, gamebirds are probably directly influenced the least by flow components. The great majority of upland gamebirds (e.g., quail), utilize the riparian corridor directly or indirectly for water and food resources (such as seeds), as well as for escape cover. Thus, steady baseflows can provide a stable water resource. Floods that inundate flood plains and terraces can enhance herbaceous vegetation productivity and increase associated food resources such as seeds or insects.

Forestbirds

The last group is forestbirds, which contains the greatest number of species and is probably influenced the most by BWR flow. Generally, infrequent, large-magnitude flood events can result in vegetation destruction and removal, channel migration, and floodplain sediment erosion and deposition. While these processes may remove preferred habitat of some avian taxa, the resulting reworked flood plain can create a more complex landscape pattern of available habitats, including sites for establishment of new cohorts of woody vegetation, and interspersed remnant stands of mature vegetation. Maximizing habitat heterogeneity both horizontally (forest patch composition) and vertically (foliage height diversity) across the landscape can increase available avian niches. Smaller magnitude floods can result in more spatially limited establishment of new cohorts, which tends to be (proximally and ultimately) more beneficial for avian communities. Between flood events, perennial baseflows benefit riparian-associated birds by providing stable sources of water and more suitable aquatic habitat for insect reproduction. The forestbirds group contains the greatest number of species of concern, including the endangered southwestern willow flycatcher (*Empidonax traillii extimus*) and the yellow-billed cuckoo (*Coccyzus americanus occidentalis*), both of which are discussed in more detail below.

Specific Examples of Flow-Avian Biota Relationships in the Bill Williams River

Southwestern Willow Flycatcher

The willow flycatcher (*Empidonax traillii*) is a riparian obligate songbird that breeds throughout much of North America. The southwestern willow flycatcher (SWFL) is one of several recognized subspecies (fig. 29). The current SWFL breeding range includes southern California (from the Santa Ynez River south), Arizona, New Mexico, extreme southern portions of Nevada and Utah, and extreme southwest Colorado. Records of probable historical breeding SWFL exist for western Texas, but recent surveys are lacking. Similarly, breeding records for Mexico are rare and are restricted to extreme northern Baja California del Norte and Sonora (Unitt, 1987; Browning, 1993).

Unitt (1987) was the first to recognize the precipitous decline in SWFL populations throughout its range, and he noted that the greatest reductions were probably in Arizona. Causes of declines were primarily due to the loss, fragmentation, and modification of riparian habitats. In response to the few fragmented populations remaining, the U.S. Fish and Wildlife Service listed the species as endangered in 1995. Critical habitat was designated in 2005 (U.S. Fish and Wildlife Service, 2005), after the first rule was set aside because of a court challenge in 2001. A recovery plan was completed for the species in 2002; the plan summarizes information concerning the bird's habitat preferences, the role hydrology plays in habitat formation and persistence, and the actions managers can take to improve riparian conditions for the bird. One recovery management action identified was the need for the evaluation of river regulation on recruitment and persistence of pioneer riparian forest and the consideration of flows that could increase available SWFL nesting habitat.

The SWFL breeds in dense riparian habitats along rivers, streams, wetlands, and reservoir deltas. The largest known populations occur at Cliff-Gila Valley New Mex., Roosevelt Lake Ariz., the lower San Pedro River and nearby Gila River Ariz., the Rio Grande in both Colorado and New Mexico, and the San Luis Rey River Calif. Riparian forest on the BWR, including the upper end of Alamo Lake, has supported nesting birds since 1994. Alamo Lake Delta contains one of the largest populations in Arizona (Paradzick and Woodward, 2003).

Qualitative descriptions of low elevation (<900 m (<3000 ft)) riparian forest suitable for SWFL nesting include dense stands of trees with high canopy cover and with close proximity to standing water or saturated soil (Sogge and others, 1997). The size of vegetation patches that support SWFL can vary widely but generally is less than 10 ha (24.7 acres) (Paradzick and Woodward, 2003). Quantitative analysis of vegetation requirements has better defined these attributes. SWFL nesting habitat in Arizona has been studied at three scales: landscape, patch, and within-patch. Although all three scales are interrelated, each suggests an important aspect of habitat needs. At the large spatial scales, Hatten and Paradzick (2003) found that SWFL nest sites in Arizona had greater foliage density (forest) and edge in the 4.5-ha (11.1-acre) neighborhood size, and greater amounts of flood plain or flat terrain within the 41-ha (101.3 acre) neighborhood size compared to random unoccupied sites. These selection patterns were similar to those found by Brodhead (2005) along the Rio Grande River. At the patch scale, SWFL preferred forest stands with high density (500–1,300 stems/ha (1,235–3,212 stems/acre))

Figure 29. Southwestern willow flycatcher (*Empidonax traillii extimus*). Photograph by Alex Smith, Arizona Game and Fish Department.

small (5–15 cm diameter at breast height (dbh) (2–6 in dbh)) tamarisk or willow stems, high foliage density in the mid (4–7 m (13–23 ft)) and upper (7–9 m (23–30 ft)) canopy, and high canopy cover (>85 percent), and most occupied patches were adjacent to water (Paradzick, 2005). Within patches, nests were placed closer to water and canopy openings and had higher stem densities of young trees compared to unoccupied plots (Allison and others, 2003).

Together these data provide a picture of essential habitat components for SWFL. Broad flood plains allow for a mosaic of dense forest patches interspersed with openings and, possibly because of lower frequency of flood scour compared to canyon reaches, for the persistence of dense forests over time. Such configurations may be important for adult and juvenile SWFL refuge, foraging, and dispersal (Hatten and Paradzick, 2003). The preference for young dense forest provides the dense canopy layer and high midstory foliage for nesting. The importance of water or saturated soil may not only influence tree growth, vigor, and stand and foliage density (Horton and others, 2001a, b), which could increase nest concealment and reproduction, but may also provide a cooler within-patch microclimate and increase the local insect food base.

The U.S. Fish and Wildlife Service (1995) listed tamarisk as a cause of SWFL decline; however, regional data on SWFL show that over 50 percent of the territories were located in stands dominated or co-dominated by tamarisk (Sogge and others, 2003). Willow was the most common native plant associated with occupied habitat, while tamarisk was the most common exotic. Other native vegetation taxa can include seepwillow, cottonwood (usually in the overstory), or box elder (*Acer negundo*). While cottonwood sometimes occurs in SWFL patches and has been used as a nest tree, Paradzick (2005) found that SWFL selected willow or tamarisk-dominated patches but not cottonwood-dominated patches. SWFL nest success and reproduction monitoring (A. Tudor, oral commun.), insect foodbase research (Durst, 2004), and physiology data (Owen and others, 2005) all point to tamarisk as viable nesting habitat.

Flow regimes and associated fluvial processes that produce vegetation that fit the descriptions above are likely to benefit SWFL (Graf and others, 2002). The preference for young dense forest and floodplain mosaics highlights the importance of reoccurring recruitment events to create and sustain habitat over the longterm. Along low-elevation rivers in the Southwestern United States, young willow trees of this size (5–15 cm (2–6 in)) are typically 4–10 years old, while tamarisk are slightly older (7–20 years old). Thus, every 5–10 years, sufficiently large floodflows with a recession limb, the tail-end of which is timed to coincide with willow and tamarisk seed dispersal (April–May on the BWR; fig 27), should allow for establishment of new cohorts. The timing of the drawdown should position willow and tamarisk at relatively low topographic positions, enhancing the creation of edges adjacent to water.

The floodflows that are required to create sites suitable for establishment of new woody riparian vegetation may also destroy SWFL habitat, causing local extinctions. These local extinctions and/or migrations to new suitable habitats are processes that may simply be a natural part of the metapopulation dynamics, which appear to be characteristic of SWFL (U.S. Fish and Wildlife Service, 2002). Similarly, moderate summer flood events that inundate the flood plain but do not necessarily destroy SWFL occupied patches could reduce ground predator (e.g., snakes, lizards) densities and thus increase nest success, a pattern observed at other willow flycatcher breeding sites (Cain and others, 2003).

The strong tie of the SWFL to hydrological conditions is also suggested by Johnson and others (1999), who noted complete SWFL reproductive failure in response to lack of river flow in New Mexico. On the BWR, relatively large low flows would be likely to benefit SWFL by supporting dense growth of the vegetation, by maintaining high soil moisture, and by providing open water habitat for insect production. Conversely, SWFL habitat would be unlikely to occur where baseflows are too low to support perennial flow (standing water) and therefore cause a lowering of groundwater tables at established sites, limiting the establishment or persistence of dense vegetation.

Yellow-Billed Cuckoo

The western yellow-billed Cuckoo was historically distributed across a vast geographic area of the western United States, east to Texas and in northern Mexico (Hughes, 1999). Birds are often found nesting and breeding in riparian habitats composed of gallery cottonwood-willow and mixed broadleaf species, as well as in mesquite bosques. Historically, yellow-billed cuckoos were considered widespread and locally common in Arizona (Swarth, 1914; Phillips and others, 1964) and typically nested in mature riparian forests and woodlands along central and southern Arizona drainages (Hamilton and Hamilton, 1965).

Habitat structure appears to be a key factor for retention of the yellow-billed cuckoo in the Southwest. study in California demonstrated that yellow-billed cuckoos have significant macro-habitat requirements and that size of the habitat patch is extremely important. Using patch size, Gaines and Laymon (1984) identified four classes of habitat quality (table 7). Further research by Laymon and Halterman (1989) found that configuration of the habitat was important for the yellow-billed cuckoo, and they proposed “primary” and “secondary” habitat quality classes. In Arizona, the western yellow-billed cuckoo has been associated with broadleaf deciduous riparian habitat dominated by cottonwood and willow (Hamilton and Hamilton, 1965; Gaines, 1974; Gaines and Laymon, 1984; Halterman, 1991). Habitat destruction, degradation, and fragmentation have caused a range retraction and population declines of the yellow-billed cuckoo throughout Arizona (Laymon and Halterman, 1987). As a result, the western yellow-billed cuckoo is a candidate for listing as an endangered species with the U.S. Fish and Wildlife Service (2001). The yellow-billed cuckoo is probably the avian species of most concern along the BWR corridor. This bird requires large (80+ ha) patches of mature cottonwood and willow trees with an understory of smaller trees and shrubs. A recent analysis of the projected distribution of this bird throughout the state shows that riparian habitat is an essential component of determining if this sensitive species is able to occupy an area (fig. 30).

The BWR corridor currently serves as a critical core area that sustains yellow-billed cuckoo residency (fig. 31). More importantly, the vegetation structure of the river corridor allows this bird to find suitable breeding habitat each year. In other areas of the State where smaller riparian patches occur (e.g., Verde Valley), yellow-billed cuckoos do not breed every year (M. Johnson oral commun.).

Components of the vegetation that provide resources for this bird are the microclimates created by a mature, closed canopy cottonwood-willow forest with a structured understory. Yellow-billed cuckoos also use tall, dense, tamarisk-dominated habitat. This type of habitat allows birds to successfully nest at a time of the year (June), when it is too hot for many passerine species to successfully raise young. This later nesting is mandated by the abundance of prey. The yellow-billed cuckoo is a sit-and-wait predator and, as such, relies on larger food items such as cicadas and large moth larvae. These food items emerge and become available later in the year than do many other insect species.

Flow regimes and associated fluvial processes that produce large tracts of closed canopy, largely cottonwood-dominated forest are necessary to benefit the yellow-billed cuckoo. Flows that enable seedling establishment of cottonwood are periodically necessary (see chapter 3, this report), but yellow-billed cuckoo habitat might benefit from slightly longer intervals between floods so that trees have time to grow and form a closed canopy. Mortality of trees in the 20- to 40-year age range appears to be relatively common along the BWR (Shafroth, Andersen, van Riper, personal observation). Thus a 20–40 year recruitment flood recurrence interval might represent a bare minimum recurrence interval to support yellow-billed cuckoo habitat. On the BWR, much of the best cuckoo habitat occurs where the moderate floods released from Alamo Dam (ca. 169.9–198.2 m^3/s (6,000–7,000 ft^3/s)) create some new establishment sites but do not destroy much of the former vegetation. Yellow-billed cuckoo habitat would benefit from moderate to large baseflows, which would maintain relatively high alluvial water tables and water availability to support dense cottonwood forest and perhaps higher insect abundances.

Table 6. Summary of flow-biota relationships for bird species found along the Bill Williams River, Ariz.

Biota	Resilience to floods	Moderate to large floods	Small floods	High to moderate baseflows	Low baseflows
Deepwater and shallowwater birds	Moderate	Mortality of deepwater birds may increase as floods create turbidity in the delta, which hides prey. Shallowwater birds temporarily lose access to foraging habitat on sandbars, but floods ultimately build sandbars and bring in nutrients.	Less of an effect than large floods on deepwater birds. Shallowwater birds lose access to foraging habitat on sandbars but habitat is ultimately replenished by flooding.	May inundate sandbars for long periods, leading to increased mortality and emigration because of loss of foraging habitat.	Allows for enhanced use of the delta by shallowwater birds, and brings nutrients to delta on a steady level.
Predators and scavengers	High	Predator and scavenger populations should increase because of increased mortality of potential food resources. Prey will be negatively affected by large floods and will be easier to capture.	Response of predators and scavengers to small floods is dependent on the response of prey biomass.	Response of predators and scavengers to moderate floods is dependent on the response of prey biomass and number of organisms killed in the flood event.	Response of predators and scavengers to small floods depends on the response of prey biomass. Small avian predators will benefit more than other avian predator types.
Gamebirds	High	May increase mortality through the removal of escape cover and/or drowning but ultimately will build cover and increase food availability through increased seed production.	Would enhance population growth because of increases in cover and food availability without widespread destruction of cover.	Would benefit growth and survivorship because of increases in cover and food (seed) availability.	Access to water, food and cover will be limited because of deeper water tables, and vegetation stress and mortality may increase.
Forestbirds	High	Loss of trees will have an immediate negative impact on populations but is needed to rejuvenate vegetation that birds rely on for cover and food resources.	Loss of understory vegetation patches will negatively affect populations, but impacts will not be as great as with large floods. May rejuvenate herbaceous vegetation over time.	Provide a constant water source and deliver nutrients to vegetation. Nutrient availability cascades up the food pyramid, increasing prey biomass and creating better breeding and stop-over habitat.	Access to water and cover will be limited because of deeper water tables and vegetation stress. Prey abundance will decrease. Forest bird mortality may increase, and emigration will occur.

Table 6. Summary of flow-biota relationships for bird species found along the Bill Williams River, Ariz. —Continued.

Biota	Resilience to floods	Moderate to large floods	Small floods	High to moderate baseflow	Low baseflows
Willow flycatcher	High	Local breeding areas will be eliminated because of vegetation removal, but destruction of gallery forests will lead to an increase in shrubby undergrowth or dense, young woody vegetation which is the preferred habitat for this species.	Fewer local breeding territories will be disturbed from vegetation removal, but recruitment of vegetation will eventually provide new habitat.	Promotes vegetation growth and increases habitat for flycatchers. Provides open and standing water habitat that has a positive impact on prey base.	Territory abandonment may occur if flows are too low to support perennial flow or shrubby vegetation.
Yellow billed Cuckoo	Moderate	Openings in closed canopy forest after flooding will negatively affect population growth.	Birds will be less effected than by large floods. They benefit through the creation of some new establishment sites without widespread destruction of existing vegetation.	Maintenance of alluvial water tables will increase vegetation growth and provide more food and habitat.	Lower water tables may stress vegetation, leading to habitat loss, lower productivity, and increased bird emigration.

Table 7. Yellow-billed cuckoo habitat requirements as identified by Laymon and Halterman (1989).

Habitat quality	Size (hectares)	Width (meters)
Unsuitable	<15	100
Marginal	20–40	100–200
Suitable	41–80	>200
Optimal	>80	600

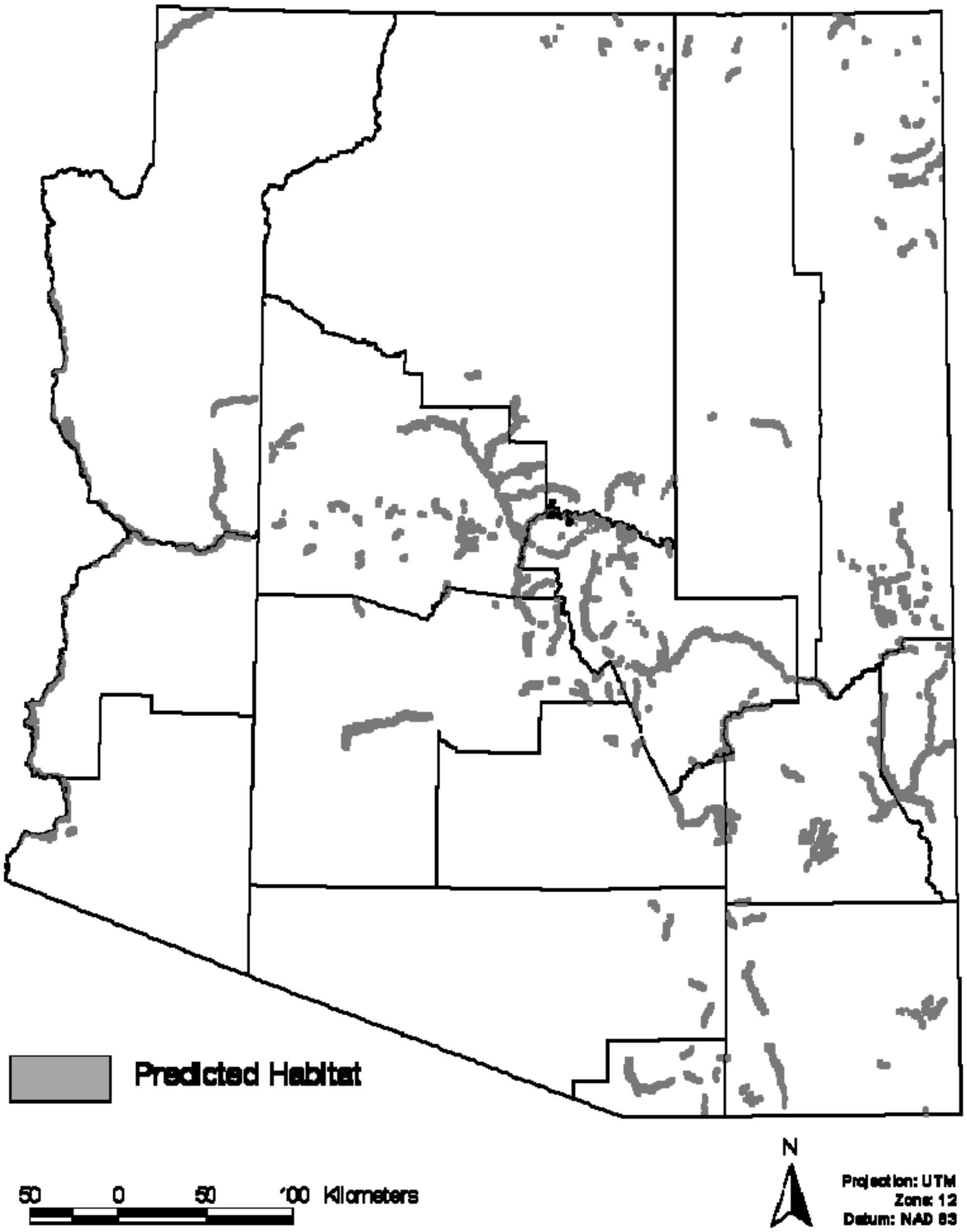

Figure 30. Yellow-billed cuckoo habitat throughout Arizona as predicted through Advanced Very High Resolution Radiometer (AVHRR) satellite imagery, clipped to perennial watercourses and buffered to 500 m (from Wallace and others, written commun.).

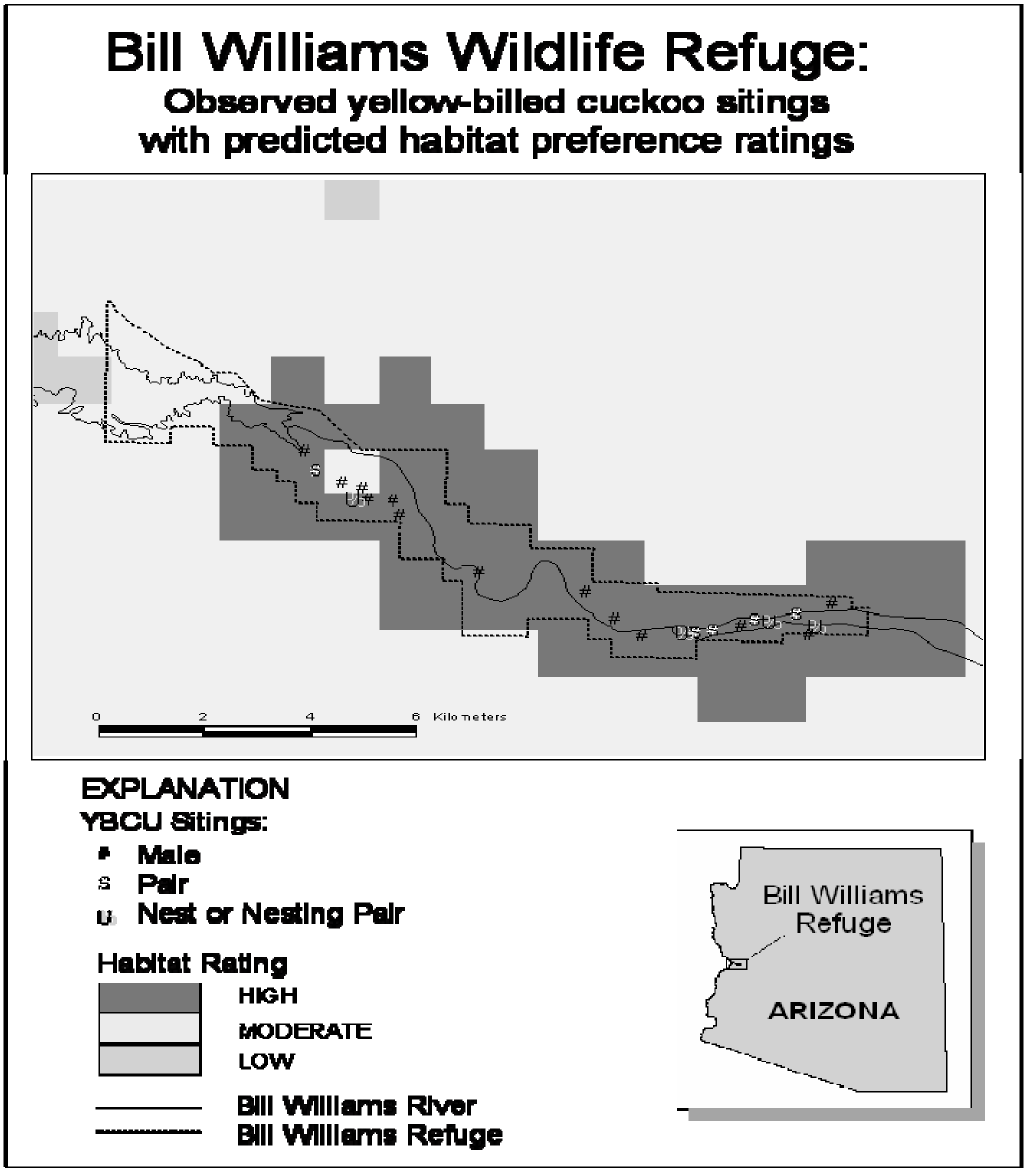

Figure 31. Advanced Very High Resolution Radiometer (AVHRR) satellite imagery predicting yellow-billed cuckoo habitat, overlaid with known yellow-billed cuckoo locations on the Bill Williams NWR (from Wallace and others, written commun.; Laymon and Halterman, 1989; K. Blair, oral commun.).

Chapter 5. Streamflow-Biota Relations: Fish and Aquatic Macroinvertebrates

By David A. Lytle[1]

Of all the organisms in the BWR ecosystem, fish and aquatic invertebrates are the most immediately affected by flood, drought, and other flow events. For this reason, sensible management of Alamo Dam flows is essential for maintaining healthy macroinvertebrate populations and reestablishing native fish species. Unfortunately there is no single “optimal” flow regime that would favor all native taxa simultaneously. The BWR aquatic fauna appears to be a mixture of species that vary greatly in their flow regime requirements. For example, some taxa require fast-flowing riffles, while others need standing ponds; some species have fast life cycles and recover rapidly from floods, while other species may be slow to recover. This section reviews the types of aquatic habitat that have occurred historically on the BWR, catalogs the different taxa occupying these habitats, and then discusses the management options for maintaining healthy populations of these organisms.

Relationships Between Habitat and Species Composition

Lotic Versus Lentic Habitats

The presence of flowing (lotic) versus standing (lentic) water can be a major control on the species composition of both fish and aquatic macroinvertebrates. In turn, the distribution of lotic versus lentic habitats is a direct consequence of flow regime because floods can convert one type to the other via removal of beaver ponds (lentic to lotic) and overbank flows (creation of side-channel lentic habitats). Because of these physical-biological connections, different flow regimes have the potential to favor very different aquatic communities. In general, aquatic species are primarily adapted to either a lotic or lentic existence, but some BWR taxa are found in both habitats (appendix C).

Lentic habitat types

Four major types of lentic habitat occur on the BWR, and each has the potential to harbor different aquatic species:

1. *Beaver ponds.* Ponds associated with beaver dams typically have a permanent hydroperiod, although some may dry during extended droughts (fig. 32). Characteristic beaver pond communities include exotic species such as largemouth bass (*Micropterus salmoides*), green sunfish (*Chaenobryttus cyanellus*), carp (*Cyprinus carpio*), and crayfish, as well as native aquatic insects such as odonates, dytiscid beetles, and aquatic Hemiptera. Stable baseflows, abundant riparian vegetation, and rarity of high-magnitude floods have apparently favored beaver populations on the lower BWR in recent years.
2. *Lakes.* Both Lake Havasu and Alamo Lake have a permanent hydroperiod, although water levels fluctuate depending on rainfall and season. Many exotic fish species have been introduced into Alamo Lake intentionally, accidentally, or illegally, probably because of easy access and popularity with the public. At least 15 exotic fish species have been found in

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Alamo Lake (appendix C); these species are potential source populations for invasion downstream in the BWR.

3. *Channel pools.* Channel pool habitats may occur seasonally in the active river channel because of reduction in baseflow during dry seasons. This transformation from lotic to lentic can also alter local community structure. In smaller montane streams typical of the BWR headwaters, lotic communities predominate in winter and consist of species that utilize flowing water such as baetid mayflies (Baetidae), net-spinning caddisflies (Hydropsychidae), and blackflies (Simuliidae) (Bogan and Lytle, written commun.; Bogan, 2005). During dry periods in late spring and summer, these stream reaches “cook down” to stream pools dominated primarily by lentic taxa such as dragonflies, dytiscid beetles, and a variety of hemipteran species. It is possible that the seasonal oscillation from lotic to lentic habitats may enhance species diversity through temporal coexistence (Bogan & Lytle, written commun.; Bogan, 2005). Some species do well in both lotic and lentic conditions: the native speckled dace (*Rhinichthys osculus*) can tolerate the high temperatures and low oxygen levels associated with lentic habitats, but it also requires fast-flowing conditions for spawning (John, 1963, 1964).
4. *Off-channel habitats.* The wide flood plain in many reaches of the BWR has produced remnant channels that are only wetted after flood events. At present no data are available concerning which species use these habitats in the BWR and whether there are off-channel “specialist” species not found in other lentic habitats. Off-channel habitats could be biologically important because their seasonal hydroperiod can exclude fish, or at least limit fish abundances to low levels. Exclusion or limitations of fish abundances could provide habitat for invertebrate species that are adapted to fish-free environments (McPeek, 1989, 1990) or that require fish-free habitats to complete portions of their life cycle (Smith and Larson, 1993).

Figure 32. Beaver dam activity, and lentic habitat created by a beaver dam. Photograph by David Lytle, Oregon State University.

Lotic Habitat Types

Lotic habitats occur seasonally or when discharges from Alamo Dam are sufficiently high. Three general types of lotic habitats are apparent within the BWR drainage:

1. *Montane bedrock streams.* These small headwater streams may fluctuate from high flows in winter to very little moving water during summer. Hydroperiod is permanent in reaches where the water table is forced up by bedrock. These habitats occur upstream of Alamo Dam and harbor an exceptionally rich diversity of benthic macroinvertebrates (Lytle, 2000). Anurans such as the native lowland leopard frog (*Rana yavapaiensis*) can also be found in spring-fed streams such as Peoples Canyon on the Santa Maria River, although chitrid fungus remains a threat to these populations (Bradley and others, 2002). Diversity is high partly because these small streams have not been invaded by exotic fish or crayfish. As such these streams could be important population reservoirs for the main stem BWR, although Alamo Lake may present a barrier to downstream dispersal of many taxa.
2. *Beaver dam outflows.* When baseflows are sufficiently high, flowing water occurs at the outflows of beaver dams. In some areas where beaver dams are dense, these outflows can be very short, flowing less than a meter into the next beaver pond. The lotic nature of these outflows, however, may harbor different taxa than do the pools (simuliid flies, baetid mayflies, and nonnative red shiners (*Notropis lutrensis*)).
3. *Channel stream habitats.* These are the flowing-water counterparts to the channel pool habitats described above (fig. 33).

Figure 33. Typical lotic habitat in a sand-dominated reach, lower Bill Williams River, river mile 5.4. Photograph by Patrick Shafroth, U.S. Geological Survey.

Overview of Aquatic Organisms in the Bill Williams River Below Alamo Dam

Aquatic Invertebrates Below Alamo Dam

Benthic macroinvertebrates were surveyed qualitatively around 1980 (United States Fish and Wildlife Service, 1981) and quantitatively during the 1990s (Vinson, 1994, 1995, 1996, 1999). Most of these surveys targeted lotic riffle habitats and thus do not characterize the macroinvertebrate communities in lentic beaver pond habitats. The BWR aquatic invertebrate fauna is typical of low-elevation Arizona rivers that possess unstable (nonbedrock) benthic substrates. Mayflies such as *Baetis* spp. (hereafter interpreted to include the new genus *Fallceon*) can be extremely abundant where suitable flowing-water riffles are present, reaching densities above 10,000/m^2 at some sites (Vinson, 1999). Other taxa that reach high abundances locally include the microcaddisfly *Hydroptila,* the baetid mayfly *Acentrella*, and chironomid fly larvae.

Fish Below Alamo Dam

The fish fauna below Alamo Dam is dominated by nonnative species including largemouth bass, green sunfish, and red shiner (United States Fish and Wildlife Service, 1992). Nonnative mosquitofish (*Gambusia affinis*) are found throughout the BWR drainage (United States Fish and Wildlife Service, 1992) and are abundant in beaver dam ponds below Alamo Dam (M. T. Bogan, personal observation, 2004). Historically, the native endangered razorback sucker (*Zyrauchen texanus*) may have used the lower BWR during periods of sustained high flows (C. Minckley, oral commun, 2004), but reduced flows on the BWR and reduced razorback populations in the main stem Colorado River have prevented their use of the BWR in recent decades. The native longfin dace (*Agosia chrysogaster*) occurred throughout the BWR and its tributaries as late as the early 1990s (United States Fish and Wildlife Service, 1992), but currently it is rare below Alamo Dam.

Alamo Lake contains a number of fish populations that could be relevant to restoration efforts downstream. Alamo Lake harbors a long list of nonnative species that could become established downstream, including bluegill (*Lepomis macrochirus)* and four species of bullhead (*Ictalurus melas* and *I. natalus*) and catfish (*I. punctatus* and *Pilodictus olivaris*)(see species list in appendix C). In tributaries above Alamo Lake, there are populations of five native species: longfin dace, speckled dace, roundtail chub, Gila mountain sucker (*Pantosteus clarki*), and desert sucker (*Catostomus insignis*). Thus, populations of both native and nonnative fish could potentially move below Alamo Dam and become established if flow conditions below the dam were to become suitable.

Relationships Between Flow Events and Species Distributions

Resistance Versus Resilience

Aquatic species vary in both their resistance and resilience to flood and drought events. Resistance refers to an individual's ability to directly withstand or avoid an event and includes such traits as survival of desiccation via diapause (some Plecoptera species) and escape from floods by using behavioral mechanisms (some native fish species, aquatic Hemiptera). Resilience is a population-level phenomenon and refers to a species' ability to rebound numerically following a disturbance. A typical resilience trait is a fast life history (rapid growth rate, short time to maturation, high fecundity) that results in a high population-level rate of increase following flood mortality. Some mayfly species, such as *Baetis*, show this life-history syndrome (Gray, 1981).

The ability of aquatic organisms to disperse and recolonize also determines how populations will be affected by flood and drought events (Gray and Fisher, 1981). All aquatic insects in the BWR drainage are capable of leaving the aquatic habitat either by flight or by crawling. Dispersal typically occurs during the adult stage, which can last from several months (many aquatic beetles and true bugs) to only a few days (most mayfly species), although juveniles of some species are capable of leaving the water temporarily (the giant water bug (*Abedus herberti)*, Lytle, 1999; and many semiaquatic Hemiptera such as water striders). Thus the seasonal timing of floods and droughts relative to the seasonal phenology of the dispersal-capable stage may be an important control on aquatic insect populations. Species also differ widely in their dispersal abilities. For example, the dragonfly *Anax junius* is capable of cross-continental migration while the giant water bug *Abedus herberti* is only capable of crawling short distances (Lytle and Smith, 2004). Because of these differing dispersal capabilities, proximity to source populations (in headwater reaches above Alamo Lake, or possibly in off-channel habitats) might determine recolonization rates.

Evolutionary Adaptations to Flood and Drought

All of the aquatic insects known from the BWR and its tributaries are native species (see appendix C), and at least some of them are known to possess adaptations for surviving flood and drought. Flood-adapted species include the giant water bug *Abedus herberti*, which uses rainfall as a cue to temporarily move to protected riparian areas during floods (Lytle, 1999), and the caddisfly *Phylloicus aeneus,* which has an adult life stage that is synchronized to avoid summer monsoon floods (Lytle, 2002).

By contrast with the invertebrates, a large part of the BWR fish fauna is nonnative, and some of these species have been shown to be disproportionately vulnerable to floods as compared to native species. For example, nonnative fish can be killed or displaced by severe floods, at least in smaller canyon streams (Meffe, 1984; Minckley and Meffe, 1987; Dudley and Matter, 1999). Many native fish species in the Sonoran Desert, including all five species found in the BWR watershed, exhibit adaptations to regular flood events and do not suffer population declines even after extremely large floods (Eby and others, 2003). Because of the resilience, of native fish in this drainage, floods have been proposed as a management tool for favoring native over nonnative fish species (Moyle and Light, 1996; Marchetti and others, 2004). It is not clear how this type of management strategy could be implemented on the main stem of the BWR because large flows may become dissipated over the relatively wide canyon bottom.

Species will be affected by different components of the flood regime depending on what 'mode of adaptation" (Lytle and Poff, 2004) they possess. Lytle and Poff (2004) describe three such modes, and provide a comprehensive list of flow regime adaptations for aquatic animals and plants (see table 1 in Lytle and Poff, 2004).

1. *Life-history adaptations.* Life-history adaptations typically involve the synchronization of events such as reproduction and growth in relation to the occurrence of flow regime events. For organisms with life-history adaptations, the seasonal timing of flood and drought events is critical. Examples of organisms with life history adaptations include caddisflies, which mature into the aerial adult stage in order to avoid these same floods.
2. *Behavioral adaptations.* Behavioral adaptations enable animals to respond directly to individual flood or drought events, often by reacting to a correlated environmental cue. Native fish such as the Sonoran topminnow (*Poeciliopsis occidentalis)* respond to the rising limb of the hydrograph and use this as a cue to orient into the current to avoid displacement (Meffe, 1984). Thus, the rate of change from baseflow to flood conditions is an important

factor. The giant water bug *Abedus herberti* uses rainfall as a cue that a flood is imminent (Lytle, 1999). While this species (and possibly other Hemiptera) is adept at surviving floods by this means, this strategy may fail during controlled release floods that occur on days without rain.

3. *Morphological adaptations.* Morphological adaptations include traits such as a streamlined body profile for living in fast water (e.g., heptageniid mayflies), large gill surface for respiration in low-oxygen conditions (e.g., *Callibaetis*), and so on. Organisms with certain suites of morphological traits will be favored under specific flow conditions (lotic versus lentic).

Examples of Flow-Biota Relationships in the Bill Williams River

The aquatic species of the BWR differ widely in terms of resistance, resilience, and evolutionary adaptation to flow events. While detailed information is not available for most taxa, it is possible to use general ecological and life-history information to make informed predictions about how flows might affect populations on the BWR. The following section focuses on three currently or historically important aquatic taxa. Relationships between life-history and streamflow for these species are summarized in table 8 at the end of this section.

Longfin Dace (*Agosia chrysogaster*): High Resistance to Floods and Droughts

Like other native desert fishes, the longfin dace is facing population declines and extirpation because of competition with nonnative fishes and changes in river hydrology. In Arizona, it is native to the BWR and Gila River drainages, and has been introduced to the Virgin River (Minckley, 1973). Because the longfin dace is adept at coping with the extreme floods and droughts typical of desert rivers, appropriate flow management could help reestablish populations below Alamo Dam. In contrast to many of nonnative fishes, the longfin dace has reasonably high resistance to both flood and drought conditions, and it likely possesses behavioral adaptations for surviving flood and drought.

Baetis Mayflies (Ephemeroptera: Baetidae): High Resilience to Floods

Baetis mayflies possess some of the fastest life cycles of all aquatic insects: in Arizona desert streams, *Baetis* (=*Fallceon*) *quilleri* can develop from egg to reproductive adult in less than 10 days, which potentially allows 35 generations per year (Gray, 1981). *Baetis* mayflies are also renowned for their ability to drift downstream and recolonize new habitats after a flood (Allan, 1995; Lytle, 2000). For these reasons, they have exceptionally high resilience to flood events. The BWR harbors at least four genera of mayflies in the family Baetidae, including *Baetis* (inclusive of *Fallceon*), *Pseudocloeon*, *Acentrella*, and *Callibaetis*. All but *Callibaetis*, a pond dweller, are found in fast-flowing, riffly habitats. *Baetis* feed by scraping attached algae and diatoms (periphyton) from the surfaces of rocks. *Baetis* mayflies can reach phenomenal densities in streams—up to tens of thousands of larvae per square meter (Vinson, 1999). For this reason they are likely an important food resource for fish, other invertebrates, and terrestrial animals such as birds.

Gomphid Dragonflies (Odonata: Gomphidae): Low Resilience to Floods

Adult gomphid dragonflies are known as clubtails from the distinct enlargement at the tip of the abdomen. During the summer months, the green and yellow marked adults can be seen patrolling stream reaches and ponds in search of flying insect prey. The larvae of some are known as sanddragons because they occupy sandy river substrates (fig. 34). Gomphids are also predatory as larvae, feeding on other insects and even small fish. At least three gomphid genera are known from the BWR, *Progomphus*, *Erpetogomphus*, and *Ophiogomphus.* Gomphid larvae are classified as lotic and are found in slower-moving reaches of rivers and streams, although they sometimes occur in ponds (Merritt and Cummins, 1996). Unlike many other aquatic insect larvae, gomphids are thought to require at least 2 years to reach maturity. Because of the longer time to maturity for this group, populations may be slow to respond to major hydrologic events (low resilience), especially if the event occurs during a time of year when no adults are present aerially. It is possible, however, that their long-lived adult stage might provide a fitness advantage during large flood or drought events (sensu Lytle, 2002).

Figure 34. Gray sanddragon *Progomphus borealis* (Gomphidae) larvae. Big Sandy River, Ariz. Photograph by L. McMullen, Oregon State University.

Table 8. Summary of flow-biota relationships for longfin dace, *Baetis* mayflies and Gomphid dragonflies.

Biota	Resilience to floods	Moderate to large floods	Small floods	High to moderate baseflows	Low baseflows
Longfin dace	High resistance to floods and droughts.	May cause short-term mortality, but could trigger spawning that ultimately increases population sizes. May also remove nonnative fish, which could release longfin dace from competitive pressure.	Unlikely to have a significant effect.	Provide more suitable habitat than low baseflows.	Baseflows could remove nonnative fish, and thus may provide long-term benefits to longfin dace.
***Baetis* mayflies**	High resilience to floods.	Floods in the fall and winter are likely to reduce mayfly populations because fewer aerial adults are present to recolonize during these cold months. This reduction would be offset if recolonization could occur via drift from upstream refugia, but because of the barrier of Alamo Dam, recolonization is unlikely..	Floods during the summer monsoon season may reduce mayflies, but populations can rebound from aerial adults. Small floods may enhance recolonization by cleaning riffles of fine sediments and enhancing algal growth.	Could favor mayfly populations, especially following large floods that create new lotic habitat by breaching beaver dams.	May reduce mayfly by eliminating riffle habitat.
Gomphid dragonflies	Low resilience to floods.	Will likely reduce Gomphid populations. Resilience will also be low if a flood occurs when few adults are present to recolonize (likely during the cold winter months). If the return interval of large floods is sufficiently long (>3 years), large floods may have long-term positive effects by removing beaver dam ponds and creating lotic habitat for recolonization.	May reduce Gomphid populations, especially if floods are strong enough to scour stream channels.	May not be ideal, as Gomphid larvae are visual predators that typically occupy slower river sections. Other desert stream predators such as belostomatid hemipterans appear to do best when flows are high in the winter (high productivity of algae-feeding prey species) and then low in late spring and summer (prey become spatially concentrated).	

Chapter 6. Streamflow-Biota Relations: Mammals, Reptiles, Amphibians, and Floodplain Invertebrates

By Douglas C. Andersen[1]

The animals that use the flood plain and associated lotic and lentic aquatic habitats of the BWR can be classified as either obligately or facultatively riparian (e.g., see Andersen and others, 2000). Facultatively riparian species may use the riparian zone extensively, but individuals can also survive and reproduce using only upland habitats. Thus, the maintenance of their populations is not strictly dependent upon the presence of the habitats associated with a riverine ecosystem. Obligately riparian species are those whose life cycle requires resources or habitats provided only by the riparian (here, riverine riparian) environment; however, even obligately riparian species may be found outside the riparian zone under particular circumstances, such as while dispersing.

The riverine ecosystem created by flows in the BWR contains a large number of aquatic, semiaquatic, and terrestrial animals that range in size from microarthropods associated with decomposing detritus to large mammals, both herbivores and predators, that use the riverine corridor as a source of food, shelter, and water. These organisms form a complex trophic web that ties together not only the various components of the riverine ecosystem (e.g., the stream, parafluvial zone, and vegetated flood plain) but also the riverine ecosystem to the surrounding desert. Even though our understanding of the mechanisms involved in determining the structure and functioning of this riverine ecosystem is rudimentary, work in other ecosystems suggests that a small number of species or groups of species will have a disproportionately large influence (Hooper and others, 2005). This section discusses some mammals known or considered likely to be in that group. We also discuss how the nature of the flow regime will influence populations of these and other riparian animals, including reptiles, amphibians, and insects. Mammals (appendix D), reptiles and amphibians (appendix E), and floodplain invertebrates (appendix F) encountered within the BWR corridor are listed in the appendices at the end of this document.

Large Herbivores

It is well established that long-term grazing and browsing by large herbivores can result in major changes in vegetation (Hobbs, 1996; Augustine and McNaughton, 1998). Overgrazing by large herbivores alters the structure and may reduce the abundance of preferred food plants, allows populations of nonpreferred plants to increase, and may promote invasion by undesirable exotic species. Historically, grazing by native ungulates using the BWR corridor was probably limited by predators or by hunting pressure from Native Americans or settlers who kept ungulate populations at relatively low levels. Use of the riparian zone by livestock, however, did degrade the vegetation. Adverse effects on vegetation and soil are a common consequence of livestock use of riparian areas in the arid Western United States (Belsky and others, 1999). The four Bureau of Land Management grazing allotments on public lands along the river below Alamo Dam are now being managed to facilitate recovery of the riparian vegetation to something approximating its pristine (i.e. presettlement) state. Although there has been no licensed livestock grazing since 1988, overgrazing may still be occurring in areas where the numbers of feral burros are excessively high.

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The natural flow regime probably had little effect on large herbivores. Flash floods likely occasionally injure or kill individual large mammals caught in them, but even some flash floods may actually feature a rising limb sufficiently slow to allow floodwaters to be avoided by simply moving into the upland.

A very small number of elk (*Cervus elaphus*) may currently use the flood plain below Alamo Dam. If present, these individuals are a spillover from a larger group of animals using the Big Sandy and Santa Maria River drainages above the dam (Clint Adams, Arizona Game and Fish Department Biologist, oral. commun.). The elk rely on the shade, forage, and other resources provided by the floodplain environment to a greater extent than do the more substantial numbers of desert mule deer (*Odocoileus hemionus*) that can be found thoughout the corridor. Along with seeking water, the deer use the flood plain to obtain green food when desert forage declines in palatability or availability. Desert bighorn sheep (*Ovis Canadensis*) enter the corridor to access water, but they likely avoid dense vegetation and preferentially feed and rest in open desert environments. Mammalian predators are discussed below.

Beavers

The influence of beaver dams and their associated ponds on fluvial geomorphic processes were discussed in chapter 2 of this report. In this chapter, we discuss aspects of their population biology and some of their links to biological and biogeochemical processes taking place in the BWR ecosystem. Aerial photographs taken in May 2002 show much of the BWR low flow channel occupied by beaver ponds (Shafroth and others, 2004). It is likely that these rodents take up residence and build dams along all reaches bordered by cottonwood or willow or where other vegetation (e.g., cattail) provides suitable forage. There has been no research examining the effects of a flood pulse on beavers in the desert Southwest. Small floods (0.014–140 m^3/s (500 to 5,000 ft^3/s)) can damage beaver dams, but assuming that food caching is unnecessary and that desert beavers typically build bank dens rather than lodges, this damage would not necessarily translate into strong detrimental effects on survival. Casual observations following a flood in this range on the BWR in autumn 2004 showed that many ponds retained water (i.e., the environment upstream of the damaged dam remained lentic rather than lotic) and that beavers were still present. We hypothesize that beavers are neither displaced nor forced to disperse following small floods but that they may be made more vulnerable to predators while repairing the dam and restoring pond water level to its pre-flood value.

We speculate that a moderate flood (140–850 m^3/s (5,000–30,000 ft^3/s)), however, can remove most beaver dams and, where current velocity is high, sweep individual beaver downstream. Lower magnitude, but protracted, flows can potentially impact a beaver dam via persistent shallow overflow, undercutting, or lateral channel migration. Dam removal will lead to the complete draining of most ponds and exposure of most bank dens, forcing animals to seek or construct new dens. The vulnerability of beavers to predators will be dramatically increased until dams are rebuilt and the security associated with the pond and its dens restored; however, it has been noted that beavers can quickly recover from the effects of flood damage. (Leidholtbruner and others, 1992).

A large flood (>850 m^3/s (> 30,000 ft^3/s)) not only destroys beaver dams and sweeps individual beaver downstream, but also can lead to stream avulsion and thereby eliminate flow in the channel the dam formerly blocked. We hypothesize that these floods directly kill individual animals (e.g., via drowning or physical injury) and that increases in vulnerability to coyotes and other predators (Collen and Gibson, 2001) and social strife among displaced animals (Payne 1984), perhaps combined with reductions in food resources (Fryxell, 2001), leads to a dramatic rise in the mortality rates among beavers that survive the flood. Thus, floods of this magnitude set the stage for a complete reshuffling of the beaver community and the spatial and temporal pattern of pond generation.

Beaver ponds increase the area of surface water (and the linear extent of shoreline) and thereby increase the hydrologic connectivity between stream and flood plain. The ponds also raise the local water table, which can enhance vertical connectivity within the alluvium. The slower flow velocities in ponds can facilitate sediment accumulation, dense algal growth, organic matter buildup, and nutrient transformations. For example, Harper (2001) found higher organic matter in sediments of beaver ponds than in adjacent stream habitat in southern Nevada. Assuming relatively high carbon availability, the anoxic conditions in pond sediments may facilitate denitrification and result in the ponds serving as a sink for nitrogen. Anoxia and subsequent denitrification could be important from a water quality standpoint if nitrogen is being added to the BWR as a consequence of upstream human activities, such as agricultural operations.

Beavers cut vegetation to obtain both food and dam-construction materials. The effects of this cutting on vegetation dynamics within the flood plain are unclear. It appears that beavers on the BWR do not create large caches of food material, presumably because they experience only short and mild winters. Thus, the well-documented accounts of beavers "eating out" groves of preferred tree species in boreal forests and other northern locations may not be applicable to warm desert environments. Although beavers certainly cut both cottonwood and willow, which likely affects local stand structure, the most important influence of beavers on vegetation along the BWR may be through their pond-building activity and the resulting saturated soils and relatively stable water tables necessary to maintain cattail and other marsh species (Stromberg and others, 1996). Beavers cut tamarisk and incorporate the stems into dams, but the extent to which tamarisk is used for food is unknown. Hensley and Fox (1948) include it in a list of food plants but provide no evidence of actual consumption. Brazell and Workman (1977) failed to find evidence of tamarisk use in a specific effort to do so in a field study.

Small Mammals

Small mammals can also influence vegetation structure through selective herbivory (Howe and Lane, 2004). A somewhat less "aquatic" obligate-riparian mammal using the BWR corridor is the Arizona cotton rat (*Sigmodon arizonae*), a generalist herbivore that resides in mesic, dense herbaceous habitat (e.g., mixed grass and cattail) such as that in the delta area and perhaps some upstream areas featuring a perennially high water table. This species could potentially influence the nature of herbaceous vegetation in the areas it inhabits. The presence of the Arizona cotton rat along the river, however, is based on only two sightings; no individuals have been captured.

Small mammals are more vulnerable to harm from flood pulses than are medium- or large-sized mammals. Even low flood pulses could potentially result in destruction of Arizona cotton rat nests and the downstream displacement of individuals. If the rising limb of the flood pulse provides sufficient time, most small mammals simply move toward higher ground, which may strand individuals on shrinking islands or force those that are able to climb up into trees or other vegetation (Andersen and others, 2000). A rapid inundation will drown small mammals caught in places from which they cannot escape (e.g., below ground), and even moderate currents will overcome species that swim poorly. Several of the small mammals using the BWR flood plain can escape floodwaters by climbing (e.g., deer mice (*Peromyscus maniculatus*) and cactus mice (*P. eremicus*)). If they manage to survive the flood, at least some small mammals swept downstream can employ strong homing instincts to return to the area from which they were carried. An example of the variable effects among species is the finding that several of the cactus mice captured on the BWR flood plain prior to an autumn 2004 flood pulse (probably <141.6 m^3/s (<5,000 ft^3/s)) were recaptured in the same locations after the flood, whereas all white-throated woodrats (*Neotoma albigula*) present prior to the flood had disappeared (Kathleen Blair, oral commun.).

Bats

At least 13 bat species use the BWR corridor (Brown, 1996). Although most of the bats roost in abandoned mines in adjacent upland, both hoary bats (*Lasiurus cinereus*) and yellow bats (*L. xanthinus*) were documented as using floodplain trees as diurnal roosts (Brown, 1996). All 13 species are insectivorous (at least in part) and primarily use the river and riparian area for foraging and as a source of drinking water. Thus, the flow regime will affect these species both directly and indirectly through the extent and configuration of surface water and effects on insect production. Large numbers of bats would obviously have the potential to consume large numbers of insect prey. Nevertheless, the roles of these species as determinants of riverine ecosystem structure are unknown.

Mammalian Predators

Numerous mammalian predators in addition to bats rely on the floodplain for food (Hoffmeister 1986), but few species other than perhaps the raccoon are likely to restrict their movements to within the riparian corridor. The largest predator present is the mountain lion (*Felis concolor*), a wide-ranging species whose prey would include deer (*Odocoileus hemionus*), peccaries (javelina; (*Tayassu tajacu*)), young burros (*Equus asinus*), and beavers. Bobcats (*Felis rufus*) are undoubtedly also present. These cats prey extensively on cottontails (*Sylvilagus audubonii*) and jackrabbits (*Lepus californicus*) when they are available, but also consume mice, lizards, and other small prey. Other carnivores include the coyote (*Canis latrans*), gray fox (*Urocyon cinereoargenteus*) and kit fox (*Vulpes macrotis*). Coyotes might be able to kill an adult beaver found away from water, but most prey would be smaller and less formidable (Gese and others, 1996). The foxes probably venture into the riparian zone primarily for water or when foraging for rodents and reptiles in adjacent upland becomes unprofitable. All the larger carnivores would prey on young beaver (kits) made vulnerable by a flood or other circumstance. Striped skunks (*Mephitis mephitis*) and spotted skunks (*Spilogale gracilis*) would also use the riparian zone, the former probably more extensively than the latter. Like the raccoon (*Procyon lotor*), the skunks are opportunistic omnivores, including invertebrates as well as small vertebrates in their diet. Both the striped skunk and the raccoon are seldom found far from water.

Engulfment in rapidly deepening floodwaters would likely displace and perhaps result in injury or even drowning of raccoons or skunks, but the larger, more mobile carnivores could likely avoid floods by moving into the upland. Large floods might actually indirectly benefit most carnivores, at least in the short term, by making prey more vulnerable, either through the prey's displacement or injury, or through a reduction in vegetation that serves as concealment cover.

Reptiles and Amphibians

Consequences of flood pulses to terrestrial lizards are probably similar to those of small rodents and shrews, with effects differing strongly among those that are arboreal (e.g., ornate tree lizard (*Callisaurus ornatus*)) and those strictly terrestrial. Most lizards and egg-laying snakes reproduce during the warm months (April to October), and flooding during this season could smother or drown developing embryos and hatchlings. Adult turtles may be able to tolerate all but high flood pulses because of their strong swimming abilities (spiny soft-shelled turtle (*Trionyx spiniferous*)), climbing and clinging abilities (mud turtles), and ability to stay submerged for extended periods of time (Chris Holdren, oral commun.). Turtles and other aquatic animals may take refuge in underwater caves (e.g., beaver dens) to avoid currents during flood events. Many turtles also have well-developed homing abilities, which would facilitate their returning to a pond from which they had been displaced by a moderate flood. Lizards that hibernate (e.g., desert iguana (*Dipsosaurus dorsalis*) and the banded gecko (*Coleonyx variegatus*)) during all or part of the cool season (about November through February) may be especially vulnerable to floods from winter frontal storms. It is unclear if innate behaviors (habitat selection) associated with searching for hibernacula lead to these species moving from floodplain sites to uplands at the end of the warm season. Winter surveys within the Bill Williams National Wildlife Refuge indicated that only side-blotched lizards (*Uta stansburiana*) were active (on warm days), suggesting that all other species, including the ornate tree lizard, hibernate (Kathleen Blair, oral commun.).

Consequences of floods to amphibians differ from those of small mammals and reptiles, and these consequences probably vary strongly with organism sizes, which is related to swimming ability. The strong swimming ability of many species means that effects of small floods may be minor and that only moderate and large floods can increase mortality and disrupt communities through downstream displacement. The introduced and undesirable (Mueller and others, 2006) American bullfrog (*Rana catesbeiana*) may be least affected by floods because of its large size. American bullfrog tadpoles, however, are likely more vulnerable to displacement by floods. Based on studies elsewhere in the Southwest (summarized in Clarkson and deVos, 1986), the tadpole stage lasts for 3–6 months for eggs laid early in the April to early July breeding season. Tadpoles from eggs laid late in the breeding season overwinter in that form and transform in March or April of the following year. Platz and others (1990) speculated that another exotic amphibian present in the lower Colorado River, the Rio Grande leopard frog (*Rana berlandieri*), would eventually find its way into the BWR drainage, but unknown factors appear to be hindering invasion (Rorabaugh and others, 2002). The native lowland leopard frog may have historically occupied parts of the BWR corridor, but it is now absent. This species breeds from March to May and, to a lesser extent, in September and October (Sartorius and Rosen, 2000). Tadpoles from the spring eggs metamorphose in early summer. This timing minimizes exposure of eggs and tadpoles to flash floods generated by monsoon rains. Amphibians may in general face greater hazards as floodwaters recede and the need to find shelter in a location with permanent water becomes paramount. Whether flood events and the presence of displaced terrestrial and aquatic vertebrates attract predators is unknown. Some species may be vulnerable to burial by winter floods. For example, the Colorado River toad (*Bufo alvarius*) may estivate to avoid seasonal drought, spending the dry period under ground until “awakened” by rains.

Floodplain Invertebrates

Very little is known about how the flow regime influences nonaquatic floodplain invertebrates or how these animals may influence floodplain structure and functioning. Apache cicadas (*Diceroprocta apache*), which feed on the roots of floodplain trees and probably other vegetation as larvae, emerge from the soil during summer of most years and climb into the vegetation immediately prior to adult eclosion. The adults then mate, and females lay their eggs inside thin stems and branches, a process that can be especially damaging to sapling cottonwoods and willows. Although cicada abundance varies from year to year, these insects are a major source of food for some birds and probably small mammals and reptiles as well. Andersen

(1994) postulated that high densities of these insects belowground could influence soil moisture properties and therefore herbaceous vegetation. Flooding alone does not appear to markedly affect cicada numbers, but the deposition and erosion processes that accompany high flood pulses might dramatically influence emergence patterns by burying larvae under material that prevents their emergence or exposing larvae to desiccating air and aboveground predators.

The western viceroy butterfly (*Limenitis archippus obsolete*) is an obligate riparian species in that adults lay eggs on and the larval caterpillars feed on Goodding's willow and possibly Fremont cottonwood (Nelson, 2003). Adults feed on nectar produced by a variety of riparian plant species, including tamarisk and seepwillow, and are hypothesized to rely on surface water accessible from vegetation-free surfaces for both moisture and mineral intake (Nelson, 2003). The flow regime may thus influence the distribution and abundance of this butterfly both indirectly, by influencing the plant community that supplies the larval host plants and nectar sources, and directly, through the generation of bare alluvial surfaces adjacent to surface water.

Examples of Flow-Biota Relationships in the Bill Williams River

Mirroring the differences among the aquatic invertebrate and fish species discussed above, other animals found in the BWR also differ widely in terms of resistance and resilience to flow events. And again, detailed information is typically lacking for most taxa, but ecological and life-history information allow us to make informed predictions about how flows might affect populations on the BWR. Table 9 focuses on three important riparian-aquatic taxa.

Table 9. Summary of flow-biota relationships for beaver (*Castor canadensis*), ornate tree lizard (*Callisaurus ornatus*) and bullfrog (*Rana catesbeiana*) in the Bill Williams River, Ariz.

Biota	Resilience to floods	Moderate to large floods	Small floods	High to moderate baseflows	Low baseflows
Beaver	Moderate resistance to floods, low resistance to drought.	Floods displace individuals and increase mortality. Ponds would be modified or destroyed, triggering a new period of dam-building and pond creation. Increases in pond water levels and river stage allow access to vegetation otherwise only accessible by traveling away from the safety of the pond. Increased growth of trees and other food plants would deliver indirect benefits.	Small floods are unlikely to have a significant effect.	Would provide more suitable habitat than low baseflows.	Would reduce the size of reaches where beaver could build ponds, leading to reduction in sustainable population size. Dry sections of channel associated with low baseflows would likely reduce recolonization rates (and perhaps preclude it) following large flood events.
Ornate tree lizard	Moderate resistance to floods, high resistance to drought.	Could cause mortality via drowning or displacement. Displacement would be particularly injurious to the territorial males. Loss of forest cover associated with a large flood event would constitute a loss of habitat. Population turnover is probably naturally high and populations could rebound quickly.	Would promote plant community development and increase available habitat, but could also destroy eggs and decrease recruitment.	Would promote canopy development and increases in prey levels.	Would affect populations only insofar as they affect woody plant community development and prey production. The presence of dry sections of channel would have little or no direct influence on populations if woody vegetation was present.
Bullfrog	Low resistance to floods, low resistance to drought.	Fall and winter floods can flush adults and tadpoles into downstream areas where many would not survive. Large floods spring and early summer floods would damage or destroy egg masses. Negative impacts would be offset if recolonization occurs via drift from upstream refugia or from movement of the mobile juveniles and adults across nonaquatic habitats. Flows during the late summer monsoon season may reduce total numbers (if the flood occurs after cessation of breeding) but enhance conditions for the surviving individuals.	Would enhance growth and survivorship in all age classes by improving conditions for the lower trophic levels.	Would promote population growth, especially following moderate floods that created new lentic habitat without destroying existing beavers ponds or emergent marsh habitat.	Would reduce bullfrog populations by eliminating lentic habitat and reducing the size of beaver ponds.

Chapter 7. Ecosystem Functioning

By Douglas C. Andersen[1]

Ecosystem functioning refers to the linked biotic and abiotic processes that transform matter and energy and move them into, out of, and through the ecosystem. The movement of water and materials through the BWR corridor together with the other processes that support the organisms living in the corridor (table 10) are examples of the ecosystem's functioning. Clearly, the river's flow regime is a major factor affecting that functioning through its direct effects on individual organisms and populations as detailed earlier and through its effects on abiotic processes like erosion and sediment transport and deposition.

A number of conceptual models have been developed to explain how the structure of a riverine ecosystem is coupled to its functioning. Thorp and others (2006) briefly reviewed these models and attempted a synthesis in which they postulate that all riverine ecosystems consist of arrays of physical patches that can be delineated by their geomorphological and hydrological characteristics. From an ecological perspective, Thorp and others (2006) considered these patches to be "functional process zones" (FPZ). Variation in the physical nature of the catchment, water quality, and local flow regime determine how these patches (and thus FPZs) are distributed in a river network. The same hydrogeomorphic patch type (and thus FPZ) can appear repeatedly along a stream, as well as in locations that can be independent of headwater-to-mouth longitudinal gradients. Further, the edges of these patches may be sharp or indistinct, and the difference in ecological characteristics (e.g., characteristic productivity, organic matter dynamics, nutrient dynamics, and community composition) between two patches may be small or large. The model of Thorp and others (2006) would seem to be a reasonable way to conceptually organize the physical and ecological variability of the BWR ecosystem. Channel substrate (bedrock canyon or alluvial valley), flow intermittency (perennial or ephemeral), and water velocity at baseflow (affected, for example, by the presence of beaver ponds) are examples of attributes differentiating patches. Differences in flow character during floods could further distinguish FPZ's.

Stream ecologists have suggested that periodic episodes of high mortality or "disturbance" generated by unusually high and low flows are the dominant organizing factor in most streams, including desert streams (Resh and others, 1988; Grimm and Fisher, 1989). Indeed, the metrics used to describe disturbance regimes—magnitude, areal extent, frequency, and predictability—are nearly identical to those used to describe flow regimes: the magnitude, duration, timing, frequency, predictability, and rate of change in discharge events. Grimm and Fisher (1989) found that flash floods, a characteristic of most naturally functioning desert streams, greatly reduced both primary producers (algae) and macroinvertebrates in a Sonoran Desert stream, Sycamore Creek, but that the system quickly returned to its preflood condition. They attributed this high resilience to warm temperatures, stable low discharge, and high light, which allowed high rates of instream primary and secondary production. They also found that the abundance of algae and other primary producers in the stream, as measured by chlorophyll a concentration, could be predicted from the magnitude of the last flood, the time since its occurrence, and current discharge (Fisher and Grimm, 1988). Macroinvertebrate abundance,

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[1] U.S. Geological Survey, Denver Field Station, Denver, Colo.

however, was less tractable, presumably because of nutrient (nitrogen) limitation that affected food quality and biotic interactions during drying episodes (Boulton and others, 1992a). Flow regime will also influence the subsurface organisms in the stream (hyporheos) (Boulton and others, 1992b; Clinton and others, 1996) as well as macroinvertebrates (Cartron and others, 2003), vegetation (Andersen, 2005; Sponseller and Fisher, 2006), and other biota in the adjacent flood plain that are sources of allochthonous inputs to the stream.

Ecosystem structure and functioning are linked. The kinds, abundances, and dispersion patterns of organisms present determine in part the nature and timing of processes that occur, and ecosystem functioning in turn influences ecosystem structure. Holmes and others (1996) found that microbially mediated denitrification in a Sonoran Desert stream occurred primarily at the upstream ends of subsurface (hyporheic) flow paths, where streamwater had just entered the subsurface zone and contained relatively high amounts of dissolved organic matter. The location and extent of downwelling and upwelling zones along a stream channel are determined in part by bed material texture, channel geometry, and hydraulic head, and at least the latter two can be influenced locally by the presence of a beaver dam (Westbrook and others, 2006). All organisms in an ecosystem contribute to its carbon dynamics and energetics, which can be characterized by such measures as the ratio of gross primary production to ecosystem respiration or the difference between the two (net ecosystem production or ecosystem metabolism). The daily change in dissolved oxygen concentration provides a means to estimate a stream's overall metabolism and to indicate whether the stream is a net source or sink of carbon. A stream's position on the source-sink gradient is determined by the interplay of water quality, stream environment, primary and secondary producers, microbes, and other components of ecosystem structure. In a comparison of stream metabolism among North American biomes (Mulholland and others, 2001), only a desert stream (Sycamore Creek) showed positive net ecosystem production. A stream's position on the source-sink gradient is not in itself important from a management standpoint, but because whole-stream metabolism integrates so many components, change in this characteristic following a shift in flow regime or other ecosystem alteration is considered useful as a benchmark against which to gage whether overall stream quality has changed (Young and others, 2004). It is important to note, however, that there are no studies of ecosystem energetics dealing with both a desert stream and its flood plain in alluvial settings like those along the BWR, where most primary and secondary production may take place away from the stream.

Another measure of function that integrates many of the abiotic and biotic components of a riverine ecosystem is the pattern and pace of litter breakdown. Many stream and floodplain invertebrates are detritivores, and their abundances and dispersion patterns within the stream corridor will have a role in ecosystem nutrient dynamics. The complicated linkages among vegetation, climate, and surface and soil decomposition processes that regulate nutrient cycling in deserts (Whitford, 1992) are made even more complex in desert riverine ecosystems by the addition of groundwater and surfacewater dynamics. Litter breakdown rates will vary through time as a result of seasonal and interannual variation in both river discharge and local weather. Nutrient accumulation, transformation, and spiraling will occur within the stream (lotic) environments as a result of organic matter originating within the stream (autochthonous input) and elsewhere, for example, the riparian zone (allochthonous input). The latter,—which is due largely to floodplain tree leaf litter, woody debris, and dissolved and particulate organic matter in sheet flow from adjacent upland—is ecologically insignificant in some desert streams (Schade and Fisher, 1997) but may be important in the BWR ecosystem because of the extensive floodplain and gallery forest along some reaches.

The type, quantity, and fate of litter accumulating on the flood plain may be key factors determining the structure and functioning of a desert riverine ecosystem like that of the BWR.

Decomposition on a dry flood plain may be as slow as that in adjacent desert upland, and perhaps slower if desert macroinvertebrate detritivores like termites are precluded by floods or high water tables (Andersen and Nelson, 2006). Thus, litter can accumulate on dry flood plains for extended periods of time, sequestering carbon and nutrients until a flood moistens, submerges, redistributes, or perhaps buries the material (Molles and others, 1995, 1998). In a study involving artificially inundating a semiarid floodplain forest site where a dike had precluded flooding for about 50 years, Valett and others (2005) reported differences in dissolved organic carbon, dissolved oxygen, inorganic nutrient content, and other floodwater parameters at the artificially flooded site and at a nearby forest site naturally inundated almost every year. They attributed these differences to the greater amount of forest floor detritus at the experimental site. Where flooding is rare or absent, this buildup of floodplain litter can also contribute to an increased incidence and severity of riparian fires. Along many regulated rivers in the American Southwest, fire now rivals or exceeds flooding in importance as a disturbance agent (Busch, 1995), and the ecosystem-level effects of fire differ greatly from that of floods. For example, Ellis (2001) found that a fire carried by large amounts of dry litter killed the aboveground parts of most floodplain trees, including Fremont cottonwood and Goodding's willow, at two sites along the middle Rio Grande. Many trees of both species appeared to have survived the fire, as indicated by the rapid appearance of root or shoot sprouts, but long-term survival was poor in areas where the fire was most severe. Two years after the fire, the only cottonwoods with viable shoots were located in an area where flooding prior to the fire had helped to reduce the fuel load.

The duration and magnitude of a flood event will largely determine the degree to which it accelerates litter breakdown. A short period of immersion from hours to less than a few weeks in quiet water may result in little or no effect (Andersen and Nelson, 2003), whereas a longer period of immersion will increase decomposition rates (Molles and others, 1995; Ellis and others, 1999). Flood magnitude (peak discharge) will determine how much of the flood plain is inundated and will affect stream power. Strong currents and entrained sediment and other materials can physically degrade litter and transport dissolved and particulate matter to distant downstream sites or completely out of the catchment. Flooding, presumably through effects on decomposition processes and nutrient transport, also appears to influence leaf chemistry, particularly nitrogen:phosphorus ratios (Tibbets and Molles, 2005), and thus litter quality. Low litter quality (high carbon:nutrient ratios) can restrict growth and reproduction of detritivores by limiting their ability to acquire nitrogen, phosphorus, and other essential nutrients.

Monitoring floodplain litter breakdown may provide an index of ecosystem quality complementary to that of whole-stream metabolism. Molles and others (1998) hypothesize that floodplain forests along naturally functioning desert rivers have a characteristic long-term forest floor respiration rate—a measure of litter decomposition and soil microbial respiration rate—determined by the prevailing flooding pattern. They argue that this rate is artificially low in areas where flooding has been reduced or eliminated by regulation and that restoration of flooding will lead to a temporary rise to unusually high levels, as decomposer populations and detrital-based food webs expand in response to the renewed availability of moisture to support litter processing. Over time, the accumulation of litter is reduced, and the system returns to a new equilibrium at which the rate of litter generation is again matched by decomposition. The restoration of floodplain detritus processing appears to have been successfully initiated in an experiment involving managed flooding along the Rio Grande (Ellis and others, 1999).

The breakdown of litter, along with importation via sediment and flood water, is also the means by which nutrients are made available to floodplain plants. The temporal and spatial patterns of nutrient spiraling—from uptake by a live plant through litter decomposition, to uptake and temporary immobilization in a microbe or other organism, to release in ground or surface water and transport along flow paths—are only now being explored in desert riverine ecosystems (Fisher and others, 1998a; Schade and others, 2001; Tibbets and Molles, 2005; Lewis and others, 2006). It is clear, however, that the flow regime plays a major part in many of the component processes and thus in the rate at which nutrients pass through the system (Fisher and others, 1998b). Heffernan and Sponseller (2004), for example, have shown that the increase in inorganic nitrogen concentration in riparian groundwater observed during flash floods likely results from both remobilization of soil nitrogen and inputs from floodwater. In contrast, they found no evidence for remobilization of phosphorus, a finding that is consistent with the idea of floodwater being the primary source of phosphorus in groundwater during flood events.

The riparian or floodplain component of riverine ecosystems can provide a number of functions that have been labeled “ecosystem services” because of their positive contribution to human welfare. Within the BWR corridor, these ecosystem services include the following:

- transport and storage of water and sediment during high discharge periods
- release of water following high discharge periods (helping to moderate flows)
- accumulation and sequestering of waterborne chemicals in sediment and plants
- nutrient retention (via nutrient spiraling)
- elimination of potential pollutants (e.g., denitrification of agriculturally derived nitrogen)
- creation of soil macropores through root processes and animal activity (enhancing soil infiltration capacity)
- streambank stabilization by plant roots (reducing erosion)
- moderation of stream temperatures (by providing shade and through hyporheic mixing and heat exchange)
- delivery of litter (coarse particulate organic matter) to the stream (and to downstream Lake Havasu)
- maintenance of biodiversity by provision of habitats and resources

The maintenance or restoration of ecological services provided by the stream and its flood plain is one of the goals driving development of flow requirements; however, the natural patterns and processes that sustain these services in riverine ecosystems are often not well understood or may be impossible to restore. For example, natural functioning as measured by sediment retention and transport processes may be difficult to mimic with reservoir releases. Stanford (1994), discussing flow recommendations for rivers in the Upper Colorado River Basin, noted that the tradeoff between very high (natural) flood peaks and lower peaks of longer duration has not been examined in detail. Because releases from reservoirs are typically low in sediment compared to natural flood flows, high flows intended to flush fine sediment downstream and restore the functional role of cobble reaches may eliminate other functions by degrading the channel, lowering the water table, and disconnecting the stream from backwaters and wetlands. Thus, in cases involving regulated rivers, new combinations of processes may be the best alternative to achieve the desired mix of ecosystem services. A summary of ecosystem processes and associated functions important in the BWR corridor is presented in table 10.

Table 10. Ecosystem processes and associated functions important in the corridor of the Bill Williams River, Ariz.

[Examples of process attributes that are influenced by flow regime are italicized]

Process	Role in ecosystem functioning
Biological processes	
Primary production *magnitude* *spatial and temporal variability*	Contributes to carbon storage; sequesters nutrients; creates physical structure; promotes biodiversity
Secondary production *form and magnitude* *spatial and temporal variability*	Modifies physical structure; sequesters nutrients; promotes biodiversity
Consumption and respiration *form and magnitude* *spatial and temporal variability*	Controls nutrient cycling; determines food web complexity; regulates energy flow and carbon balance
Succession and other types of community change *susceptibility to invasion* *resilience and resistance to disturbance*	Generates spatial and temporal heterogeneity; can promote biodiversity
Biogeochemical processes	
Nutrient uptake, immobilization, and release *decomposition* *adsorption in sediments*	Regulates nutrient spiraling and primary productivity; removes pollutants; influences biodiversity
Carbon and nutrient flux across upland-floodplain and floodplain-river ecotones *river-floodplain exchange rate*	Regulates nutrient spiraling, promotes upland biodiversity; links riverine and upland ecosystems
Fluvial and hydrological processes	
Sediment mobilization (erosion), transport, and deposition	Controls long-term downstream movement of materials; generates spatial and temporal heterogeneity in landforms (i.e., patch generation and destruction) and aquatic habitats; regulates nutrient spiraling and primary productivity; links river and flood plain
Coarse and fine particulate organic matter mobilization, transport, and deposition	Controls long-term downstream movement of carbon and nutrients; generates spatial and temporal heterogeneity in landform substrate quality and aquatic habitats (i.e., role in large woody debris dynamics); regulates nutrient spiraling and primary productivity; links river and flood plain
Inundation, water infiltration, storage, and release	Contributes to discharge (flood) control, flow maintenance, and groundwater recharge; belowground water mixing and movement links upland, floodplain, and river
Movement of dissolved materials	Regulates nutrient spiraling and primary productivity; links river and floodplain

Chapter 8. Summary of Unified Ecosystem Flow Requirements for the Bill Williams River Corridor

By Andrew Hautzinger[1], Andrew Warner[2], John Hickey[3], and Vanessa B. Beauchamp[4]

During the Bill Williams River Ecosystem Flow Workshop, participants were split into three groups according to their specialties, and each group was tasked with drafting flow requirements. The three groups were "Aquatics," which included coverage of fishes, aquatic macroinvertebrates and amphibians (hereafter Aquatics Group); "Riparian Vegetation and Birds" (hereafter Riparian-Birds Group); and "Riparian Vegetation and Terrestrial Fauna Other than Birds" (hereafter Riparian Non-Birds Group). Both of the riparian groups considered vegetation because of its central role in supporting fauna.

At a minimum, the flow requirements defined by each group addressed baseflows and floods and defined the magnitude, timing, duration, and frequency of these events, as well as rates of change between different flow conditions. Some groups provided additional resolution, characterizing low, moderate, and high baseflows and small, moderate, and large floods. After flow requirements were developed, each of the three groups presented theirs in a plenary session. The participants were then divided into two new working groups tasked with unifying the requirements for baseflows and floods, respectively. These "Unified Baseflow" and "Unified Flood" groups were formed by way of a remix of the scientists from the three previous biota based groups. The process used to define a unified set of flow requirements for the BWR corridor is illustrated in figure 35.

The unified flow requirements defined for the BWR corridor below Alamo Dam are presented in figure 36. Each of the building blocks portrayed in this figure represents an expected ecological outcome associated with different flow conditions. The flow requirements in the figure consist of baseflows and floodflows, both of which are further delineated as low, moderate, or high (for baseflows) and small, moderate, or large (for floods) as denoted in the key. In addition to the magnitude of flow, the requirements define the necessary timing and duration of the events, and rates of change between event types. The frequency of specific event types—for example, once every 5 years—is also included and captures the importance of interannual variability in flow conditions.

The recommended river flows denoted in figure 36 would be generated by water releases from Alamo Dam and are targets for release from the reservoir recognizing flow attenuation downstream. It should be noted that the moderate and large flood flows suggested in figure 36 could not be attained unless structural modifications were made to Alamo Dam, which has a current maximum outlet capacity of roughly 198.2 m^3/s (7,000 ft^3/s). It should also be noted that these flow requirements—and especially the flood components—are presented with the assumption that commensurate changes would be made to the sediment regime below Alamo Dam. Tasks needed to identify and implement appropriate sediment management options

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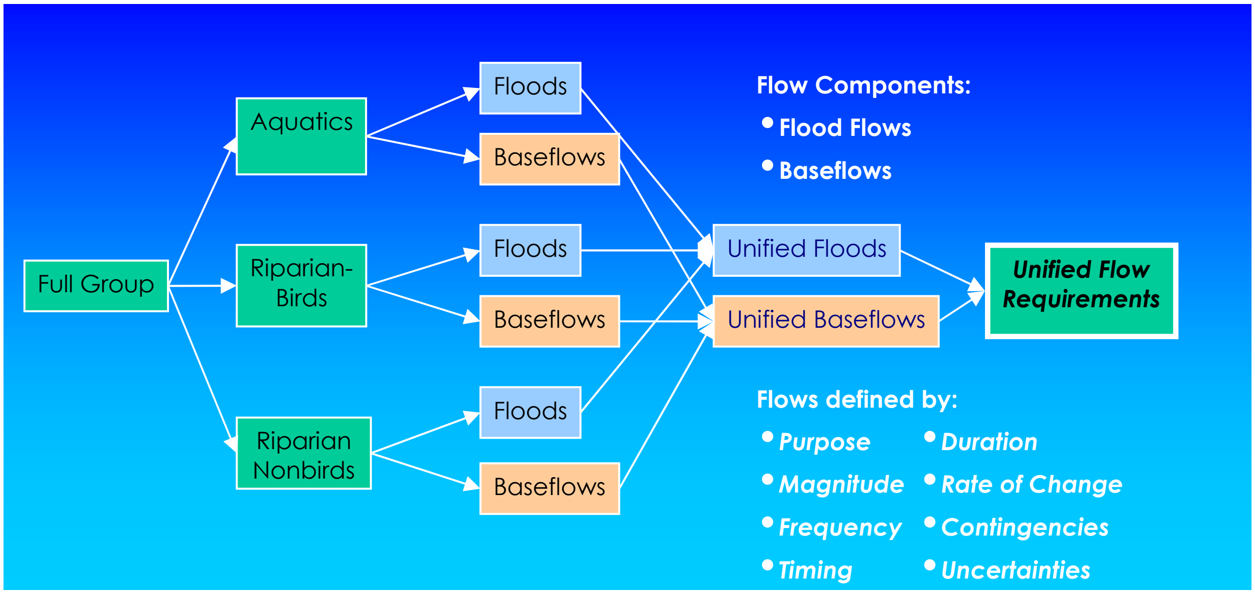

Figure 35. A model of the collaboration process used at the Bill Williams Ecosystem Flow Workshop held in Tempe, Ariz., March 16–18, 2005.

associated with larger flow events are discussed below in both the Priority Monitoring and Research and Conclusions sections.

Flow Requirements by Biological Group

The following sections describe flow requirements developed by the workshop's three biological groups (Aquatics, Riparian-Birds, and Riparian Non-Birds). Each section describes the approach followed by a group to develop flow requirements and presents the flow requirements and any supporting information used to justify the flow requirements. As the text shows, each group's approach was unique, and each group's section bears distinctive marks in both format and content. The three groups also discussed knowledge gaps and uncertainties.

Aquatics Group

Approach

The Aquatics Group accepted the workshop's general objective of maximizing native biodiversity on the BWR below Alamo Dam and agreed that natural flow patterns may be important for maximizing some native biodiversity (e.g., fishes, aquatic invertebrates, and a few reptiles and amphibians). Currently, there are no established populations of native fish on the BWR below Alamo Dam, but there are good prospects for reestablishing them in this reach: flow needs were specified in part to support the possible reestablishment of these native species. The group secondarily considered the natural flow patterns for any year as percentages of exceedances of average daily, predam flows, which confirmed a consistent seasonal pattern. Moreover, it was agreed that high flow "bricks" (the characteristic shape of postdam high flows) would have significant negative effects on aquatic life and that flow "spikes" (the natural shape of predam high flows) and variability are important (see chapter 2, this report).

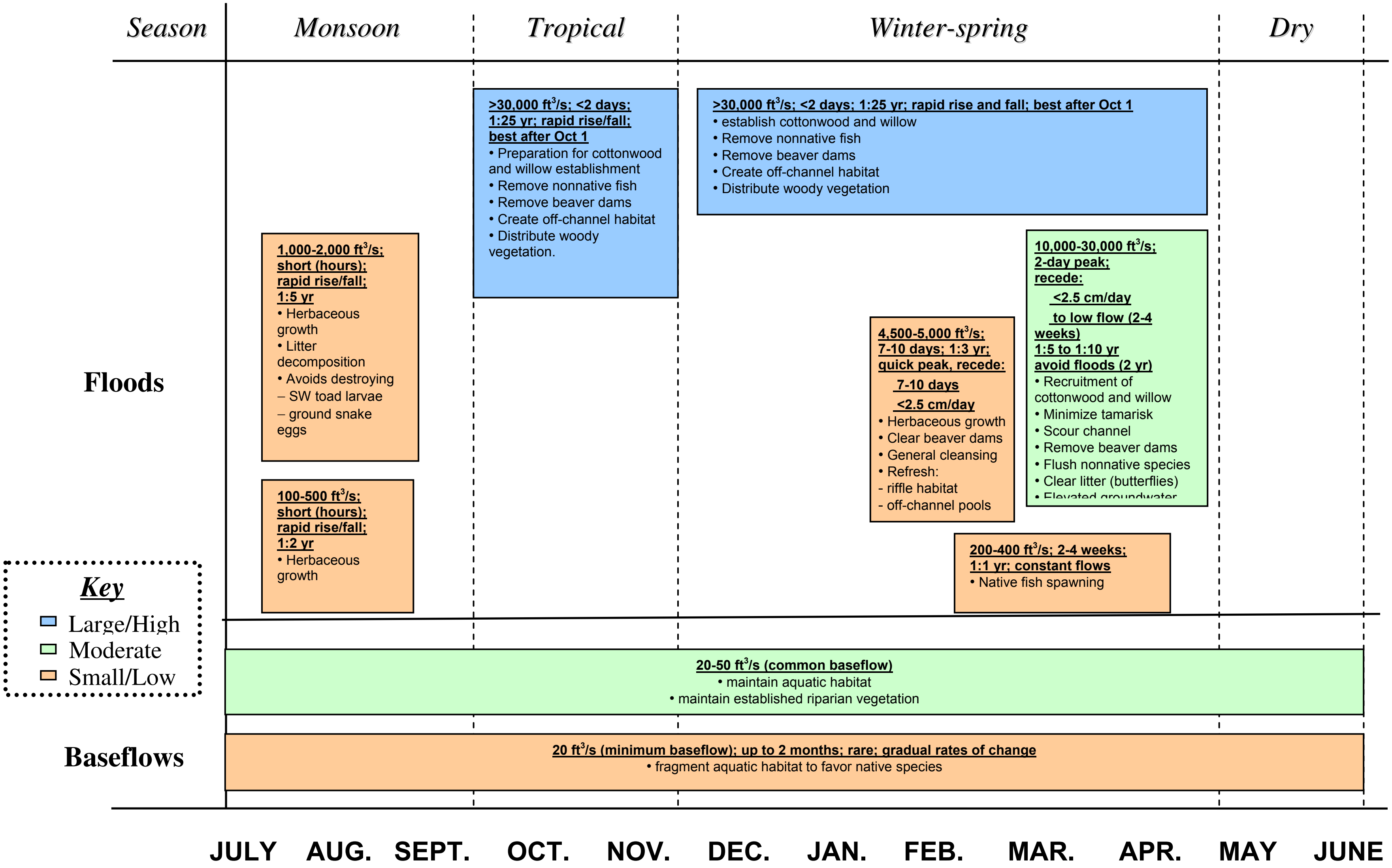

Figure 36. Unified flow requirements for the Bill Williams River, Ariz. Building blocks are used to link ecology to dam releases.

Flow Requirements and Justifications

Baseflow Requirements

To maximize aquatic biodiversity and discourage increases in exotic species richness and abundance, the Aquatics Group recommended that baseflows during the tropical season (late fall) and winter-spring should be elevated, and dry season (summer) baseflows should be depressed for a kind of "cook down," which is consistent with the predam hydrograph (table 11). In dry years, dry season baseflows should be 0.15 m^3/s (5 ft^3/s), an amount which was thought to fragment stream habitat into isolated pools and allow side channel pools to dry, to the disadvantage of nonnative fish and to the benefit of aquatic invertebrates. For the monsoon and tropical season in dry years, baseflows should be elevated to 0.57 m^3/s (20 ft^3/s) to improve native fish habitat and provide cooler temperatures and better water chemistry. Winter-spring baseflows should be further elevated to 1.4 m^3/s (50 ft^3/s) for greater fish habitat and favorable riffle conditions for some aquatic invertebrates. For wet years, this whole seasonal pattern should be maintained but with increased magnitudes, as follows: dry 0.28 m^3/s (10 ft^3/s); monsoon-tropical 1.4 m^3/s (50 ft^3/s); and winter-spring 2.3 m^3/s (80 ft^3/s). As a rare event, if native fish are absent, baseflows should be dropped to 0 m^3/s (0 ft^3/s) for up to 2 months to eliminate nonnative fish.

Floodflow Requirements

A principal function of flood flows is to maximize habitat diversity by occasionally removing beaver dams and scouring off-channel habitats. Another consideration was to discourage nonnative fish and bullfrogs (bullfrogs are not established on the BWR but are a likely invader). Smaller, more frequent floods would support native fish spawning. Return intervals rather than conditions in wet and dry years were specified for floods. For the dry season, no floods are recommended because flooding would interfere with leopard frog and lentic invertebrate reproduction. No large floods were considered necessary for the monsoon season, consistent with the predam hydrograph. For the tropical season, one to two spiked floods between 141.6 and 849.5 m^3/s (5,000 and 30,000 ft^3/s) were recommended, with a return interval of 5 years, mainly to remove beaver dams and to create some off-channel habitats (an objective that could also be achieved with spring floods). For early winter-spring (mid-November to mid-February), a moderate, single spike flood between 28.3 and 70.8 m^3/s (1,000 and 2,500 ft^3/s) was recommended with a return interval of 1–2 years to refresh the riffle habitat after the beaver dams have been removed and to refill side and off-channel pools. For late winter-spring (late February–early April), yearly "bricked" (relatively constant) small floods between 5.7 and 11.3 m^3/s (200 and 400 ft^3/s) are recommended to enhance native fish spawning. A large flood exceeding 1,415.9 m^3/s (50,000 ft^3/s) during either the tropical or winter-spring season with a return interval of 10 years is recommended to flush out nonnative fish and to create off-channel habitats (table 12).

Riparian-Birds Group

Approach

The Riparian-Birds group started by considering the groupings of bird guilds that were identified in the chapter 4 of this report and modified them by splitting the shallowwater birds into shore and marsh birds and identifying forest birds as passerines. For each of the bird guilds the group identified aspects of life-history as they related to seasonal rainfall patterns including aspects about when breeding, nesting, rearing/fledgling, and migration occurred, as applicable. When possible, the group also identified how different birds use the different habitats associated with the BWR corridor, with an emphasis on the habitat requirements of the southwestern willow flycatcher and western yellow-billed cuckoo (table 13). Using this information, the group then linked flow requirements to the bird and vegetation life-history requirements. To create one prescription for the Riparian-Birds Group, the group then resolved any conflicts in the proposed prescriptions.

Table 11. Baseflow requirements established by the Aquatics Group at the Bill Williams River Ecosystem Flow Workshop.

	Extremely low baseflows	Low baseflows	Moderate baseflows	High baseflows
Name	"Cook down"	Maintenance (low end)	Winter-spring maintenance	Winter-spring maintenance
Purpose	Hyper-dry conditions to fragment habitat in favor of natives.	Dry conditions to fragment habitat in favor of natives.	Facilitate fish habitat and favorable riffle conditions for invertebrates.	Facilitate fish habitat and favorable riffle conditions for invertebrates.
Timing	Variable.	Variable.	Variable.	Variable.
Magnitude				
Dry Year	5 ft^3/s	0–10 ft^3/s	10–50 ft^3/s	n/a (dry year)
Wet Year	10 ft^3/s	0–10 ft^3/s	n/a (wet year)	50–80 ft^3/s
Frequency	Rare	Common	Common	Less Common
Duration	<2 months	Months	Months	Months
Rate of change	Gradual	Gradual	Gradual	Gradual
Contingency	Natives present?	Wet or dry year?	Wet or dry year?	Wet or dry year?

Table 12. Floodflow requirements established by the Aquatics Group at the Bill Williams River Ecosystem Flow Workshop.

	Small floods		**Moderate floods**	**Large floods**	
Name	Habitat establishment	Native fish spawning	Tropical season cleansing	Tropical season nonnative fish flush	Winter-spring season nonnative fish flush
Purpose	Refresh riffle habitat and refill side and off-channel pools.	Enhancement of native fish spawning, favor lotic invertebrate taxa.	Removal of beaver dams and creation of off-channel habitat.	Flush out nonnative fishes and creation of off-channel habitat.	Blow out nonnative fishes and creation of off-channel habitat.
Timing	Mid-November to Mid-February	Late February to early April	September 15 to November 14	September 15 to November 14	November 15 to April 30
Magnitude	1,000–2,500 ft^3/s	200–400 ft^3/s	5,000–30,000 ft^3/s	>50,000 ft^3/s	> 50,000- ft^3/s
Frequency	1:1–2 years	1:1 years	1:5 years	1:10 years	1:10
Duration	3–4 days	2–4-weeks	Two separate peaks, both sharp, spiked events.	One peak, spiked.	1 peak, spiked
Rate of change	None cited.	Elevated flows should be held relatively constant for the full duration.	None cited.	None cited.	None cited
Contingencies	None cited.	None cited.	None cited.	OK to occur in the Winter-spring Season with a combined frequency of 1:10 years.	OK to occur in the Tropical Season with a combined frequency of 1:10 years.
Uncertainties	None cited.	None cited.	Magnitude needed to redistribute woody vegetation. Spatial extent of vegetation removal. Relationship with other reset factors (drought, fire, and infestation).	Actions other than flow management may be needed to control/eradicate nonnatives. There are important connections between release temperature and fish stranding.	

Table 13. Bird species life-history requirements by season as established by the Riparian-Birds Group at the Bill Williams River Ecosystem Flow Workshop.

Bird group or species	**Season**			
	Monsoon	Tropical	Winter-Spring	Dry
Deep Water			Overwinter, migrate, breed.	
Shore	Fall migration commences Sept. 1; forage on exposed sandbars.		Spring migration occurs Feb. 1– May 1; peaks about Apr. 1; forage on exposed sandbars; sandpipers overwinter.	
Marsh	Foraging; flow fluctuations OK; black rails and clapper rails may have different needs.	Forage.	Forage; breeding occurs late March– April; limit floods during breeding season.	Fledging occurs mid-May; forage.
Predators			Overwintering.	
Game Birds	Forage (seeds and herbaceous plants); for juvenile survival, need standing water near upland edges.	Forage.	Forage.	Breed end of May, early June; forage.
Passerines	Migrants depart.	Residents forage and overwinter.	Residents forage and overwinter; migrants arrive/breed Feb. through Mar..	Same as winter through June 1; rearing through June 30.
Southwestern willow Flycatcher	Fledging and depart.			Arrive about May 1; breed, nest, rear nestlings; require saturated soils, standing water, and early successional cottonwood-willow
Western yellow-billed cuckoo	Rear nestlings, fledging, depart; require mature cottonwood with understory (patch size >15 ha) and soil moisture.			Arrive about June 1 or later; breed, nest.

Flow Requirements and Justifications

Baseflow Requirements

Baseflows were designed to account for year-to-year climatic variability. Transitions in required flows generally occurred in accordance with the seasons as defined by rainfall patterns, with some exceptions (September 15–November15: tropical storms; November 15–April 30: winter-spring frontal storms; May1–June 30: dry; July 1–Sept. 15: monsoons; see Chapter 1, this report). It is important that these transitions are made over the course of 2–3 days to prevent abrupt changes in flows being experienced by the biota. Particularly for lower flows, the effect of the aquifer underlying Planet Valley and its hydrologic status creates significant uncertainties regarding the ecological effects of baseflows within and downstream of Planet Valley.

Baseflow requirements include elevated baseflows of 0.57–1.4 m^3/s (20–50 ft^3/s) in the monsoon and dry seasons to mediate vegetation stress during the hottest parts of the year and therefore, provide microclimate humidity for nesting birds and increase aquatic insect forage. Lower baseflows of 0.28–0.71 m^3/s (10–25 ft^3/s) were recommended during tropical and early winter-spring seasons (mid-September to late December), when water stress is expected to be less of an issue, and increased baseflows were recommended later in the winter-spring season (0.28–1.1 m^3/s (10–40 ft^3/s)) to support new vegetation growth (table 14).

Floodflow Requirements

Flood flows were recognized as being important for production of herbaceous growth and therefore, creation of associated insect habitat for forage and creation of the necessary conditions for recruitment of woody riparian vegetation. Small, short-duration floods were prescribed for the monsoon season with frequent (2-year return interval) floods ranging from 2.8 to 14.2 m^3/s (100 to 500 ft^3/s) to stimulate herbaceous plant growth and provide standing water for insect production.

Infrequent (6-year return interval) monsoon season floods ranging from 14.2 to 28.3 m^3/s (500 to 1,000 ft^3/s) were also prescribed, with the recommendation that these floods be synchronized with a rainfall event to boost downstream flows (table 15). Moderate (5– to 10–year return interval, 383.2–849.5 m^3/s (10,000–30,000 ft^3/s)) and large (100-year return interval, >849.5 m^3/s (>30,000 ft^3/s)) flows in the tropical or winter-spring seasons were recommended to stimulate recruitment of cottonwoods and willows (table 15). One important caveat of these floods is that they have an initially steep rate of change but the receding limb of the flood must be managed to provide a stage change of no more than 2.5 cm/day (1 in./day) to the desired base flow and then held constant to provide suitable root growth conditions. When cottonwood and willow recruitment is successful, subsequent flooding should be avoided for 2 years to allow good vegetation establishment.

Table 14. Baseflow requirements as established by the Riparian-Birds Group at the Bill Williams Ecosystem Flow Workshop.

Time period (Season)	Minimum Low flow (ft^3/s)	Maximum Low flow (ft^3/s)	Ecological purpose (baseflows)
July 1–Sept. 15 (monsoon season).	20	50	Elevated baseflows are needed to mediate vegetation water stress during the hot, unpredictable monsoon season, augment microclimate humidity for nesting birds, and increase/maintain aquatic insect forage base.
Sept. 16–Dec. 31 (tropical season and winter-spring season in part).	10	25	Reduced baseflows are adequate to meet vegetation maintenance needs during a generally low water-stress period.
Jan. 1–Apr. 30 (remainder of winter-spring season).	10	40	Increased baseflows during favorable climatic periods are needed to support new vegetation growth.
May 1–June 30 (dry season).	20	50	Elevated baseflows are needed to mediate vegetation water stress during the hot, dry season, augment microclimate humidity for nesting birds, and increase/maintain aquatic insect forage base.

Table 15. Floodflow requirements established by the Riparian-Birds Group at the Bill Williams River Ecosystem Flow Workshop.

	Small floods			**Moderate floods**		**Large floods**
Purpose	Monsoon forage (small magnitude). Stimulate herbaceous plant growth for forage and provide standing water for insect production.	Monsoon forage (intermediate magnitude). Stimulate herbaceous plant growth for forage and provide standing water for insect production.	Winter forage. Stimulate herbaceous plant growth for forage, provide bird cover, support flowering and seeding, boost insect productivity, provide maintenance flow for cottonwood and willow, and saturate soils.	Cottonwood-willow recruitment primer. Scour (remove) the vegetation, reworking the flood plain, redistributing sediment, and establishing bare soil sites.	Cottonwood-willow recruitment. Stimulate recruitment of cottonwood and willow (may result in limited recruitment of tamarisk).	Remove vegetation, scour and create new channels, set stage for establishment of new vegetation.
Timing	Mid-July to mid-August.	Mid-July to mid-August.	February 1 to February 28.	Tropical season (9/16 to 11/15), preferably after October 1 to limit tamarisk recruitment.	Mid-March to end of April.	November 16 to April 30 (winter-spring season).
Magnitude	100–500 ft^3/s	500–1,000 ft^3/s	500–5,000 ft^3/s	10,000–30,000 ft^3/s	10,000–30,000 ft^3/s	>30,000 ft^3/s
Frequency	1:2 years	1:6 years	1:3 years	1:15 to 30 years	1:5 to 10 years	1:100 years
Duration	Short, on the order of hours. Drop rapidly. Can have multiple small spikes.	Short, on the order of hours. One peak. Drop rapidly.	7 days sustained small flood.	One peak, spiked. Up and down within 1–2 days.	2-day duration peak with a multiday tail that blends into the desired baseflow.	One peak, maintain 2–6 days.

Table 15. Floodflow requirements established by the Riparian-Birds Group. —Continued

	Small floods			**Moderate floods**		**Large floods**
Rate of change	None specified, but event is sharp and brief to limit tamarisk recruitment.	None specified, but event is sharp and brief to limit tamarisk recruitment.	Taper lower receding limb at 2.5 cm/day.	Steep. A specific rate of change is not important. More important that the event simply occur quickly (in mimicry of natural hydrograph).	Lower portion of the receding limb should not exceed a stage change of more than 2.5 cm/day. Maintain this rate of change down to desired base or low flow condition and hold for 2 to 4 weeks to encourage deep root growth.	Steep. The lower portion of the receding limb for floods Feb. through mid-Apr. should not exceed a stage change of more than 2.5 cm/day. Maintain this rate of change down to desired base or low flow condition and hold for 2 to 4 weeks to encourage deep root growth.
Contingencies	None cited.	Time with El Niño or prevailing wet hydrologic cycle. Try to time peak with a rainfall event to boost downstream flows.	None cited.	Try to couple this with a cottonwood-willow recruitment flood in the following spring.	Avoid floods for 2 years after this event. Start small with respect to flood magnitude to gage effects on vegetation and geomorphic change.	In a cottonwood-willow recruitment scenario, avoid floods for 2 years after the event. Start with relatively small large flood events to gage the effects on vegetation and channel/floodplain geomorphic change.
Uncertainties	Spatial extent of surface flows, and as a consequence the ecological benefit, needs to be determined for these flows.	Spatial extent of surface flows, and as a consequence the ecological benefit, needs to be determined for these flows.	Even at the upper range, it is uncertain whether the flows will be high enough to benefit mesquite bosque community.	Magnitude needed to remove vegetation and rework the flood plain is unknown.	Transition point from peak to start of 2.5 cm/day recession during the receding limb may not be one set value depending on channel/floodplain condition. The time to hold at a low base flow after recession to encourage root growth is uncertain.	Magnitude of flood needed to remove woody vegetation is unknown. Relationship of spatial extent of vegetation removal with flood discharge amount is yet to be quantified. Relationships with other ecological processes, such as drought, fire, and infestation, are unknown. See other uncertainties described for moderate floods.

Riparian Non-Birds Group

Approach

The Riparian Non-Birds Group identified a suite of riparian obligate mammals, reptiles, amphibians, and invertebrates native to the BWR for which the life-history was fairly well known. This list included the viceroy butterfly, beaver, ground snake (*Sonora semiannulata*) , desert shrew (*Notiosorex crawfordi*), southwestern toad (*Bufo microscaphus*), cotton rat and hoary bat (*Lasiurus cinereus*). For each species, critical times in their life-history such as dormancy, and reproductive periods, as well as foraging needs, which may be dependent on or could be impacted by the flow regime were identified. A majority of these species were directly or indirectly dependent on cottonwood-willow habitat or mesquite for habitat or forage. For example, the desert shrew and ground snake forage on invertebrates found in cottonwood-willow litter, the hoary bat roosts in cottonwood and willow trees and viceroy butterfly caterpillars feed on willow trees. The cotton rat is an exception in that it forages in grassy herbaceous areas rather than in the cottonwood understory. Given the importance of these types of forest and open floodplain habitats, flow requirements were defined to produce these habitats, particularly cottonwood-willow forests and mesquite bosques. These flow requirements were then adjusted or added to as necessary to accommodate the mammals and herptofauna discussed, with an emphasis on avoiding stressful conditions (large floods or low baseflows) during vulnerable life stages.

Flow Requirements and Justifications

Baseflow Requirements

As with the Riparian-Birds Group, this group also recognized the importance of baseflows for maintaining water levels for plant growth and flood flows for stimulating recruitment of cottonwoods and willows. Wet-year low flows between 0.28 and 1.4 m^3/s (10 and 50 ft^3/s) and dry-year low flows between 0.28 and 2.8 m^3/s (10 and 100 ft^3/s) were recommended with the contingency that these flows should vary within this range to stimulate deep root growth which would allow vegetation to survive drought conditions (table 16).

Floodflow Requirements

Floodflow requirements included wet-year winter-spring floods greater than 198.2 m^3/s (7,000 ft^3/s) 1 out of every 10 years and dry-year winter-spring floods of 56.6 m^3/s (2,000 ft^3/s) every 2–3 years to create conditions necessary for cottonwood and willow reestablishment and to flush out beaver dams (table 17). The Riparian Non-Birds Group also recognized the importance of slow flood recession (<2.5 cm/day) and avoidance of other floods for 2 years after a recruitment event to promote successful tree establishment. Summer monsoon pulse floods (28.3–56.6 m^3/s (1,000–2,000 ft^3/s) once every 2–3 years) were also recommended to stimulate herbaceous plant growth and litter decomposition (table 17).

Table 16. Baseflow requirements established by the Riparian Non-Birds Group at the Bill Williams River Ecosystem Flow Workshop.

	Wet year—Low Flow	Dry Year—Low Flow
Purpose	Maintain water levels for plant growth.	Maintain water levels for plant growth.
Timing	all year	all year
Magnitude	10– 50 ft^3/s	10–100 ft^3/s
Frequency	Continuous.	Continuous.
Duration	Continuous.	Continuous.
Rate of change	Flows should vary between high and low magnitude.	Flows should vary between high and low magnitude.
Contingency	No scouring floods of over 500 ft^3/s after first year post-event and 500–1,000 ft^3/s floods permissible in the second year	Raise baseflow overall during the driest part of year to reduce stress (10–100 ft^3/s).

Table 17. Floodflow requirements established by the Riparian Non-Birds Group at the Bill Williams River Ecosystem Flow Workshop.

	Wet-year flood	Dry-year—winter flood	Dry-year—summer flood
Purpose	Scouring of channel and flood plain for reestablishment of cottonwood and willow. Timing in accord with seeding of these trees, but before Tamarix maximum seeding	Scouring of channel and for reestablishment of cottonwood and willow. Timing in accord with seeding of these trees, but before salt cedar seeding and to avoid dormancy and breeding of animals earlier in the year. To flush out beaver dams, to elevate water table for herbaceous plants, to clear out litter for viceroy butterflies, and to wash out exotic species.	To help herbaceous plant growth and litter decomposition. Timing is to avoid destruction of ground snake eggs and southwestern toad larvae.
Timing	Late Feb–Apr. 1	Late Feb–Apr. 1	July 15–Sept. 15
Magnitude	>7,000 ft^3/s	2,000 ft^3/s	1,000–2,000 ft^3/s
Frequency	1:10	Once every 2–3 years	Once every 2–3 years
Duration	2–7 days	2–3 days (at Lake Havasu)	Hours
Rate of change	Quick start up and gradual recession—about 2.5 cm/day (change in water level).	Quick start up and gradual recession—about 2.5 cm/day (change in water level).	Quick start up and shut down.
Contingency	No further scouring floods afterwards for 2 years—maintain high baseflows.	Raise baseflow overall during the driest part of year to reduce stress (10–100 ft^3/s).	Flooding will likely depend upon seasonal weather conditions.

Unification of Biological-Group Flow Requirements

Unified Baseflows

Process

A constant theme in the unified baseflows discussions dealt with the recognition that the BWR exhibited great longitudinal variability, such that at a given baseflow release out of Alamo Dam, many different flows would likely be expressed over the project area. While this spatial variation certainly complicated the analysis, it was also considered a factor likely to provide a range of appropriate flows for a wide suite of the biota via the anticipated constant baseflow releases from the dam.

One point of difference between the groups related to varying degrees of interest in the seasonal timing of flow changes. The Aquatics Group was interested in an increase in the winter baseflows, while the riparian groups saw a buffering benefit via higher baseflows during the heat of the summer. Similarly, the Aquatics Group's typical flow requirements were more static than were those of the riparian groups, which recommended more frequent intraseason and interseason variations in baseflows (e.g., to facilitate root development). The Aquatics Group indicated that there were fairly high levels of uncertainty associated with the recommended flow magnitudes, but this group had an appreciably higher level of confidence with regard to the shape of a recommended hydrograph.

All three biotic groups identified the need to have different baseflows based on antecedent conditions (e.g., in the event of floods that recruit new growth, higher baseflows would be desirable for a period of time afterwards to support the newly established seedlings). The Aquatics Group especially focused on different baseflow regimes being a function of either being in a dry year or a wet year.

The most pronounced difference between the three groups' requirements was that the Aquatics Group emphasized the need for a period of extremely low baseflows or no flows, which they referred to as a "cook down" event that would tend to favor native over nonnative aquatic species. It was pointed out that while many native species have mechanisms to survive periods of extreme drought, the issue of recolonization by natives is of concern because of the current lack of refugia. Neither of the riparian groups articulated this "cook down" element as a beneficial flow component.

Results

Extremely low Baseflows (~0–5 ft^3/s)

As noted above, extremely low baseflows were only advocated by the Aquatics Group and were not explicitly carried forward into the unified baseflows. The need for a rare "cook down" event was tied to the desire to fragment stream habitat into isolated pools to the anticipated advantage of the native species. The two riparian groups were concerned with the risks to the riparian vegetation associated with severely depressed water levels.

The unification process forged a compromise in which there would be no releases below 0.57 m^3/s (20 ft^3/s), somewhat based on the longitudinal variation (described above), which would likely create "cook down" conditions in limited areas along the river during periods of lower baseflow releases. It was agreed by all that it is crucial that appropriate monitoring be conducted to better understand how the lowest flows manifest throughout the project area.

Low Baseflows (0–10 ft^3/s)

Again, the Unified Baseflow Group recommended that there be no baseflows below the 0.57 m^3/s (20 ft^3/s) level. Hence, the recommendation for extremely low baseflows (0–0.28 m^3/s (0–10 ft^3/s)) was essentially the same as the Aquatic Group's "cook down" recommendation described above.

Moderate Baseflows (10 to 50 ft^3/s)

All three groups saw important benefits associated with moderate baseflows, especially in acknowledgment that these moderate baseflows will probably be the system's most common flow condition. Both riparian groups advocated flows in this category to range from 0.57 to 1.4 m^3/s (20 to 50 ft^3/s), with a major advantage being groundwater recharge and an associated higher water table for benefit to vegetation. The Riparian Non-Birds Group also saw a possible benefit in decomposition of plant materials (processes that require some degree of moisture), although there exists uncertainty as to what level of flows would be needed to support this function. The Aquatics Group saw benefit in keeping flow levels consistently elevated from September15–April 30. The group also suggested making different baseflow prescriptions for wet or dry flow years.

While the groups expressed appreciation that water availability will often be a strongly limiting factor, all three groups saw distinct advantages for baseflows to be typically higher rather than lower. Aquatically, higher baseflows would improve water quality conditions (e.g., lower temperatures, higher dissolved oxygen) and would thus tend to reduce the biological stressors during the heat of the summer; however, longer term high baseflows were not advocated by the Aquatics Group to be included in the reconciled baseflow requirement. With respect to vegetation, higher baseflows would typically translate into higher water table elevations, which would be advantageous for riparian plants. All three groups also saw advantages from occasional baseflows on the lower end of this range. As described above, the Aquatic Group advocated the "cook down" concept. Both riparian groups indicated an interest in occasional short-duration lowering of water levels to facilitate more extensive root development. Short duration drops in water table level were especially of interest in those periods of time following establishment events.

High Baseflows (50–100 ft^3/s)

There was little expressed interest in baseflows in the 1.4–3 m^3/s (50–100 ft^3/s) range. Group discussion focused on how this type of flow was not a common part of the natural hydrograph, except typically on the declining limb of a flood, and therefore flow requirements for these types of flows would more logically be left to the Unified Flood Flows Group. It is also likely that the goals associated with the higher end of the moderate baseflows (up to 1.4 m^3/s (50 ft^3/s)) also would apply to this flow category. With the uncertainties associated with how a given low flow will manifest in a given reach, the group consensus was to not explicitly call for baseflows in the 1.4–2.8 m^3/s (50–100 ft^3/s) range.

Unified Baseflows

Most of the baseflows recommended by the three biotic groups had significant overlap with each other and were easily unified (table 18). The Unified Baseflow Group's discussions centered primarily on issues related to uncertainties on how baseflows would be expressed across the project area. This inability to route or model baseflows through the project area, especially through the Planet Ranch reach, was a constant issue during the Unified Baseflow Group's discussion. It was the group's unanimous opinion that resources needed to be prioritized to address flow-routing questions.

It was viewed as a critical objective that the BWR system be sufficiently understood such that physical goals (tied to ecological objectives) be rendered in terms of quantifiable flow levels. Further, there emerged a philosophical consensus that these goals and objectives not be hardwired but that they rather have built-in ranges and variations such that they more closely mimic natural dynamics. This mimicry of the natural dynamics was thought to be especially critical in transition zones of the hydrograph, as typified by the declining limb of a flood hydrograph.

Table 18. Unified baseflow requirements developed at the Bill Williams Ecosystem Flow Workshop .

	Extremely low baseflows (0–5 ft^3/s)	Moderate baseflows (10 ft^3/s–50 ft^3/s)
Name	"Cook down"	Maintenance
Purpose	Hyper-dry conditions to fragment habitat in favor of natives.	Aquatic and riparian habitat maintenance and (contingency) stimulate root development with younger plants.
Timing	n/a	~ 1year long
Magnitude	20 ft^3/s	10– 50 ft^3/s
Frequency	No flows<20 ft^3/s	Common
Duration	No flows<20 ft^3/s	Weeks/months
Rate of change	n/a	Gradual
Contingency	Monitor and evaluate	???

Unified Floods

Floodflow requirements, developed independently by the Aquatics, Riparian-Birds, and Riparian Non-Birds Groups, were merged into one set of requirements referred to herein as Unified Floods (table 19). Floods were defined by name, purpose, timing, magnitude, frequency, duration, rates of change, contingencies, and uncertainties.

Process

The Unified Floods Group began by comparing floods recommended by each of the three groups. In general, the independent requirements were more similar than dissimilar. The recommendations of the Riparian groups corresponded especially well for their winter-spring moderate floods designed to regenerate cottonwood and willow riparian areas and their monsoon small floods to stimulate growth of herbaceous plants. The biggest difference was for the frequency and magnitude of large floods. The Aquatics Group recommended both the largest and most frequent large flood event, calling for floods of greater than 1,415.9 m^3/s (50,000 ft^3/s) with a return period of 1:10 years. The Riparian-Birds Group recommended smaller and less frequent events calling for floods of greater than 849.5 m^3/s (30,000 ft^3/s) with a return period of 1:100 years. The Riparian Non-Birds group did not request any floods near those magnitudes.

The unification process involved pulling different recommended floods into single events without sacrificing any purposes of the original flood events. When the Unified Floods Group was concerned that an original purpose might not be accomplished by the flood event after merging, this concern was discussed. If the discussion did not resolve the concerns, the flood in question was treated as a separate flood event in the Unified Floods requirements.

Results

Small Floods (100–5,000 ft^3/s)

Both Riparian groups recommended periodic small floods in the monsoon season to support herbaceous plant growth, which is an important source of forage for insects, birds, and animals. The Aquatics Group also advocated a flood designed to facilitate fish-spawning conditions. Other groups recommended small floods to reorganize channel and sandbar sediments and stimulate herbaceous growth, which provides winter foraging habitat for birds, and to remove beaver dams and cleanse the system of exotic fish and aquatic invertebrates. The magnitude was set at the upper end of the range, while the timing was set according to the requirements of the Riparian-Birds Group to encourage an advantageous creation of seasonal forage for passerines and upland game birds (table 19).

Moderate Floods (5,000–30,000 ft^3/s)

The Riparian Non-Birds group had two flood events that were merged into this unified flood. Some purposes of their cottonwood and willow recruitment event (scouring, removal of beaver dams, litter, and exotics) were also partially taken care of by the winter forage and cleansing flood discussed above (table 19). An important contingency for this flood is incorporation of the annual native fish spawn. To accommodate the spawn, when the recession limb is between 5.7 and 11.3 m^3/s (200 and 400 ft^3/s), flows should be held relatively steady for 2–4 weeks before continuing to gradually recede.

Large Floods (Greater than 30,000 ft^3/s)

The Aquatics Group had two flood events that were merged into this unified flood event. Purposes of their tropical season cleansing event (removal of beaver dams and creation of off-channel habitat) were also partially taken care of by the unified cottonwood and willow recruitment flood discussed above.

The combined frequency (1:10 years) recommended by the Aquatics Group for blowing out nonnative fishes in the tropical and winter-spring seasons was decreased during unification (1:25 years), but this reduction in frequency was offset by decoupling their blowout floods in the tropical and winter-spring seasons. In other words, Unified Floods Group called for two independent high flood events, whose purposes include blowing out nonnative fishes, each with a frequency of 1:25 years.

The increase in magnitude during unification was acceptable to the Riparian-Birds Group, though it was reinforced that the value of this flood (in terms of setting the stage for renewal of riparian habitat) would be maximized if coupled with a cottonwood-willow recruitment flood in the following spring.

The second large flood recommendations came from the Aquatics and Riparian-Birds Groups, and aligned quite well with each other. The increase in frequency from the Riparian-Birds Group's requirements (1:100 to 1:25 years) was acceptable, but representatives from that group stressed that the BWR is a critical resource for migratory birds and that these large floods should start near the bottom of the specified flow ranges to allow scientists to gage the effects on bird habitat before progressing to higher flows.

Unified Floods

Most floods recommended by the biotic groups had significant overlap with each other and were easily unified. Debate within the Unified Floods Group focused mainly on (1) the degree of flexibility in timing floods designed to cleanse the system, which was agreed to be quite high; (2) the frequency of large floods, which essentially meant striking a balance between protecting the current ecological value of the BWR by cautiously exploring high flows and the need to reestablish those high flows as a powerful disturbance mechanism that encourages more dynamic and natural behavior of the ecosystem; and (3) the philosophical relationship between the cottonwood-willow recruitment flood and the higher and less frequent floods designed to rework the riparian areas and blow out the nonnative fishes, which was described by the group as an analogy of the recruitment floods being used to manage crop rotation for the cottonwood and willow while the higher floods were used to clear the fields.

The single most important caveat for the Unified Floods is that these requirements assume that changes to the flood regime will be implemented with commensurate changes to the sediment budget of the BWR below Alamo Dam. This coupling of the flood regime and sediment regime is of critical importance. If any of the moderate or large floods (peak flows greater than or equal to 283.2 m^3/s (10,000 ft^3/s)) were implemented without an accompanying sediment adjustment, the effects downstream are expected to be quite negative.

Table 19. Unified floodflow requirements developed at the Bill Williams Ecosystem Flow Workshop.

	Small floods				Moderate floods	Large floods	
Name	Monsoon forage (low)	Monsoon forage (high)	Native fish spawning	Winter forage and cleansing	Cottonwood and willow recruitment	Nonnative fish flush and riparian rework (tropical season)	Nonnative fish flush and riparian rework (winter-spring season)
Purpose	Stimulate herbaceous growth for forage.	Herbaceous plant growth and litter decomposition.	Enhancement of native fish spawning.	Herbaceous growth, beaver dam removal, general cleansing.	Stimulate mixed recruitment of cottonwood and willow (with a little tamarisk).	Nonnative fish blowouts, manipulate distribution of woody vegetation.	Nonnative fish blowouts, manipulate distribution of woody vegetation.
Timing	Mid-July to mid-August.	Mid-July to mid-August.	Late February to early April.	February 1 to February 28.	March 15 to April 30.	September 15 to November 14 but preferably after October 1 to limit tamarisk recruitment.	November 15 to April 30.
Magnitude	100–500 ft^3/s	1,000–2,000 ft^3/s	200–400 ft^3/s	4,500–5,000 ft^3/s	10,000–30,000 ft^3/s	>30,000 ft^3/s	> 30,000 ft^3/s
Frequency	1:2 years	1:5 years	Annually	1:3 years	1:5–10 years	1:25	1:25
Duration	Very short, rapid drop (hours). Can have multiple short spikes.	Very short, rapid (hours). One peak.	2–4 weeks.	Peak quickly then recede for 7–10 days.	2-day spike with a multiday tail that blends into recession.	One peak, spiked. Up and down within 2 days.	1 peak, 3–6 days
Rate of change	None, but event is sharp and brief to limit tamarisk recruitment.	Quick start up and shut off.	Elevated flows should be held relatively constant for the full duration.	Taper lower receding limb at 2.5 cm/day.	Lower receding limb should not fall more than 2.5 cm/day. Recede down to a low baseflow and hold at the low base for 2–4 weeks to encourage deep root growth.	Steep. Rates not key; important to be quick.	Steep. Hit 2.5 cm/day recession on lower limb if timing is right for recruitment.
Contingency	None cited.	Look for link to regional climactic conditions.	None cited.	None cited.	Avoid floods for 2 years after this event. Start small, but be aggressive in terms of increasing magnitude of peak within specified range. Accommodate annual native fish spawning flood as part of recession.	Try to couple this with a cottonwood and willow recruitment flood in the following spring.	In a recruitment scenario, avoid floods for 2 years after the event.

Discussion of Knowledge Gaps, Priority Monitoring, and Research Needs

Each of the biotic groups noted uncertainties and knowledge gaps identified while formulating their flow requirements. Several knowledge gaps were echoed by multiple biota-based groups and by the subsequent flow-based groups. The following sections summarize knowledge gaps from all of the workshop groups; these gaps presented roughly in order of priority.

Sediment Budget and Transport Dynamics

The sediment budget of the BWR has been very much altered by the presence of Alamo Dam, which is effectively a sink for all coarse sediment mobilized upstream of the lake. Below the dam, unregulated tributaries continue to be productive sediment sources, but the ability of flows in the BWR below Alamo Dam to redistribute this sediment has been greatly reduced by decreases in large flood flows. There are unresolved questions about (1) the sustainability and evolution of the current channel and riparian forest since Alamo Dam was constructed, (2) potential negative effects resulting from implementation of the ecological flow requirements—the flood flows in particular—without commensurate adjustments to the sediment budget, and (3) gradation of sediment deposited in floodplain areas and whether these materials are conducive to plant growth. The workshop participants articulated the need to develop sediment budgets and sediment transport models to evaluate this critical system component.

Magnitude and Duration of Flows Required to Achieve the Purposes of the Ecological Flow Requirements, Especially for the Prescribed Floods

There was a general uncertainty about whether the different components of the ecological flow requirements would achieve their designed purposes, especially with respect to the flood flows. This uncertainty was mentioned by all the groups in ways that implied (1) that the groups anticipate thresholds of flood magnitude that will need to be met or exceeded to accomplish specific functions, (2) that the flood flow requirements formulated in this workshop reflected the biotic groups' best estimates of these thresholds, and (3) that there is a need to better define these thresholds through experimentation and adaptive management. Specific uncertainties listed by the groups related to this topic included flow magnitudes needed to remove beaver dams, mobilize sediment, remove vegetation, stimulate decomposition, rework floodplain areas, and depress the nonnative fish population. It was agreed that further streamflow and groundwater level monitoring efforts, done in tandem with acquisition of biological data, were key to further develop the linking of flows to ecological responses.

Connections Between Surface Water, Ground Water, and Related Biotic Communities

The BWR below Alamo Dam courses through a series of narrow canyons and wider alluvial valleys. The valleys tend to have a moderating effect on stream flows where surface flows recharge underlying aquifers in times of high flow, and those aquifers later augment surface flows in times of low flow. There was a general uncertainty regarding connections between stream flow and the underlying aquifers, especially with regard to Planet Valley. This uncertainty was spatial and temporal in nature (how do surfacewater releases from Alamo Dam translate downstream to Lake

Havasu, what are the groundwater responses, and how do these relationships vary seasonally?) and was a concern for baseflows and, to a lesser extent, small and moderate floods. These questions were related back to rooting dynamics and the sustainability of riparian vegetation as a function of groundwater levels. A need to better understand the impacts of (and to develop contingencies for changes in) groundwater pumping in the basin was also noted.

Role of Floods in the Tropical and Monsoon Seasons

Tropical and monsoon floods occur less frequently and tend to be of shorter duration and lower magnitude than those in the winter-spring season, but they can still be powerful flood events. Also, because tropical and monsoon seasons follow the dry season (during which any flows above minimal baseflows are quite rare) flow fluctuations in those seasons may be important hydrologic stimuli from an ecological perspective. There was a general uncertainty regarding the ecological roles of high flows in the tropical and monsoon seasons, including whether tropical floods were important precursors for successful recruitment of cottonwoods and willows during winter-spring floods, effects of monsoon floods on tamarisk, and whether there would be ecological consequences if tropical floods were not prescribed.

Nutrient Cycling, Decomposition, and the Role of Fire

There was a general uncertainty regarding connections between flow, decomposition, nutrient cycling, and fire. Knowledge gaps noted by the groups created an interrelated sequence of uncertainties beginning with fundamental questions about the drivers of decomposition and how nutrients cycle within the system. These questions led to recognition of uncertainties about the balance of litter production and decomposition and the potential increase in fire frequency in situations where production outpaces decomposition. This discussion of a potential increase in fire frequency, led to the question of the role of fire as a disturbance mechanism for riparian forests.

Conclusions

The results from this workshop will be used to further the commitment of the U.S. Army Corps of Engineers and the other members of the Bill Williams River Corridor Steering Committee to make science-based management decisions with regard to the operation of Alamo Dam and the affected environment. This redoubled commitment on the part of member agencies builds upon over 15 years of flow-related work on the BWR system. The history on the BWR provides a body of work that has consistently acknowledged the core need to meaningfully apply the concept of adaptive management.

The implementation of an effective adaptive management scheme is of high priority to the Bill Williams River Corridor Steering Committee, and it is clear to the committee that with complicated systems like that of the BWR, the ability to adaptively manage is proportional to the commitment to monitoring and experimentation. The workshop's defined flow requirements will be evaluated to identify which components can be immediately implemented and which will need further study. The knowledge and research gaps that were identified will be used to develop a strategic monitoring plan and priority research agenda, and opportunities will be identified to better link reservoir operations with scientific research.

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Appendix A. Stage-Discharge Relationships Along the Bill Williams River.

Table A1. Approximate locations of eight cross sections used to estimate stage-discharge relations along the Bill Williams River, Ariz. Cross sections are in downstream to upstream order. River miles are miles upstream of Highway 95 Bridge (see fig. 4).

Cross section number	Location description	Reach (fig. 4)	Analysis
1	River mile 3	Reach 11	fig. A.1
2	River mile 5.4	Reach 10	fig. A.2
3	River mile 6.3	Reach 10	fig. A.3
4	River mile 8.8	Reach 10	fig. A.4
5	River mile 24.5	Reach 7	fig. A.5
6	River mile 19.3	Reach 5	fig. A.6
7	River mile 28.6	Reach 3	fig. A.7
8	River mile 30.9	Reach 1	fig. A.8

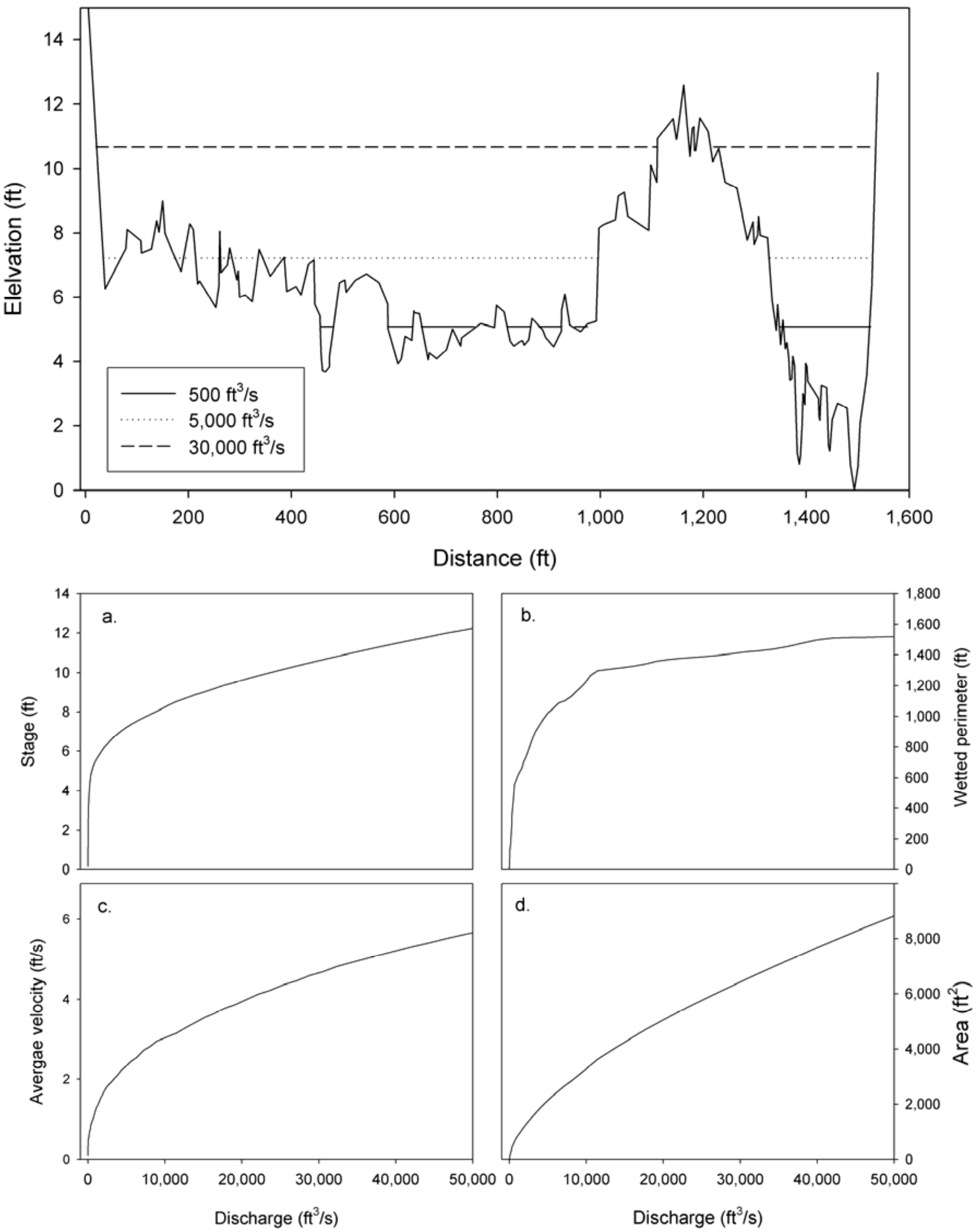

Figure A1. Bill Williams River, Ariz., Transect 1 with stages marked for discharges of 500, 5000 and 30,000 ft^3/s. Lower graphs show (a) stage-discharge, (b) wetted perimeter-discharge, (c) velocity-discharge, and (d) cross-sectional area-discharge relationships.

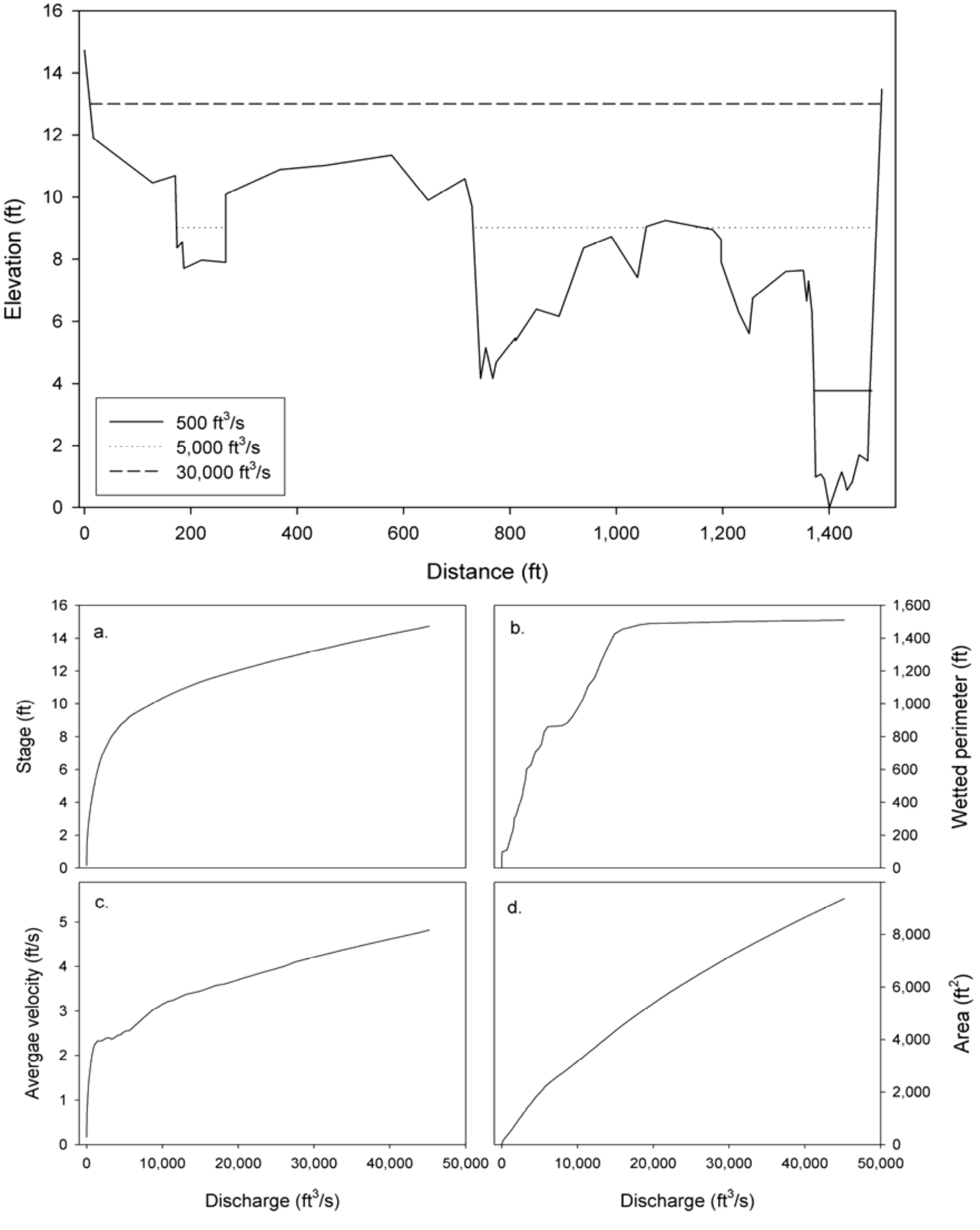

Figure A2. Bill Williams River, Ariz., Transect 2 with stages marked for discharges of 500, 5000 and 30,000 ft^3/s. Lower graphs show (a) stage-discharge, (b) wetted perimeter-discharge, (c) velocity-discharge, and (d) cross-sectional area-discharge relationships.

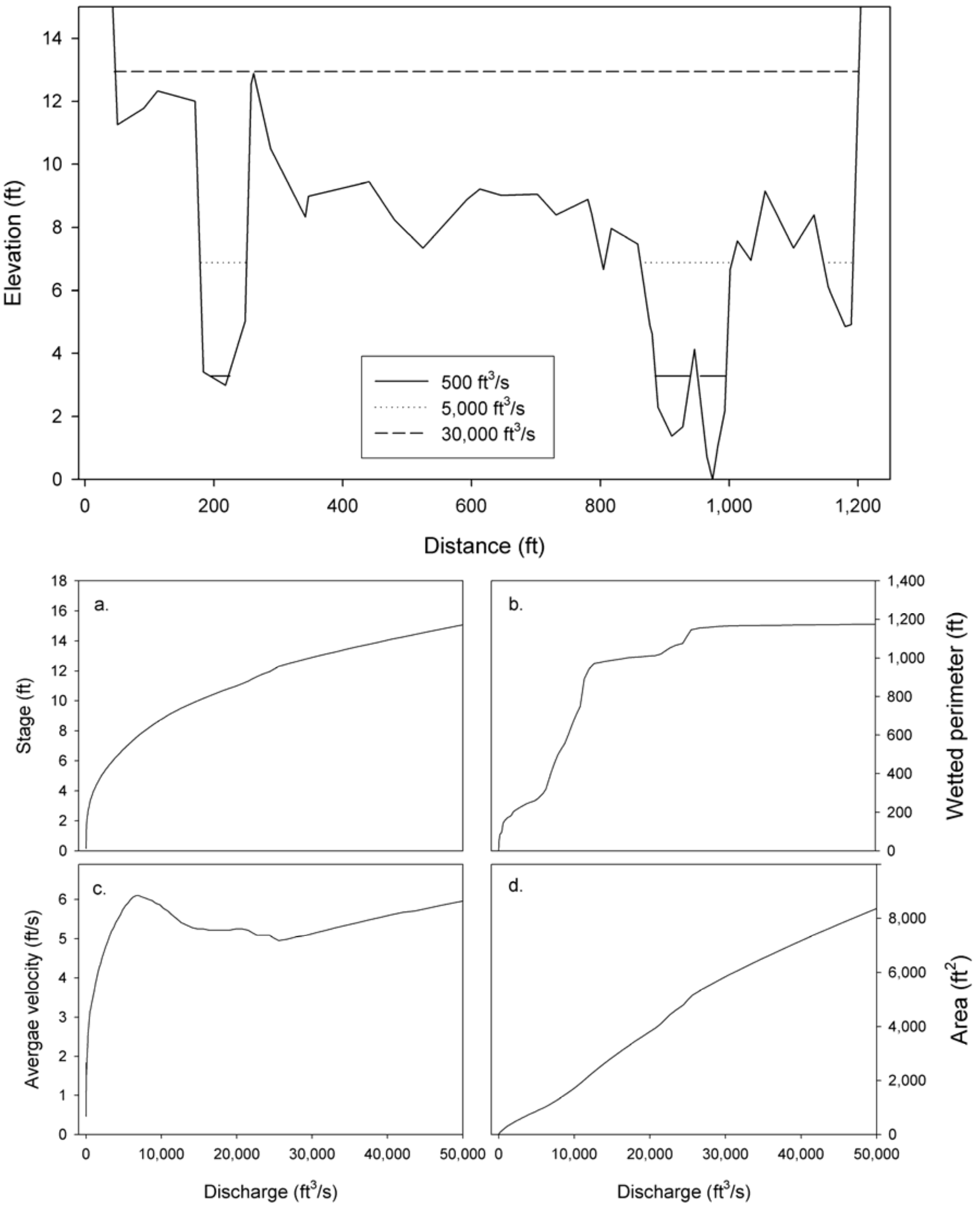

Figure A3. Bill Williams River, Ariz., Transect 3 with stages marked for discharges of 500, 5000 and 30,000 ft^3/s. Lower graphs show (a) stage-discharge, (b) wetted perimeter-discharge, (c) velocity-discharge, and (d) cross-sectional area-discharge relationships.

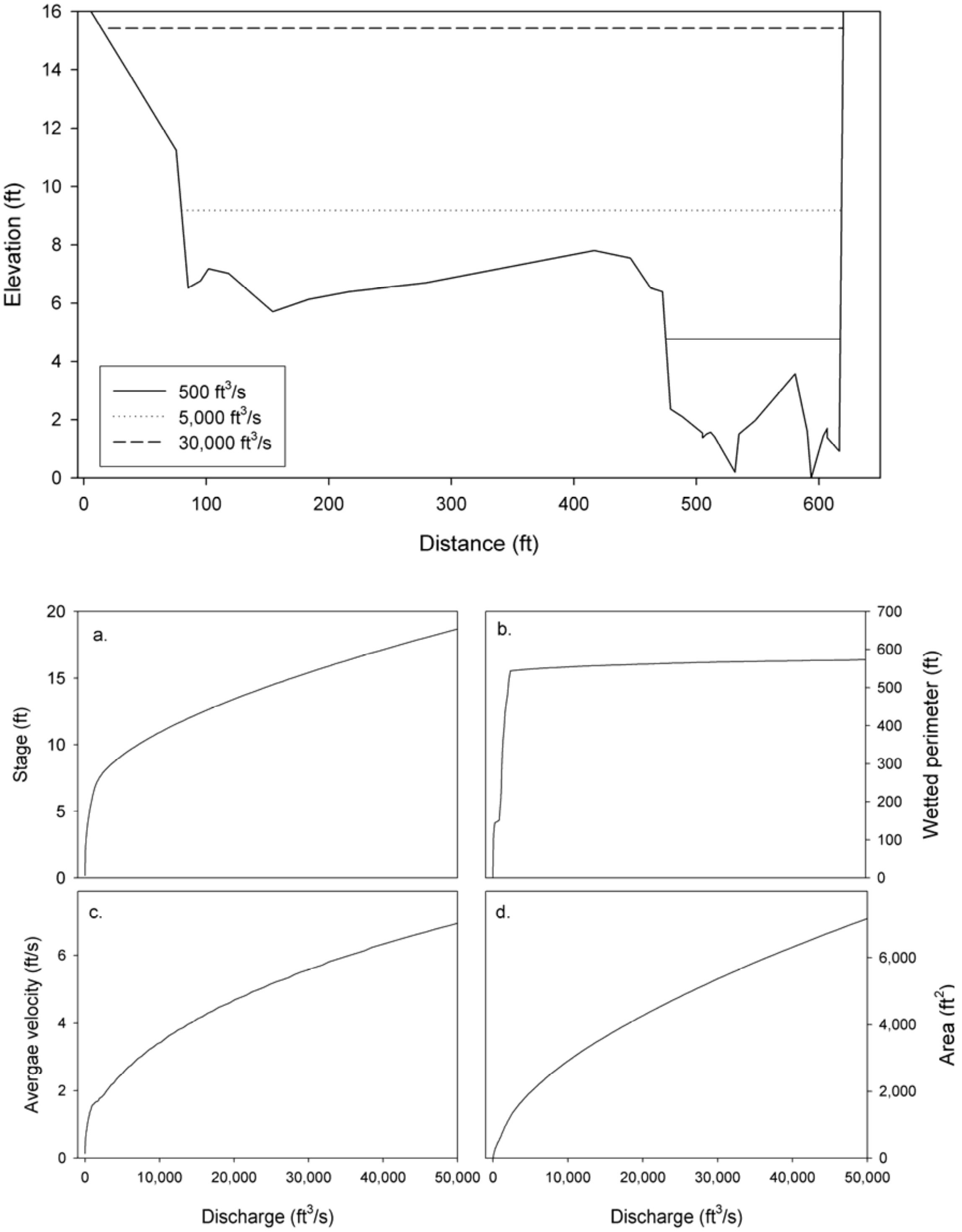

Figure A4. Bill Williams River, Ariz., Transect 4 with stages marked for discharges of 500, 5000 and 30,000 ft^3/s. Lower graphs show (a) stage-discharge, (b) wetted perimeter-discharge, (c) velocity-discharge, and (d) cross-sectional area-discharge relationships.

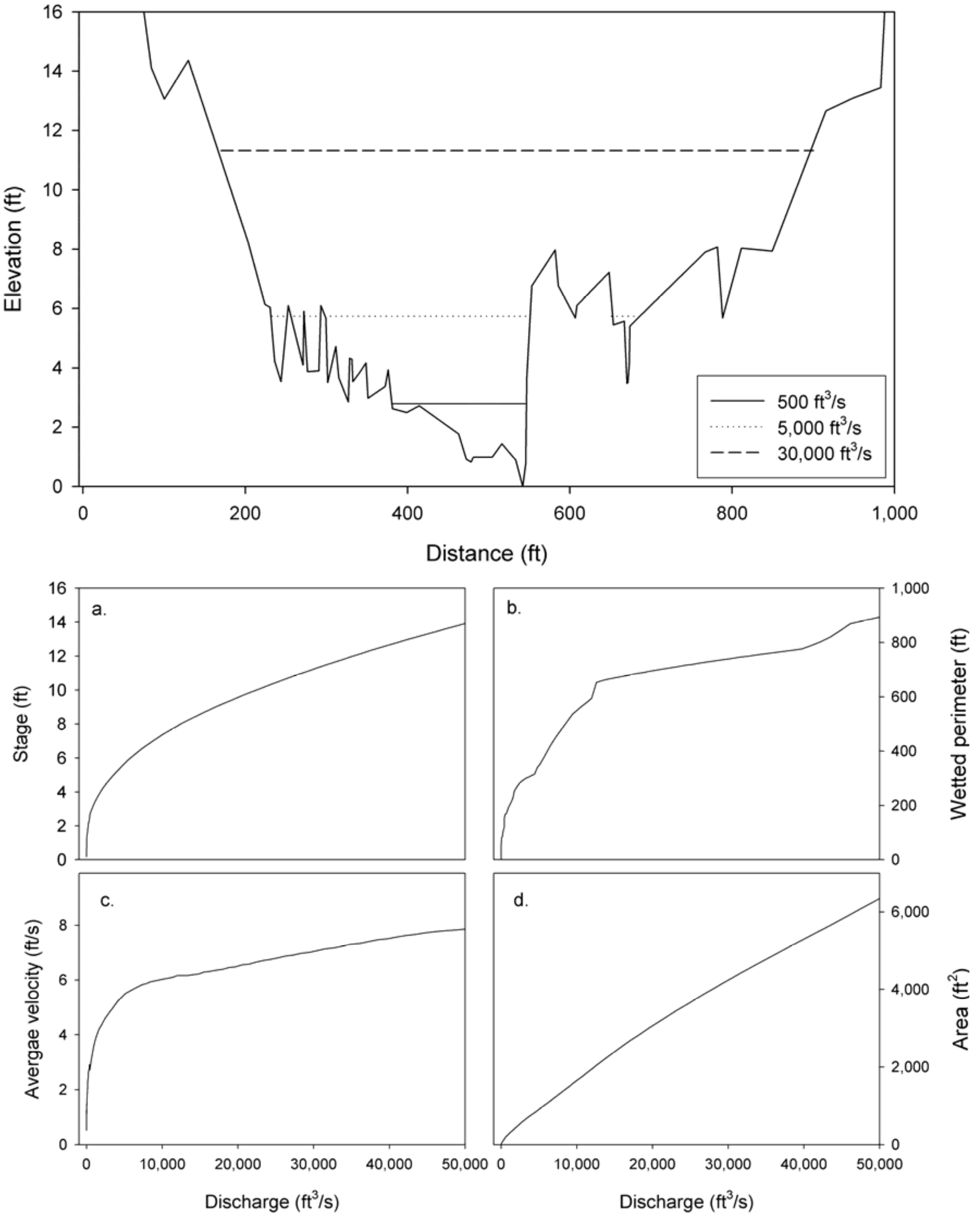

Figure A5. Bill Williams River, Ariz., Transect 5 with stages marked for discharges of 500, 5000 and 30,000 ft^3/s. Lower graphs show (a) stage-discharge, (b) wetted perimeter-discharge, (c) velocity-discharge, and (d) cross-sectional area-discharge relationships.

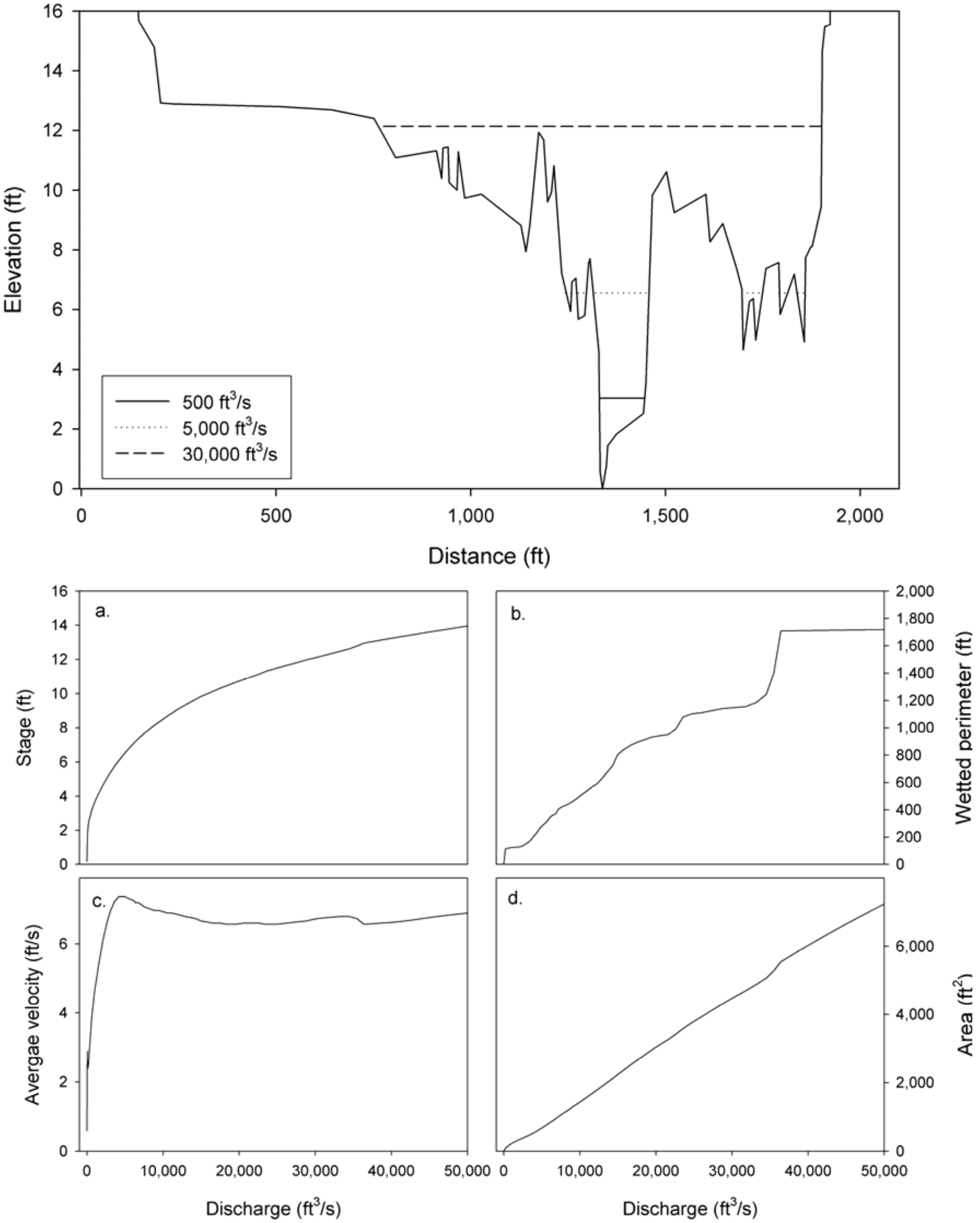

Figure A6. Bill Williams River, Ariz., Transect 6 with stages marked for discharges of 500, 5000 and 30,000 ft^3/s. Lower graphs show (a) stage-discharge, (b) wetted perimeter-discharge, (c) velocity-discharge, and (d) cross-sectional area-discharge relationships.

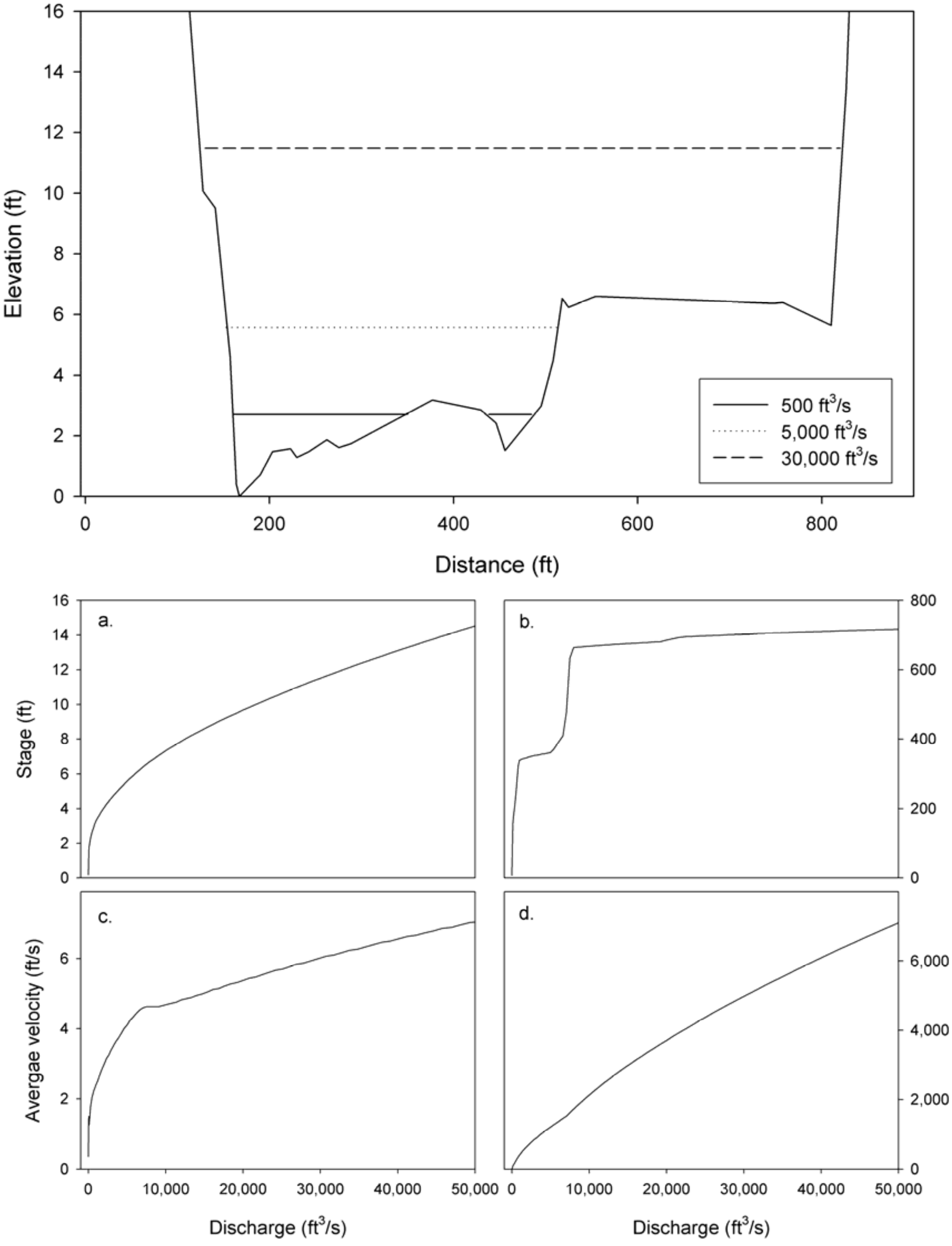

Figure A7. Bill Williams River, Ariz., Transect 7 with stages marked for discharges of 500, 5000 and 30,000 ft^3/s. Lower graphs show (a) stage-discharge, (b) wetted perimeter-discharge, (c) velocity-discharge, and (d) cross-sectional area-discharge relationships.

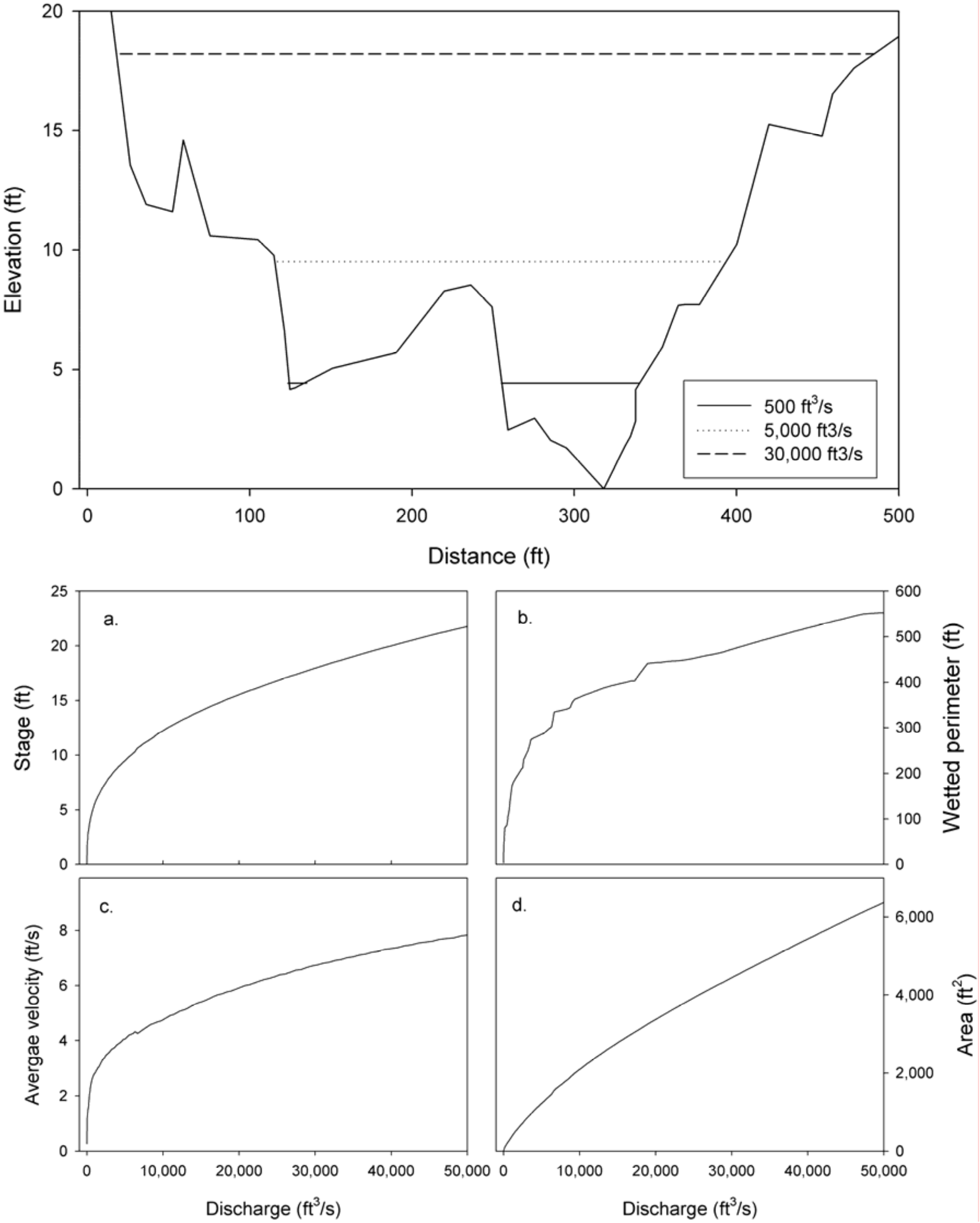

Figure A8. Bill Williams River, Ariz., Transect 8 with stages marked for discharges of 500, 5000 and 30,000 ft^3/s. Lower graphs show (a) stage-discharge, (b) wetted perimeter-discharge, (c) velocity-discharge, and (d) cross-sectional area-discharge relationships.

Appendix B. Birds of the Bill Williams River Corridor

Table B1. Deepwater bird species found within the corridor of the Bill Williams River, Ariz.

Group/common name	Scientific name	Nativity
Loons		
Red-throated loon	*Gavia stellata*	native
Pacific loon	*Gavia pacifica*	native
Common loon	*Gavia immer*	native
Yellow-billed loon	*Gavia adamsii*	native
Grebes		
Least grebe	*Tachybaptus dominicus*	native
Pied-billed grebe	*Podilymbus podiceps*	native
Horned grebe	*Podiceps auritus*	native
Red-neck grebe	*Podiceps grisegena*	native
Eared grebe	*Podiceps nigricollis*	native
Western grebe	*Aechmophorus occidentalis*	native
Clark's grebe	*Aechmophorus clarkii*	native
Storm-petrels		
Black storm-petrel	*Oceanodroma melania*	native
Least storm-petrel	*Oceanodroma microsoma*	native
Boobies		
Blue-footed booby	*Sula nebouxii*	native
Brown booby	*Sula leucogaster*	native
Pelicans		
American white pelican	*Pelecanus erythrorhynchos*	native
Brown pelican	*Pelecanus occidentalis*	native
Frigatebirds		
Magnificent frigatebird	*Fregata magnificens*	native
Duck, geese, and swans		
Tundra swan	*Cygnus columbianus*	native
Greater white-fronted goose	*Anser albifrons*	native
Snow goose	*Chen caerulescens*	native
Ross's goose	*Chen rossii*	native
Canada goose	*Branta canadensis*	native
Canvasback	*Aythya valisineria*	native
Redhead	*Aythya americana*	native
Ring-necked duck	*Aythya collaris*	native
Greater scaup	*Aythya marila*	native
Lesser scaup	*Aythya affinis*	native
Surf scoter	*Melanitta perspicillata*	native
White-winged scoter	*Melanitta fusca*	native
Long-tailed duck	*Clangula hyemalis*	native
Bufflehead	*Bucephala albeola*	native
Common goldeneye	*Bucephala clangula*	native
Barrow's goldeneye	*Bucephala islandica*	native
Hooded gerganser	*Lophodytes cucullatus*	native
Common gerganser	*Mergus merganser*	native
Red-breasted merganser	*Mergus serrator*	native
Ruddy duck	*Oxyura jamaicensis*	native
Cormorants		
Neotropical cormorant	*Phalacrocorax brasilianus*	native
Double-crested cormorant	*Phalacrocorax auritus*	native

Table B2. Shallowwater and shore bird species found within the corridor of the Bill Williams River, Ariz.

Group/common name	Scientific name	Nativity
Sandpipers, phalaropes, and allies		
Greater yellowlegs	*Tringa melanoleuca*	native
Lesser yellowlegs	*Tringa flavipes*	native
Solitary sandpiper	*Tringa solitaria*	native
Willet	*Catoptrophorus semipalmatus*	native
Spotted sandpiper	*Actitis macularius*	native
Whimbrel	*Numenius phaeopus*	native
Long-billed curlew	*Numenius americanus*	native
Marbled godwit	*Limosa fedoa*	native
Western sandpiper	*Calidris mauri*	native
Least sandpiper	*Calidris minutilla*	native
Baird's sandpiper	*Calidris bairdii*	native
Dunlin	*Calidris alpina*	native
Short-billed dowitcher	*Limnodromus griseus*	native
Long-billed dowitcher	*Limnodromus scolopaceus*	native
Wilson's snipe	*Gallinago delicata*	native
Wilson's phalarope	*Phalaropus tricolor*	native
Storks		
Wood stork	*Mycteria americana*	native
Ibises		
White-faced ibis	*Plegadis chihi*	native
Stilts and Avocets		
Black-necked stilt	*Himantopus mexicanus*	native
American avocet	*Recurvirostra americana*	native
Gulls and Terns		
Parasitic jaeger	*Stercorarius parasiticus*	native
Franklin's gull	*Larus pipixcan*	native
Bonaparte's gull	*Larus Philadelphia*	native
Heermann's gull	*Larus heermanni*	native
Ring-Billed gull	*Larus delawarensis*	native
California gull	*Larus californicus*	native
Herring gull	*Larus argentatus*	native
Thayer's gull	*Larus thayeri*	native
Western gull	*Larus occidentalis*	native
Sabine's gull	*Xema sabini*	native
Caspian tern	*Sterna caspia*	native
Common tern	*Sterna hirundo*	native
Arctic tern	*Sterna paradisaea*	native
Forster's tern	*Sterna forsteri*	native
Black tern	*Chlidonias niger*	native
Cranes		
Sandhill crane	*Grus canadensis*	native

Table B2. Shallowwater and shore bird species found within the corridor of the Bill Williams River, Ariz. —Continued

Group/common name	Scientific name	Nativity
Duck, geese, and swans		
Wood duck	*Aix sponsa*	native
Gadwall	*Anas strepera*	native
Eurasian wigeon	*Anas penelope*	native
American wigeon	*Anas americana*	native
Mallard	*Anas platyrhynchos*	native
Blue-winged teal	*Anas discors*	native
Cinnamon teal	*Anas cyanoptera*	native
Northern shoveler	*Anas clypeata*	native
Northern pintail	*Anas acuta*	native
Green-winged teal	*Anas crecca*	native
Lapwings and plovers		
Black-bellied plover	*Pluvialis squatarola*	native
American golden-plover	*Pluvialis dominica*	native
Snowy plover	*Charadrius alexandrinus*	native
Semipalmated plover	*Charadrius semipalmatus*	native
Killdeer	*Charadrius vociferus*	native
Herons, bitterns, and allies		
American bittern	*Botaurus lentiginosus*	native
Least bittern	*Ixobrychus exilis*	native
Great blue heron	*Ardea herodias*	native
Great egret	*Ardea alba*	native
Snowy egret	*Egretta thula*	native
Little blue heron	*Egretta caerulea*	native
Cattle egret	*Bubulcus ibis*	native
Green heron	*Butorides virescens*	native
Back-crowned night-heron	*Nycticorax nycticorax*	native

Table B3. Predator and scavenger bird species found within the corridor of the Bill Williams River, Ariz.

Group/common name	Scientific name	Nativity
New world vultures		
Turkey vulture	*Cathartes aura*	native
California condor	*Gymnogyps californianus*	native
Hawks, kites, eagles, and allies		
Osprey	*Pandion haliaetus*	native
White-tailed kite	*Elanus leucurus*	native
Mississippi kite	*Ictinia mississippiensis*	native
Bald eagle	*Haliaeetus leucocephalus*	native
Northern harrier	*Circus cyaneus*	native
Sharp-shinned hawk	*Accipiter striatus*	native
Cooper's hawk	*Accipiter cooperii*	native
Northern goshawk	*Accipiter gentilis*	native
Common black-hawk	*Buteogallus anthracinus*	native
Harris-hawk (Historic)	*Parabuteo unicinctus*	native
Red-shouldered hawk	*Buteo lineatus*	native
Broad-winged hawk	*Buteo platypterus*	native
Swainson's hawk	*Buteo swainsoni*	native
Zone-tailed hawk	*Buteo albonotatus*	native
Red-tailed hawk	*Buteo jamaicensis*	native
Ferrugious hawk	*Buteo regalis*	native
Golden eagle	*Aquila chrysaetos*	native
Caracaras and falcons		
Crested caracara	*Caracara cheriway*	native
American kestrel	*Falco sparverius*	native
Merlin	*Falco columbarius*	native
Peregrine falcon	*Falco peregrinus*	native
Barn owls		
Barn owl	*Tyto alba*	native
Typical owls		
Flammulated owl	*Otus flammeolus*	native
Western screech-owl	*Megascops kennicottii*	native
Great horned owl	*Bubo virginianus*	native
Elf owl	*Micrathene whitneyi*	native
Burrowing owl	*Athene cunicularia*	native
Long-Eared owl	*Asio otus*	native
Short-Eared owl	*Asio flammeus*	native
Northern saw-whet owl	*Aegolius acadicus*	native

Table B4. Game bird species found within the corridor of the Bill Williams River, Ariz.

Group/common name	Scientific name	Nativity	Group/common name	Scientific name	Nativity
Turkeys			**Pigeons and doves**		
Wild turkey	*Meleagris gallopavo*	native	Rock dove	*Columba livia*	native
New world quail			Band-tailed pigeon	*Patagioenas fasciata*	native
Gambel's quail	*Callipepla gambelii*	native	White-winged dove	*Zenaida asiatica*	native
Rails, gallinules, and coots			Mourning dove	*Zenaida macroura*	native
Black rail	*Laterallus jamaicensis*	native	Inca dove	*Columbina inca*	native
Clapper rail	*Rallus longirostris*	native	Common ground-dove	*Columbina passerina*	native
Sora	*Porzana carolina*	native			
Common moorhen	*Gallinula chloropus*	native			
American coot	*Fulica americana*	native			

Table B5. Forest bird species found within the corridor of the Bill Williams River, Ariz.

Group/common name	Scientific name	Nativity	Group/common name	Scientific name	Nativity
Cuckoos and Roadrunners			**Hummingbirds**		
Yellow-billed cuckoo	*Coccyzus americanus*	native	Broad-billed hummingbird	*Cynanthus latirostris*	native
Greater roadrunner	*Geococcyx californianus*	native	Black-chinned hummingbird	*Archilochus alexandri*	native
Goatsuckers			Anna's hummingbird	*Calypte anna*	native
Lesser nighthawk	*Chordeiles acutipennis*	native	Costa's hummingbird	*Calypte costae*	native
Common nighthawk	*Chordeiles minor*	native	Calliope hummingbird	*Stellula calliope*	native
Common poorwill	*Phalaenoptilus nuttallii*	native	Broad-tailed hummingbird	*Selasphorus platycercus*	native
Swifts			Rufous hummingbird	*Selasphorus rufus*	native
Black swift	*Cypseloides niger*	native	**Kinglets**		
Vaux's swift	*Chaetura vauxi*	native	Golden-crowned kinglet	*Regulus satrapa*	native
White-throated swift	*Aeronautes saxatalis*	native	Ruby-crowned kinglet	*Regulus calendula*	native

Table B5. Forest bird species found within the corridor of the Bill Williams River, Ariz. —Continued

Group/common name	Scientific name	Nativity	Group/common name	Scientific name	Nativity
Gnatcatchers			**Tyrant flycatchers**		
Blue-gray gnatcatcher	*Polioptila caerulea*	native	Olive-sided flycatcher	*Contopus cooperi*	native
Black-tailed gnatcatcher	*Polioptila melanura*	native	Greater pewee	*Contopus pertinax*	native
Woodpecker and allies			Western wood-pewee	*Contopus sordidulus*	native
Lewis’ woodpecker	*Melanerpes lewis*	native	Willow fycatcher	*Empidonax traillii*	native
Acorn woodpecker	*Melanerpes formicivorus*	native	Hammond’s flycatcher	*Empidonax hammondii*	native
Gila woodpecker	*Melanerpes uropygialis*	native	Gray flycatcher	*Empidonax wrightii*	native
Williamson’s sapsucker	*Sphyrapicus thyroideus*	native	Dusky flycatcher	*Empidonax oberholseri*	native
Yellow-bellied sapsucker	*Sphyrapicus varius*	native	Pacific-slope flycatcher	*Empidonax difficilis*	native
Red-naped sapsucker	*Sphyrapicus nuchalis*	native	Black phoebe	*Sayornis nigricans*	native
Ladder-backed woodpecker	*Picoides scalaris*	native	Eastern phoebe	*Sayornis phoebe*	native
Northern flicker	*Colaptes auratus*	native	Say’s phoebe	*Sayornis saya*	native
Gilded flicker	*Colaptes chrysoides*	native	Vermilion flycatcher	*Pyrocephalus rubinus*	native
Creepers			Ash-throated flycatcher	*Myiarchus cinerascens*	native
Brown creeper	*Certhia americana*	native	Brown-crested flycatcher	*Myiarchus tyrannulus*	native
Wrens			Tropical kingbird	*Tyrannus melancholicus*	native
Cactus wren	*Campylorhynchus brunneicapillus*	native	Cassin’s kingbird	*Tyrannus vociferans*	native
Rock wren	*Salpinctes obsoletus*	native	Thick-billed kingbird	*Tyrannus crassirostris*	native
Canyon wren	*Catherpes mexicanus*	native	Western kingbird	*Tyrannus verticalis*	native
Bewick’s wren	*Thryomanes bewickii*	native	**Crows and jays**		
House wren	*Troglodytes aedon*	native	Steller’s jay	*Cyanocitta stelleri*	native
Winter wren	*Troglodytes troglodytes*	native	Western scrub-jay	*Aphelocoma californica*	native
Marsh wren	*Cistothorus palustris*	native	Pinyon jay	*Gymnorhinus cyanocephalus*	native
Kingfishers			American crow	*Corvus brachyrhynchos*	native
Belted kingfisher	*Ceryle alcyon*	native	Common raven	*Corvus corax*	native

Table B5. Forest bird species found within the corridor of the Bill Williams River, Ariz. —Continued

Group/common name	Scientific name	Nativity
Shrikes		
Loggerhead shrike	*Lanius ludovicianus*	native
Swallows		
Purple martin	*Progne subis*	native
Tree swallow	*Tachycineta bicolor*	native
Violet-green swallow	*Tachycineta thalassina*	native
Bank swallow	*Riparia riparia*	native
Cliff swallow	*Petrochelidon pyrrhonota*	native
Barn swallow	*Hirundo rustica*	native
Chickadees and titmice		
Mountain chickadee	*Poecile gambeli*	native
Bridled titmouse	*Baeolophus wollweberi*	native
Verdin		
Verdin	*Auriparus flaviceps*	native
Bushtits		
Bushtit	*Psaltriparus minimus*	native
Nuthatches		
Red-breasted nuthatch	*Sitta canadensis*	native
White-breasted nuthatch	*Sitta carolinensis*	native
Waxwings		
Cedar waxwing	*Bombycilla cedrorum*	native
Tanagers		
Hepatic tanager	*Piranga flava*	native
Summer tanager	*Piranga rubra*	native
Western tanager	*Piranga ludoviciana*	native
Vireos		
Bell's vireo	*Vireo bellii*	native
Yellow-throated vireo	*Vireo flavifrons*	native
Plumbeous vireo	*Vireo plumbeus*	native
Cassin's vireo	*Vireo cassinii*	native
Hutton's vireo	*Vireo huttoni*	native
Warbling vireo	*Vireo gilvus*	native
Red-eyed vireo	*Vireo olivaceus*	native
Mockingbirds and Thrashers		
Gray catbird	*Dumetella carolinensis*	native
Northern mockingbird	*Mimus polyglottos*	native
Sage thrasher	*Oreoscoptes montanus*	native
Brown thrasher	*Toxostoma rufum*	native
Bendire's thrasher	*Toxostoma bendirei*	native
Curve-billed thrasher	*Toxostoma curvirostre*	native
Crissal thrasher	*Toxostoma crissale*	native
LeConte's thrasher	*Toxostoma lecontei*	native
Thrushes		
Western bluebird	*Sialia mexicana*	native
Mountain bluebird	*Sialia currucoides*	native
Townsend's solitaire	*Myadestes townsendi*	native
Swainson's thrush	*Catharus ustulatus*	native
Hermit thrush	*Catharus guttatus*	native
American robin	*Turdus migratorius*	native
Varied thrush	*Ixoreus naevius*	native

Table B5. Forest bird species found within the corridor of the Bill Williams River, Ariz. —Continued

Group/common Name	Scientific name	Nativity	Group/common name	Scientific name	Nativity
Sparrows			**Wood-warblers**		
Green-tailed towhee	*Pipilo chlorurus*	native	Blue-singed warbler	*Vermivora pinus*	native
Spotted towhee	*Pipilo maculatus*	native	Golden-winged warbler	*Vermivora chrysoptera*	native
Canyon towhee	*Pipilo fuscus*	native	Orange-crowned warbler	*Vermivora celata*	native
Rufous crowned sparrow	*Aimophila ruficeps*	native	Nashville warbler	*Vermivora ruficapilla*	native
American tree tparrow	*Spizella arborea*	native	Virginia's warbler	*Vermivora virginiae*	native
Chipping sparrow	*Spizella passerina*	native	Lucy’s warbler	*Vermivora luciae*	native
Brewer’s sparrow	*Spizella breweri*	native	Northern parula	*Parula americana*	native
Black-chinned sparrow	*Spizella atrogularis*	native	Yellow warbler	*Dendroica petechia*	native
Vesper sparrow	*Pooecetes gramineus*	native	Chestnut-sided warbler	*Dendroica pennsylvanica*	native
Lark sparrow	*Chondestes grammacus*	native	Magnolia warbler	*Dendroica magnolia*	native
Sage sparrow	*Amphispiza belli*	native	Black-throated blue warbler	*Dendroica caerulescens*	native
Savannah sparrow	*Passerculus sandwichensis*	native	Yellow-rumped warbler	*Dendroica coronata*	native
Grasshopper sparrow	*Ammodramus savannarum*	native	Black-throated gray warbler	*Dendroica nigrescens*	native
Le Conte’s sparrow	*Ammodramus leconteii*	native	Black-throated green warbler	*Dendroica virens*	native
Fox sparrow	*Passerella iliaca*	native	Townsend’s warbler	*Dendroica townsendi*	native
Song sparrow	*Melospiza melodia*	native	Bay-breasted warbler	*Dendroica castanea*	native
Swamp sparrow	*Melospiza georgiana*	native	Black-and-white warbler	*Mniotilta varia*	native
White-throated sparrow	*Zonotrichia albicollis*	native	American redstart	*Setophaga ruticilla*	native
Golden-crowned sparrow	*Zonotrichia atricapilla*	native	Prothonotary warbler	*Protonotaria citrea*	native
Dark-eyed junco	*Junco hyemalis*	native	Worm-eating warbler	*Helmitheros vermivorum*	native
McCown’s longspur	*Calcarius mccownii*	native	Ovenbird	*Seiurus aurocapilla*	native
Old world sparrows			Northern waterthrush	*Seiurus noveboracensis*	native
House sparrow	*Passer domesticus*	exotic	Louisiana waterthrush	*Seiurus motacilla*	native
			MacGillivray’s warbler	*Oporornis tolmiei*	native

Table B5. Forest bird species found within the corridor of the Bill Williams River, Ariz. —Continued

Group/common name	Scientific name	Nativity	Group/common Name	Scientific name	Nativity
Wood-warblers (cont.)			**Finches and allies**		
Common yellowthroat	*Geothlypis trichas*	native	Purple finch	*Carpodacus purpureus*	native
Hooded warbler	*Wilsonia citrina*	native	Cassin's finch	*Carpodacus cassinii*	native
Wilson's warbler	*Wilsonia pusilla*	native	House finch	*Carpodacus mexicanus*	native
Painted redstart	*Myioborus pictus*	native	Red crossbill	*Loxia curvirostra*	native
Yellow-breasted chat	*Icteria virens*	native	Pine siskin	*Carduelis pinus*	native
Blackbirds			Lesser goldfinch	*Carduelis psaltria*	native
Bobolink	*Dolichonyx oryzivorus*	native	Lawrence's goldfinch	*Carduelis lawrencei*	native
Red-winged blackbird	*Agelaius phoeniceus*	native	American goldfinch	*Carduelis tristis*	native
Eastern meadowlark	*Sturnella magna*	native	Evening grosbeak	*Coccothraustes vespertinus*	native
Western meadowlark	*Sturnella neglecta*	native	**Cardinals and allies**		
Yellow-headed blackbird	*Xanthocephalus xanthocephalus*	native	Northern cardinal	*Cardinalis cardinalis*	native
Rusty blackbird	*Euphagus carolinus*	native	Rose-breasted grosbeak	*Pheucticus ludovicianus*	native
Brewer's blackbird	*Euphagus cyanocephalus*	native	Black-headed grosbeak	*Pheucticus melanocephalus*	native
Common grackle	*Quiscalus quiscula*	exotic	Blue grosbeak	*Passerina caerulea*	native
Great-tailed grackle	*Quiscalus mexicanus*	native	Lasuli bunting	*Passerina amoena*	native
Bronzed cowbird	*Molothrus aeneus*	native	Indigo bunting	*Passerina cyanea*	native
Brown-headed cowbird	*Molothrus ater*	native	Varied bunting	*Passerina versicolor*	native
Hooded oriole	*Icterus cucullatus*	native	Painted bunting	*Passerina ciris*	native
Bullock's oriole	*Icterus bullockii*	native	**Starlings**		
Scott's oriole	*Icterus parisorum*	native	European btarling	*Sturnus vulgaris*	exotic
Larks			**Silky-flycatchers**		
Horned lark	*Eremophila alpestris*	native	Phainopepla	*Phainopepla nitens*	native

Appendix C. Aquatic Invertebrates of the Bill Williams River Corridor

Table C1. Aquatic invertebrate species found corridor of the Bill Williams River, Ariz.

Species/group common name	Species/group scientific name	Nativity	Habitat
AQUATIC INSECTS			
Mayflies	**Order Ephemeroptera**		
	Baetidae		
	Baetis	native	lotic
	Callibaetis pictus	native	lentic
	Acentrella	native	lotic
	Pseudocloen	native	lotic
	Fallceon	native	lotic
	Paracloeodes	native	lotic
	Leptohyphidae		
	Trichorithodes fallax	native	lotic
	Ephemerellidae		
	Drunella	native	lotic
	Heptageniidae		
	Rhithrogena	native	lotic
Dragonflies and damselflies	**Order Odonata**		
	Coenagrionidae		
	Argia vivida	native	lentic/lotic
	Enallagma praevarum	native	lentic
	Zoniagrion,	native	
	Calopterygidae		
	Hetaerina	native	lentic
	Cordulegastridae		
	Cordulegaster	native	lentic/lotic
	Aeschnidae		
	Anax junius	native	lentic
Dragonflies and damselflies—continued	**Gomphidae**		
	Progomphus	native	
	Erpetogomphus compositus	native	
	Ophiogomphus	native	
	Libellulidae		
	Perithemis	native	
	Sympetrum illotrum	native	
	Somatochlora	native	
Stoneflies	**Order Plecoptera**		
	Nemouridae		
	Malenka	native	lotic
Water bugs	**Order Hemiptera**		
water boatmen	**Corixidae**		
	Graptocorixa serrulata	native	lentic
water striders	**Gerridae**		
	Gerris	native	lentic/lotic
broad-shouldered water	**Veliidae**		
	Rhagovelia	native	lentic/lotic
	Microvelia	native	
	Naucoridae		
	Ambrysus	native	lotic
giant waterbugs	**Belostomatidae**		
	Abedus herberti	native	lotic
	Belostoma	native	lentic
toad bugs	**Gelastocoridae**		
	Gelastocoris oculatus	native	

Table C1. Aquatic invertebrate species found within the corridor of the Bill Williams River, Ariz. —Continued

Species/group common name	Species/group scientific name	Nativity	Habitat
Aquatic moths	**Order Lepidoptera**		
	Pyralidae		
	Petrophila	native	
Caddisflies	**Order Trichoptera**		
saddlecase makers	**Glossosomatidae**		
	Culoptila	native	lotic
	Protoptila	native	lotic
	Helicopsychidae		
snail case makers	*Helicopsyche*	native	lotic
netspinning caddis	**Hydropsychidae**		
	Cheumatopsyche	native	lotic
	Smicridea	native	lotic
microcaddis	**Hydroptilidae**		
	Hydroptila	native	lotic
	Metrichia	native	lotic
	Leucotrichia	native	lotic
	Ochrotrichia	native	lotic
long-horned caddis	**Leptoceridae**		
	Nectopsyche dorsalis	native	lotic
	Oecetis	native	lotic
Beetles	**Order Coleoptera**		
	Haliplidae		
	Peltodytes simplex	native	lentic
predaceous diving beetles	**Dytiscidae**		
	Agabus	native	
	Rhantus	native	
	Deronectes	native	
	Stictotarsus corpulentus	native	
	Oreodytes	native	
	Liodessus	native	
	Laccophilus decipens	native	
	Copelatus	native	
water scavenger beetles	**Hydrophilidae**		
	Tropisternus obscurus	native	
	Berosus	native	
	Enochrus	native	
	Hydrochus	native	
	Helochares	native	
	Laccobius	native	
riffle beetles	**Elmidae**		
	Zaitzevia	native	lotic
	Microcylloepus	native	lotic
	Optioservus	native	lotic
	Dryopidae		
	Posthelichus productus	native	lotic
	Helichus striatus	native	lotic
	Hydroscaphidae		
	Hydroscapha natans	native	
water penny beetles	**Psephenidae**	native	lotic

Table C1. Aquatic invertebrate species found within the corridor of the Bill Williams River, Ariz. —Continued

Species/group common name	Species/group scientific name	Nativity	Habitat
Flies	**Order Diptera**		
biting midges	**Ceratopogonidae**		
	Probezzia	native	lotic
soldier flies	**Stratiomyiidae**		
	Euparyphus	native	lotic
	Caloparyphus	native	lotic
	Nemotelus	native	lotic
midges	**Chironomidae**	native	lentic/lotic
dance flies	**Empididae**		
	Hemerodromia	native	
black flies	**Simuliidae**		
	Simulium	native	
crane flies	**Tipulidae**		
	Hexatoma	native	
	Holorusia	native	
	Antocha	native	
	Erioptera	native	
common flies	**Muscidae**	native	
dixid midges	**Dixidae**		
	Dixella	native	
NON-INSECT AQUATIC ARTHROPODS			
Scuds, sideswimmers	**Order Amphipoda**		
	Hyalellidae		
	Hyalella azteca	native	lentic
	Gammaridae		
	Gammarus	native	lentic
	Talitridae	native	
Sow bugs	**Order Isopoda**		
	Onisciidae	native	
	Sphaeromidae		
	Exosphaeroma	native	
	Order Decapoda		
	Palaemonidae		
grass shrimp	*Palaemontes*	exotic	
crayfish	**Astacidae**		
	Cambarus	exotic	lentic/lotic
	Procambarus clarki	exotic	lentic/lotic

Table C2. Fish species found within the corridor of the Bill Williams River, Ariz.

Species/group common name	Species/group scientific name	Nativity	Distrib[1].	Habitat
	Cyprinidae			
longfin dace	*Agosia chrysogaster*	native	LAUH	lentic
goldfish	*Carassius auratus*	exotic	A	lentic
carp	*Cyprinus carpio*	exotic	L	lentic
roundtail chub	*Gila robusta*	native	U	lotic
bonytail chub	*Gila elegans*	native	L?	
red shiner	*Notropis lutrensis*	exotic	LAU	lotic
fathead minnow	*Pimephales promelas*	exotic	L	
speckled dace	*Rhinichthys osculus*	native	UH	lotic
	Catostomidae			
desert sucker	*Catostomus insignis*	native	U	lotic
Gila mountain sucker	*Pantosteus clarki*	native	U	lotic
razorback sucker	*Zyrauchen texanus*	native	L?	
	Ictaluridae			
black bullhead	*Ictalurus melas*	exotic	AU	lentic/lotic
yellow bullhead	*Ictalurus natalus*	exotic	AU	lentic/lotic
channel catfish	*Ictalurus punctatus*	exotic	A	lentic/lotic
flathead catfish	*Pilodictus olivaris*	exotic	A	lentic/lotic
	Poeciliidae			
mosquitofish	*Gambusia affinis*	exotic	LAUH	lentic/lotic
	Centrarchidae			
largemouth bass	*Micropterus salmoides*	exotic	LAU	lentic/lotic
smallmouth bass	*Micropterus dolomieui*	exotic	U	lotic
green sunfish	*Chaenobryttus cyanellus*	exotic	AU	lentic/lotic
bluegill	*Lepomis macrochirus*	exotic	A	lentic
redear sunfish	*Lepomis microlophus*	exotic	A	lentic
shellcracker	*L. microlophus* x *C. cyanellus*	exotic	A	
	Cichlidae			
Mozambique mouthbrooder	*Tilapia mossambica*	exotic	A	lentic
Zilli's tilapia	*Tilapia zillii*	exotic	U	
	Clupeidae			
threadfin shad	*Dorosoma petenense*	exotic	A	lentic

[1] Distribution: L – lower Bill Williams River below Alamo Dam, A – Alamo Lake only, U – upstream of Alamo Lake, and H – headwater reaches, small streams.

Appendix D. Mammals of the Bill Williams River Corridor

Table D1. Mammal species found within the corridor of the Bill Williams River, Ariz.

Species/group common name	Species/group scientific name	Nativity
	Order Chiroptera	
	Phyllostomatidae	
California leaf-nosed bat	*Macrotus californicus*	native
	Vespertilionidae	
Pallid bat	*Antrozous pallidus*	native
Townsend’s big-eared bat	*Corynorhinus townsendii*	native
Big brown bat	*Eptesicus fuscus*	native
Hoary bat	*Lasiurus cinereus*	native
Western yellow bat	*Lasiurus xanthinus*	native
Western red bat	*Lasiurus blossevellii*	native
California myotis	*Myotis californicus*	native
Cave myotis	*Myotis velifer*	native
Yuma myotis	*Myotis yumanensis*	native
Fringed myotis	*Myotis thysanodes*	native
Arizona myotis	*Myotis occultus*	native
Western pipistrelle bat	*Pipistrellus hesperus*	native
	Molossidae	
Western mastiff bat	*Eumops perotis*	native
Pocketed free-tailed bat	*Nyctinmops fermorosaccus*	native
Mexican free-tailed bat	*Tadarida brasiliensis*	native
	Order Lagomorpha	
	Leporidae	
Desert cottontail	*Sylvilagus audubonii*	native
Black-tailed jackrabbit	*Lepus californicus*	native
	Order Rodentia	
	Sciuridae	
Round-tailed ground squirrel	*Spermophilus tereticaudus*	native
Cliff chipmunk	*Eutamias dorsalis*	native
	Castoridae	
Beaver	*Castor canadensis*	native
	Cricetidae	
Cactus mouse	*Peromyscus eremicus*	native
Deer mouse	*Peromyscus maniculatus*	native
White-throated woodrat	*Neotoma albigula*	native
Muskrat	*Ondatra zibethicus*	native
Arizona cotton rat	*Sigmodon arizonae*	native
Western harvest mouse	*Reithrodontomys megalotis*	native
	Heteromyidae	
Desert pocket mouse	*Chaetodipus penicillatus*	native
Bailey’s pocket mouse	*Perognathus baileyi*	native
Merriam’s kangaroo rat	*Dipodomys merriami*	native
Desert kangaroo rat	*Dipodomys deserti*	native
Pacific pocket mouse	*Perognathus longimembris*	native
	Geomyidae	
Botta’s pocket gopher	*Thomomys bottae*	native
	Erithoziontidae	
North American porcupine	*Erethizon dorsatum*	native

Table D1. Mammal species found within the corridor of the Bill Williams River, Ariz. —Continued

Species/group common name	Species/group scientific name	Nativity
	Order Carnivora	
	Canidae	
Coyote	*Canis latrans*	native
Gray fox	*Urocyon cinereoargenteus*	native
San Joaquin kit fox	*Vulpes macrotis*	native
	Procyonidae	
Northern raccoon	*Procyon lotor*	native
Ring tailed cat	*Bassariscus astutus*	native
	Mustelidae	
Western spotted skunk	*Spilogale gracilis*	native
Striped skunk	*Mephitis mephitis*	native
American badger	*Taxidea taxus*	native
	Felidae	
Mountain lion	*Felis concolor*	native
Bobcat	*Felis rufus*	native
	Order Insectivora	
	Soricidae	
Crawford's desert shrew	*Notiosorex crawfordi*	native
	Order Artiodactyla	
	Tayassuidae	
Collared peccary	*Tayassu tajacu*	native
	Suidae	
Wild boar	*Sus scrofa*	exotic
	Cervidae	
Mule deer	*Odocoileus hemionus*	native
Elk	*Cervus elaphus*	native
	Antilocapridae	
Pronghorn	*Antilocapra americana*	native
	Bovidae	
Bighorn sheep	*Ovis canadensis*	native
	Order Perissodactyla	
	Equidae	
Wild burro	*Equus asinus*	exotic

Appendix E. Reptiles and Amphibians of the Bill Williams River Corridor

Table E1. Reptile and amphibian species found within the corridor of the Bill Williams River, Ariz.

Species/group common name	Species/group scientific name	Nativity
REPTILES	**Class Reptilia**	
Turtles and tortoises	**Order Testudines**	
Softshell turtles	**Trionychidae**	
Spiny softshell	*Trionyx spiniferus (Apalone spinifera)*	exotic
Box and water turtles	**Emydidae**	
Slider[A]	*Chrysemys scripta*	exotic
Painted turtle[A]	*Chrysemys picta*	exotic
Musk and mud turtles	**Kinosternidae**	
Sonoran mud turtle[B]	*Kinosternon sonoriense*	native
Alligators, crocodiles and caimans	**Order Crocodylia**	
	Alligatoridae	
American alligator[C]	*Alligator mississippiensis*	exotic
Lizards and snakes	**Order Squamata**	
Banded geckos	**Eublepharidae**	
Western banded gecko	*Coleonyx variegatus*	native
Iguanid lizards	**Iguanidae**	
Desert iguana	*Dipsosaurus dorsalis*	native
	Phrynosomatidae	
Side blotched lizard	*Uta stansburiana*	native
Long-tailed brush lizard	*Urosaurus graciosus*	native
Zebra-tailed lizard	*Callisaurus draconoides*	native
Ornate tree lizard	*Urosaurus* (?*Callisaurus*) *ornatus*	native
Mojave fringe-toed lizard[A]	*Uma scoparia*	native
Whiptail lizards	**Teiidae**	
Western whiptail	*Aspidoscelis tigris*	native
Poisonous lizards	**Helodermatidae**	
Gila monster	*Heloderma suspectum*	native
Blind snakes	**Leptotyphlopidae**	
Western blind snake	*Leptotyphlops humilis*	native
Typical snakes	**Colubridae**	
Coachwhip	*Masticophis flagellum*	native
California kingsnake	*Lampropeltis getulus*	native
Western patchnose snake	*Salvadora hexalepis*	native
Checkered gartersnake	*Thamnophis flagellum*	native
Gopher snake	*Pituophis melanoleucus*	native
Glossy snake	*Arizona elegans*	native
Spotted leafnosed snake	*Phyllorhynus decurtatus*	native
Lyre snake	*Trimorphodon biscutatus*	native
Spotted night snake	*Hypsoglena torquata*	native
Pit vipers	**Viperidae**	
Western diamondback	*Crotalus atrox*	native
Mojave rattlesnake	*Crotalus scutulatus*	native
Sidewinder rattlesnake[A]	*Crotalus cerastes*	exotic

[A] The species is undocumented but probably present, based on its known range and documented presence nearby.

[B] The species is possibly present, based on its historic distribution (currently uncommon native species) or known nearby presence (introduced exotic species).

[C] The American alligator was introduced and is likely now extirpated.

Table E1. Reptile and amphibian species found within the corridor of the Bill Williams River, Ariz —Continued.

Species/group common name	Species/group scientific name	Nativity
AMPHIBIANS	**Class Amphibia**	
Frogs and toads	**Order Anura**	
True toads	**Bufonidae**	
Woodhouse's toad	*Bufo woodshousei*	native
Red spotted toad	*Bufo punctatus*	native
Southwestern toad	*Bufo microscaphus*	native
Great plains toad	*Bufo cognatus*	native
Colorado river toad[A]	*Bufo alvarius*	native
Spadefoot toads	**Pelobatidae**	
Couch's spadefoot toad	*Scaphiopus couchi*	native
True frogs	**Ranidae**	
Lowland leopard frog	*Rana yavapaiensis*	native
American bullfrog[B]	*Rana catesbeiana*	exotic
Rio Grand leopard frog[B]	*Rana berlandieri*	exotic
Treefrogs	**Hylidae**	
Pacific treefrog[A]	*Hyla regilla*	native
Salamanders	**Order Caudata**	
Mole salamanders	**Ambystomatidae**	
Tiger salamander[B]	*Ambystoma tigrinum*	exotic

[A] The species is undocumented but probably present, based on its known range and documented presence nearby.

[B] The species is possibly present, based on its historic distribution (currently uncommon native species) or known nearby presence (introduced exotic species).

Appendix F. Terrestrial Invertebrates of the Bill Williams River Corridor

Table F1. Terrestrial invertebrate species found within the corridor of the Bill Williams River, Ariz.

Species/group common name	Species/group scientific name	Nativity
	Class Arachnida	
	Order Araneae	
	Theridiiae	
Western widow	*Latrodectus mactans*	native
Miturgidid spiders	**Miturgidae**	
	Syspira sp.	native
Wolf spiders	**Lycosidae**	
	Pardosa sp.	native
	Varicosa gosiuta	native
Spitting spiders	**Scytodidae**	
	Scytodes sp.	native
Scorpions	**Order Scorpionidae**	
	Iuridae	
Giant hairy desert scorpion	*Hadrurus arizonensis*	native
	Buthidae	
Centeroides scorpions	*Centeroides exilicauda*	native
	Vaejovidae	
Vajovid scorpions	*Vaejovis confusus*	native
	Order Pseudoscorpionidae	
Daddy longlegs	**Phalangiidae**	
	OPILIONES	
	Gagrellidae	
Harvestman	*Trachyrhinus marmoratus*	native
	Order Uropygi	
	Thelyphonidae	
Vinegarone	*Mastigopoproctus giganteus*	native
	Order Amblypygi	
Tailless whipscorpion	**Tarantulidae**	
	Paraphrynus mexicanus	native
	Order Solpugida	
	Eremobatidae	
Windscorpion	*Eremobates gracilidens*	native
	Eremothera sculpturata	native
	Class Insecta (Hextapoda)	
	Odred Dermatera	
	Labiduridae	
Riparian earwig	*Labidura riparia*	native
	Order Orthoptera	
	Acrididae	
Grasshopper	*Schistocerca nitens*	native
	Tridactylidae	
Pygmy mole cricket	*Neotridactylus apicalis*	native
	Gryllidae	
Cricket	*Gryllus* sp.	
	Order Mantodea	
	Mantidae	
Agile ground mantis	*Litaneutra minor*	native

Table F1. Terrestrial invertebrate species found within the corridor of the Bill Williams River, Ariz. —Continued

Species/group common name	Species/group scientific name	Nativity
	Order Blattaria	
	Blattellidae	
Cockroach	*Blatella vaga*	
	Polyphagidae	
Cockroach	*Argenivaga bolliana*	
Webspinners	**Order Embiidina**	
	Order Hemiptera	
	Coreidae	
Leaf-footed bug	*Leptoglossus clypealis*	native
	Reduviidae	
	Zelus renardii	native
Assassin bug	*Reduvius personatus*	native
	Pentatomidae	
Predatory stink bug	*Podisus acutissimus*	native
	Order Homoptera	
	Tibicinidae	
Apache cicada	*Diceroprocta apache*	native
	Order Neuroptera	
Antlions	**Myremeleontidae**	
	Order Coleoptera	
Ground beetles	**Carabidae**	
	Pinacodera sp.	native
Metallic wood-boring beetles	**Buprestidae**	
	Acmaeodera coneata	
	Anthaxia (*Melanthaxia*) sp.	
Tiger beetles	**Cicindelidae**	
	Megacephala carolina	
Scarab beetles	**Scarabaeidae**	
	Anomala flavilla	native
	Anomala nocturnus	native
	Cyclocephala hirta	native
	Cyclocephala longula	native
	Diplotaxis anxius	native
	Diplotaxis knausii	native
June beetle	*Polyphylla cavifrons*	native
	Stenosphenus debilis	native
	Dryopidae	
Long-toed water beetle	*Posthelichus productus*	native
Click beetles	**Elateridae**	
	Bostrichidae	
Apple twig borer	*Amphicerus bicaudatus*	
	Chrysomelididae	
Leaf beetle	*Plagiodera arizonae*	native

Table F1. Terrestrial invertebrate species found within the corridor of the Bill Williams River, Ariz. —Continued

Species/group common name	Species/group scientific name	Nativity
	Coccinellidae	
Ladybird beetle	*Chilocorus cacti*	native
Nine-spotted ladybug beetle	*Coccinella septempunctata*	native
Convergent ladybug beetle	*Hippodamia convergens*	native
Mealybug destroyer	*Cryptolaemus montrouzieri*	exotic
	Tenebrionidae	
Darkling beetle	*Diapersis* sp.	native
	Pechalium subvittatum	native
	Eleodes armata	native
	Eleodes sp.	native
	Zopherus sp.	native
	Centrioptera sp.	native
	Cryptoglossa verrucosa	native
Long-horned beetles	**Cerambycidae**	
Cottonwood twig borer	*Oberea quadricallosa*	native
Giant root borer	*Prionus* sp.	native
	Meloidae	
Arizona blister beetle	*Lytta auriculata*	native
	Zonitis punctipennis	native
Leaf Beetles	**Chrysomelidae**	
	Plagiodera sp.	native
	Plagiodera arizonae	native
	Cryptocephalus binotatus	native
Weevils	**Curculionidae**	
	Ophyrastes sp.	native
	Order Diptera	
Mosquitos	**Culicidae**	
	Culoseta inornata	
	Culex quinquefasciatus	
	Chaoborinae	
	Chaoborus sp.	native
Horse flies	**Tabanidae**	
	Tabanus sp.	native
	Silvius sp.	native
Mydas flies	**Mydidae**	
	Opomydas limbatus	native
	Pseudonomoneura californica	native
	Mydas ventralis	
Robber flies	**Asilidae**	
	Eccritosia zamon	native
	Efferia spp.	
March flies	**Bibionidae**	
	Bibiodes halteralis	native

Table F1. Terrestrial invertebrate species found within the corridor of the Bill Williams River, Ariz. —Continued

Species/group common name	Species/group scientific name	Nativity
	Order Lepidoptera	
	Danaidae	
Monarch	*Danaus plexippus*	native
Queen	*Danaus gilippus*	native
	Nymphalidae	
Painted lady	*Vanessa (Cynthia) cardui*	native
Mourning cloak	*Nymphalis antiopa*	native
Viceroy	*Limenitis (Basilarchia) archippus*	
Common buckeye	*Jumonia coenia*	native
Red admiral	*Vanessa atalanta*	native
Red spotted purple	*Limenitis arthemis*	native
Variegated fritillary	*Euptoieta claudia*	native
	Papilionidae	
Black swallowtail	*Papilio polyxenes*	native
Zelicaon (Anise) swallowtail	*Papilio zelicaon*	native
	Pieridae	
Checkered white	*Pontia protodice*	native
Orange (Alfalfa) sulphur	*Colias eurytheme*	native
Cloudless sulphur	*Phoebis sennae*	native
Sleepy orange (Nicippe yellow)	*Eureme nicippe*	native
Dainty sulphur	*Nathalis iole*	native
	Libytheidae	
Snout butterfly	*Libytheana carinenta*	native
	Riodinidae	
Fatal metalmark	*Calephelis nemesis*	native
Wright's metalmark	*Calephelis wrighti*	native
Palmer's metalmark	*Apodemia palmeri*	native
Mormon metalmark	*Apodemia mormo*	native
	Lycaenidae	
Marine blue	*Leptotes marina*	native
Pygmy blue	*Brephidium exilis*	native
Cerannus blue	*Hemiargus ceraunus*	native
Reakirt's blue	*Hemiargus isola*	native
Great purple hairstreak	*Atlides halesus*	native
Gray hairstreak	*Strymon melinus*	native
Leda hairstreak	*Ministrymon leda*	native
	Hesperiidae	
Common checkered skipper	*Pyrgus communis*	native
Small checkered skipper	*Pyrugus scriptura*	native
MacNiell's sootywing skipper	*Hesperopsis gracielae*	native
Funeral duskywing	*Erynnis funeralis*	native
Northern white-skipper	*Heliopetes ericetorum*	native
Orange skipperling	*Copaedes aurantiacus*	native
Fiery skipper	*Hylephila phyleus*	native
Euphala skipper	*Lerodea eufala*	native

Table F1. Terrestrial invertebrate species found within the corridor of the Bill Williams River, Ariz. —Continued

Species/group common name	Species/group scientific name	Nativity
	Noctuidae	
Black witch	*Ascalapha odorata*	native
	Cossidae	
Carpenter moth	*Prionoxystus robiniae*	
	Sphingidae	
Big popular sphinx	*Pachysphinx modesta*	native
White-lined sphinx	*Hyles lineata*	native
Tobacco hornworm moth	*Manduca sexta*	native
Ants and wasps	**Order Hymenoptera**	
	Formicidae	
Harvester ant	*Pogonomyrmex californicus*	native
Native Fire ant	*Solenopsis aurea*	native
	Apidae	
European honey bee	*Apis mellifera*	exotic
	Anthophoridae	
Large carpenter bee	*Xylocopa varipuncta*	native
	Anthophora sp.	native
	Diadasia sp.	native
	Bethylidae	
Bethylid	*Epyris myrmecophilus*	native
	Chrysididae	
Cuckoo wasp	*Parnopes concinnus*	native
Pteromalid wasp	**Pteromalidae**	
	Ichneumonidae	
Ichneumonid wasps	*Compsocryptus apicalis*	native
	Melanichneumon sp.	native
	Netalia sp.	native
Sphecid wasps	**Sphecidae**	
Thread-waisted wasp	*Ammophila aberti*	native
	Ammophila sp.	native
	Bembecinus quinquespinosus	native
Sand wasp	*Bembix melanaspis*	native
	Chalybion californicum	native
	Liris argentata	native
	Liris muspa	native
	Liris beata	native
	Microbembex aurata	native
	Microbombex nigrifons	native
	Moniaecera sp.	native
	Philanthus gibbosus	native
	Prionx foxi	native
Black and yellow mud dauber	*Sceliphron caementarium*	native
	Trypoxylon sp.	native

Table F1. Terrestrial invertebrate species found within the corridor of the Bill Williams River, Ariz. —Continued

Species/group common name	Species/group scientific name	Nativity
	Halictidae	
Green metalic bee	*Dialictus* sp.	native
	Agapostemon sp.	native
	Tiphiidae	
Five-banded tiphiid wasp	*Myzinum quinquecinctum*	native
	Myzinum spp.	native
	Colocistis brevis	native
	Colocistis castanea	native
	Paratiphia sp.	native
	Tiphia sp.	native
	Mutillidae	
Thistledown velvet ant	*Dasymutilla gloriosa*	native
Red velvet ant	*Dasymutilla magnifica*	native
Velvet ant	*Dasymutilla satanas*	native
	Chyphotes spp.	native
	Photopsis sp.	native
	Pompilidae	
Spider wasp	*Ageniella joannae*	native
	Agenioideus birkmanni	native
	Anoplius fulgidus	native
	Aporinellus fasciatus	native
	Aporinellus taeniatus	native
	Apornellus medianus	native
	Pepsis pallidolimbata	native
	Pepsis thisbe	native
	Pompilus parvulus	native
	Scoliidae	
Scarab hunter wasp	*Campsomeris tolteca*	native
	Megachilidae	
Mason bee	*Osmia* sp.	native
	Formicidae	
Rough harvester ant	*Pogonomyrmex rugosus*	native
	Vespidae	
Paper wasp	*Polistes* sp.	native
	Pterocheilus pimorum	native