Hydrologic and Geomorphic Characteristics of the Bill Williams River, Arizona

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INTRODUCTION

The Bill Williams River system drains more than 5200 mi$^2$ of west-central Arizona. It is the largest tributary of the Colorado River between the Virgin River and the Gila River. However, the name “Bill Williams River” is applied to a relatively short reach of this major drainage system—from the confluence of the Big Sandy and Santa Maria rivers to the Colorado River confluence at Lake Havasu (Figure 1). The watershed of the Bill Williams River spans very diverse physiography, however, ranging from high elevation forested mountains in the Central Highlands and low-lying, rugged desert mountains in the western Sonoran Desert. Historically, the hydrologic regime of the Bill Williams River was generally similar to its comparably sized counterparts to the east—the Verde and Salt Rivers. However, natural streamflow in the Bill Williams River is more variable overall than in these rivers.

Since 1969, the hydrologic regime of the Bill Williams River has been dramatically altered by flow regulation through Alamo Dam, which is located just below the Big Sandy - Santa Maria confluence. Alteration of the hydrologic regime has involved extreme reduction of peak discharges (up to 95%) and several periods of protracted releases of low to moderate discharges. These conditions are not even remotely comparable to the natural streamflow patterns that had controlled the geomorphology of the river channel prior to the construction of the dam. Thus, changes in channel position and geometry since 1969 reflect the closely interrelated effects of streamflow regulation practices on changes in riparian vegetation density, sediment transport and storage, and streamflow hydraulics.

The objectives of this report are to characterize the general geomorphology and hydrology of the Bill Williams River. The relatively recent history of channel changes on the Bill Williams River is characterized with two sets of detailed maps derived from examination and interpretation of aerial photographs from 1953 and 1995. In conjunction with the photograph analysis and mapping, aspects of the hydrology of the BWR are also presented. For the purposes of the River Navigability Study, a stipulated goal of the present study was to define “ordinary high and low watermarks” along the Bill Williams River. This is a challenging task because these terms do not have a clearly meaningful physical or statistical basis; furthermore since the river’s flow regime has been so dramatically altered by flow regulation, it is difficult to address questions involving “ordinary” conditions on the river. In attempting to deal with
Gaging Stations shown on map:

1. Bill Williams River at Planet, Arizona (5140 mi³)
2. Bill Williams River below Alamo Dam (4633 mi³)
3. Bill Williams River near Alamo, Arizona (4730 mi³)
4. Santa Maria River near Alamo, Arizona (1493 mi³)
5. Santa Maria River near Bagdad, Arizona (1128 mi³)
6. Big Sandy River near Wikieup, Arizona (2742 mi³)

*Discharge data as reported by USGS, reason for discrepancy unknown

Figure 1. Map of the Bill Williams River Basin, Arizona.
these issues, our approach was to delineate boundaries of the high and low flow channels in
the pre-dam and post-dam periods from the basis of the earliest and most recent available
aerial photographs. The mapping approach that has been adopted results in a characterization
of the geomorphology of the river from which the spatial distribution of ordinary high and
low watermarks, however defined, should be obtainable.

HYDROLOGY OF THE BILL WILLIAMS RIVER

The Bill Williams River (BWR) begins at the confluence of the Big Sandy and Santa
Maria rivers. Prior to the construction of Alamo Dam, this junction was located in a wide
alluvial valley that is currently occupied by Alamo Reservoir. Consequently, the BWR now
begins at the base of the dam. The river flows for approximately 35 miles through a series of
canyons and alluvial valleys before it terminates as a delta in Lake Havasu near the U.S.
Highway 95 bridge crossing.

At the site of Alamo Dam, the contributing drainage area to the BWR is approximately
4330 mi$^2$. The Big Sandy River basin constitutes 65% (~2510 mi$^2$) of this area, and the Santa
Maria River basin constitutes the remaining 35% (~1520 mi$^2$). At its mouth, the BWR drains
an estimated 5200 mi$^2$, which makes it slightly larger than the Salt River drainage area above
Roosevelt Lake and only slightly smaller than the Verde River drainage area above
Horseshoe Reservoir. These general physiographic similarities are underscored by the pre­
dam record of flooding on the BWR. Several of the largest reported historical peaks on the
BWR are larger than the largest peaks reported for the Salt and the Verde rivers. However, it
is not clear that the earliest and largest estimates are particularly well substantiated.

Gaging Stations

Stream gaging records in the Bill Williams River basin are limited in spatial and temporal
scope. The Big Sandy River has 30 years of continuous record, the Santa Maria River has a
discontinuous composite record length of 51 years, and the Bill Williams River has a
composite record length of 67 years. Each of the gaging stations are shown in Figure 1 and
the annual flood series from each site is shown in Figures 2 and 3. There are a few other
gages in the basin with much shorter, typically discontinuous records. These records are not
provided in the report.
Figure 2. Annual flood series for the major tributaries to the Bill Williams River
Figure 3. Annual flood series for the stream gages on the Bill Williams River.
**Big Sandy River.**

The Big Sandy River is the predominant contributor to most streamflows on the Bill Williams River. It begins at the confluence of Trout and Knight Creeks approximately 30 miles southwest of Kingman, Arizona. The Big Sandy watershed encompasses most of the eastern half of the Hualapai Mountains from which runoff is received through many small tributaries. The most significant contribution of runoff comes from streams at the north end and along the east side of the Big Sandy Valley (e.g. Knight Creek, Trout Creek, and Burro Creek) where the basin encompasses a large portion of the high, rugged, and massive Mohon Mountains, Bozarth Mesa, Aquarius Mountains, and Aquarius Cliffs.

The Big Sandy River gaging station--Big Sandy River near Wikieup, Arizona--is actually located near the old townsite of Signal, Arizona about 30 miles south of Wikieup and approximately 15 miles upstream of the confluence with the Santa Maria. At the gage, the Big Sandy River drains 2810 mi$^2$. The official period of record is 1966-1996. The flood of record is 68,700 cfs, which was recorded on February 9, 1993. Much of this runoff came from the Burro Creek watershed; a peak flood discharge estimated at 55,300 cfs occurred near the mouth of Burro Creek 3 hours prior to the peak discharge on Big Sandy River. The confluence of the Big Sandy and Burro Creek is 7 miles upstream of the gaging station.

The annual flood series for the Big Sandy River is shown in Figure 2a. The continuous record is from 1966 to the present, and there is one particularly notable historical discharge estimate of 100,000 cfs reported from “near Signal” in September, 1939 (Smith and Heckler, 1955). This site is quite close to the present site of the gaging station. No attempt was made to assess the veracity of this extraordinary discharge estimate for the purposes of this report. It is, however, probably best viewed as a maximum estimate. Descriptive statistics for this stream gage are listed in Table 1.

**Santa Maria River.**

The Santa Maria River drains approximately 1520 mi$^2$ of rugged but generally lower-lying and more arid terrain than is characteristic of much of the Big Sandy River watershed. There have been two different gaging stations on the Santa Maria River, and the composite period of record is 1939 to the present. The flood of record is 33,600 cfs (at the gage near Alamo), which occurred in August 1951. The station “Santa Maria River near Alamo” was
moved upstream to the station “Santa Maria River near Bagdad” in 1967 so as to eliminate the influence of inundation and backwater effects from Alamo Lake. The resultant decrease in the contributing drainage area was 311 mi². The location change had a marked effect on the daily flow characteristics of the river. The station near Alamo has a 27 year record (1939-1966) and recorded no days of zero flow (although there are 396 missing values). The discontinuous record for the station near Bagdad is also 27 years long and recorded 6474 days of zero flow (only 382 missing values). This means that for approximately 65% of the 9662 days in the record, there was no streamflow at the gage. Some descriptive statistics of the daily streamflow records are summarized in Table 1.
Table 1. Daily Streamflow characteristics of the two principal tributaries of the Bill Williams River. Discharges are in cubic feet per second.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>BIG SANDY RIVER NEAR WIKIEUP</th>
<th>SANTA MARIA RIVER NEAR ALAMO</th>
<th>SANTA MARIA RIVER NEAR BAGDAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEAN</td>
<td>94</td>
<td>34</td>
<td>56 / 72</td>
</tr>
<tr>
<td>STANDARD DEVIATION</td>
<td>723</td>
<td>325</td>
<td>397 / 263</td>
</tr>
<tr>
<td>COEFFICIENT OF VARIATION</td>
<td>7.7</td>
<td>9.6</td>
<td>7.1 / 3.6</td>
</tr>
<tr>
<td>COUNT</td>
<td>10778</td>
<td>9648</td>
<td>7106 / 2556</td>
</tr>
<tr>
<td>ZERO VALUES</td>
<td>0</td>
<td>0</td>
<td>4941 / 1534</td>
</tr>
<tr>
<td>MISSING VALUES</td>
<td>382</td>
<td>396</td>
<td>334 / 48</td>
</tr>
<tr>
<td>MINIMUM</td>
<td>2.5</td>
<td>0.8</td>
<td>0 / 0</td>
</tr>
<tr>
<td>MAXIMUM</td>
<td>26100</td>
<td>15500</td>
<td>8410 / 4810</td>
</tr>
<tr>
<td>Skew</td>
<td>18.6</td>
<td>25.1</td>
<td>11.0 / 9.8</td>
</tr>
<tr>
<td>Median</td>
<td>6</td>
<td>3</td>
<td>44 / 24</td>
</tr>
<tr>
<td>Mode</td>
<td>8</td>
<td>3</td>
<td>6 / 5</td>
</tr>
</tbody>
</table>
Bill Williams River.

There have been two primary gaging stations on the Bill Williams River. Over time, the history of the gages has become somewhat obscured and discharge values reported for some gages in relatively recent literature are not necessarily representative of what occurred at the gage in question. For example, the earliest gaging stations on the BWR were “Bill Williams River near Swansea (1913-1915), followed by “Williams River near Swansea” (1913-1915), “Williams River at Planet” (1928-1943), and finally “Bill Williams River near Planet” (1943-1946). Examination of historical surface water records indicates that each of these corresponds to the same station (indicated by the number 1 on the map in Figure 1). Listed in the station record for the Bill Williams River near Planet are three exceptionally large floods in 1891, 1916, and 1927. According to Patterson and Somers (1960), these values are estimates made “on the basis of floodmarks in Striped Canyon, about 23 miles upstream”. This site is very near the present location of Alamo Dam and thus accounts for a difference in drainage area from the gage near Planet of approximately 500 mi². This 23 mile stretch also includes several wide alluvial reaches that would undoubtedly involve attenuation of the peak from the upper gorge. Thus these estimates relate more directly to the Alamo gage site, and not the Planet gage site. This is how the data are depicted in Fig. 3a.

In 1939, a gage on the Bill Williams River was established near Alamo, Arizona. Patterson and Somers report a flood stage estimate from this site for a large flood in 1937, but the continuous record begins in 1940. The 1937 stage estimate has subsequently been reported as a discharge value by Garrett and Gellenbeck (1991). This value is shown on the plot in Figure 3b. In 1968, the gage was moved to a point just below Alamo Dam.

Large Historical Floods Reported From The Bill Williams River Basin

As was noted previously the pre-dam flood history of the Bill Williams River rivals that of the Salt and Verde Rivers in terms of the reported peak discharge magnitudes. However, some of the earliest estimates are not particularly well substantiated. Clearly, though, the floods were large. For example, the reported magnitude of the February 1891 flood is 200,000 cfs, making it the largest reported flood discharge from a basin of approximately 5000 mi² in the lower Colorado River basin. Unfortunately, original field notes and U.S. Geological Survey memos regarding these particularly outstanding estimates could not be obtained during the preparation of this report. Some anomalies in the various flood series of
the Bill Williams that are apparent from the published information include:

1. A progressive decrease in the reported discharges of large floods between 1891 and the construction of the dam. This trend is particularly obvious in the early part of the century.
2. Large floods originally reported only as gage heights were reported as peak discharges in subsequent reports with minimal or no qualification.
3. Reported flood dates originally qualified with terms like “probably” were reported as matter-of-fact in subsequent reports.
4. Reports of discharges that were made at a point 23 miles upstream from the gage in question constituting a 500 mi$^2$ difference in the contributing drainage area.

Given these factors and in absence of follow-up studies on the outstanding historical flood discharge estimates, it is prudent to treat these values as likely maximum discharges for the floods in question.

Table 2. Comparison of pre-dam and post-dam characteristics of daily streamflow on the Bill Williams River near Alamo and below Alamo Dam.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pre-Dam</th>
<th>Post-Dam</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>92.56</td>
<td>160.25</td>
<td>73%</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>687.78</td>
<td>531.69</td>
<td>-23%</td>
</tr>
<tr>
<td>Coefficient of Variation</td>
<td>7.43</td>
<td>3.32</td>
<td>-55%</td>
</tr>
<tr>
<td>Count</td>
<td>10684</td>
<td>9709</td>
<td>975</td>
</tr>
<tr>
<td>Zero values</td>
<td>0</td>
<td>696</td>
<td>696</td>
</tr>
<tr>
<td>Missing values</td>
<td>256</td>
<td>183</td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>.05</td>
<td>0</td>
<td>.05</td>
</tr>
<tr>
<td>Maximum</td>
<td>25200</td>
<td>6980</td>
<td>-72%</td>
</tr>
<tr>
<td>Skew</td>
<td>19.92</td>
<td>7.35</td>
<td>-63%</td>
</tr>
<tr>
<td>Median</td>
<td>9.4</td>
<td>12</td>
<td>28%</td>
</tr>
<tr>
<td>Mode</td>
<td>11</td>
<td>0</td>
<td>-</td>
</tr>
</tbody>
</table>

Effect Of Alamo Dam On Streamflow In The Bill Williams River

Some descriptive statistics of the pre-dam and post-dam average daily streamflow values are compared in Table 2. Large differences in most of the parameters reflect some of the effects of flow regulation on the “natural” hydrology of the Bill Williams River. Values
expressed as percentages indicate change in the stated variable from pre-dam to post-dam conditions. For the most part these changes record the influence of the flow regulation at the dam but secular climatic variability probably has affected some of the variables as well. Streamflow variability has been reduced by the dam, which is not surprising.

The most striking hydrological characteristic of the Bill Williams River flow regime in the twentieth century is the alteration of the relationship between instantaneous peak discharge and trends in average daily, monthly, and annual streamflow values associated with flow regulation by Alamo Dam. This is clearly illustrated in Figure 4, where the annual peak series is shown in direct relation to the time series of monthly runoff for the period 1940 to 1995. The most obvious feature of the annual flood series is that the post-dam peaks are too small to render on the graph, which is scaled for the pre-dam peaks. When considered in relation to the exceptionally large historical peak discharges, the reduction is extreme. The largest post-dam instantaneous peak discharge is 6980 cfs, which occurred in March of 1993. This value is less than 11% of the maximum instantaneous peak in the official period of record and less than 5% of the largest reported historical peak discharge. In contrast, the total annual volume of flow has remained essentially the same and in fact shows an apparent increase due simply to the occurrence of exceptional flows in 1980 and 1993. 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.

Another interesting consequence of flow regulation by Alamo Dam is the increase in the frequency of days with zero flow. According to the record, no days of zero flows occurred prior to the construction of the dam; in contrast, 975 days of zero flow are reported for the post-dam period of record (approximately 10% of the total period). The statistical characteristics of the streamflow regime have been dramatically altered by the effect of flow regulation at the dam. This is clear from the comparison of pre and post-dam conditions.
Figure 4. Comparison of total monthly flow and instantaneous peak discharges reported from the Bill Williams gage near Alamo (1940-1968) and below Alamo Dam (1969-1995).
Figure 5. Log-Pearson Type 3 duration-frequency analysis of daily flow values for the Bill Williams River at Alamo (pre-dam) and below Alamo Dam (post-dam).
shown in Table 2. Flow-duration statistics have also changed significantly (Table 3, Figure 5). Exceedance probabilities of annual maximum daily streamflow magnitudes calculated for pre-dam and post-dam conditions indicate an extreme shift in the predicted distribution of T-year flow values. Of course, flow regulation practices violate assumptions in the analysis, but the comparison is instructive. Note that the maximum discharge released through the dam (6980 cfs) is shown with a horizontal line and it corresponds to an event with a recurrence interval of approximately 18-20 years. This is apparently the operating constraint of the dam, indicating that the analysis is largely spurious. This value corresponds to the predicted 3-4 year event in terms of the pre-dam hydrology of the system.

Prior to the construction of Alamo Dam, the natural flow regime of the BWR was one of intermittent flows of widely varying magnitudes. In general, the highest sustained flows were typical of winter months and the lowest flows were typical of the dry late spring and early summer period. In this period of time, none of the gages on the Bill Williams River reported instances of zero flow, although the streamflow was characteristically intermittent, with subsurface flow occurring in the alluvial basins and surface flow through the narrow gorges. Following construction of the dam, streamflow generally follows the same seasonal patterns although protracted releases have extended streamflow well beyond its typical temporal range.
Table 3. Duration-Frequency Statistics for Daily Streamflow on the Bill Williams River, pre-dam and post-dam.

<table>
<thead>
<tr>
<th>Exceedance Probability</th>
<th>Recurrence Interval</th>
<th>LP-3 Predicted Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Post-Dam</td>
</tr>
<tr>
<td>0.005</td>
<td>200</td>
<td>25,200</td>
</tr>
<tr>
<td>0.01</td>
<td>100</td>
<td>19,000</td>
</tr>
<tr>
<td>0.02</td>
<td>50</td>
<td>13,700</td>
</tr>
<tr>
<td>0.025</td>
<td>40</td>
<td>12,100</td>
</tr>
<tr>
<td>0.04</td>
<td>25</td>
<td>9,250</td>
</tr>
<tr>
<td>0.05</td>
<td>20</td>
<td>8,020</td>
</tr>
<tr>
<td>0.1</td>
<td>10</td>
<td>4,790</td>
</tr>
<tr>
<td>0.2</td>
<td>5</td>
<td>2,440</td>
</tr>
<tr>
<td>0.3</td>
<td>3.33</td>
<td>1,440</td>
</tr>
<tr>
<td>0.4</td>
<td>2.5</td>
<td>897</td>
</tr>
<tr>
<td>0.5</td>
<td>2</td>
<td>564</td>
</tr>
<tr>
<td>0.6</td>
<td>1.66</td>
<td>347</td>
</tr>
<tr>
<td>0.7</td>
<td>1.43</td>
<td>201</td>
</tr>
<tr>
<td>0.8</td>
<td>1.25</td>
<td>103</td>
</tr>
<tr>
<td>0.9</td>
<td>1.11</td>
<td>38.4</td>
</tr>
<tr>
<td>0.95</td>
<td>1.053</td>
<td>16.2</td>
</tr>
<tr>
<td>0.96</td>
<td>1.042</td>
<td>12.4</td>
</tr>
<tr>
<td>0.975</td>
<td>1.026</td>
<td>7.32</td>
</tr>
<tr>
<td>0.98</td>
<td>1.02</td>
<td>5.75</td>
</tr>
<tr>
<td>0.99</td>
<td>1.01</td>
<td>2.79</td>
</tr>
<tr>
<td>0.995</td>
<td>1.005</td>
<td>1.40</td>
</tr>
</tbody>
</table>

GEOMORPHOLOGY OF THE BILL WILLIAMS RIVER CHANNEL

The Bill Williams River channel is characterized by a series of relatively narrow gorges that are separated by distinctly wider, alluvial reaches. Photographic and field evidence indicates that the bed of the river is filled with alluvium throughout the length of the river. It is likely that bedrock is particularly shallow in the narrow gorge downstream from the dam, and maybe in other narrow canyon reaches as well. At low flows, the river follows a braided pattern characterized by relatively low sinuosity channels separated by medial bars composed of sand and gravel. During high flows (prior to the dam) the channel has apparently occupied
all of the late Holocene floodplain except in some peripheral portions of the wide alluvial valleys. 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.

**Interpretation of Historical Aerial Photographs**

We examined a series of historical aerial photographs to characterize the geomorphology of the BWR channel. We used seven sets of aerial photographs that covered the length of the Bill Williams River—1953, 1964, 1976, 1985, 1992, 1993, and 1995. Of these, two sets were analyzed in detail—1953 and 1995. These particular sets were chosen for several reasons:

1. The 1953 set was the earliest available series of high-quality, large-scale photos.
2. A series of large floods that were typical of the pre-dam hydrology of the river occurred in the years preceding 1953.
3. The 1995 set was the most recent available series of aerial photographs
4. The 1995 photos were taken during and following the second largest sustained release of streamflow through Alamo Dam since its construction. The prior largest (record) release was in 1993.

Thus, these two sets of photos serve to bracket a critical and unique period in the recent history of the Bill Williams River. Analysis and mapping of the 1953 photos establishes the "natural" geomorphic framework of the river and the 1995 photos show its present state.

Comparison of these two photo series reveals the cumulative change that transpired over the intervening 42 years. Similarly detailed analyses of each of the photo sets between these two end dates would reveal changes that have subsequently been overprinted by streamflow in the intervening period, but this level of detail was not feasible given the available resources for the project. Such an approach is highly recommended for subsequent attempts to document progressive changes in channel geomorphology and riparian vegetation density and distribution resulting from the alteration of the flow regime imposed by Alamo Dam.

Over the period 1953-1969, no flows with magnitudes in excess of the most recent large flood preceding the 1953 photos (August 1951; Peak discharge: 65,100 cfs) were recorded on the Bill Williams. Since 1968, no flows even approaching such flood magnitudes have occurred. Thus the changes that have occurred over the interval spanned by the photos have been largely restricted to the lowest series of alluvial surfaces along the river. Lateral erosion of many of the higher surfaces has also occurred. Comparison of the entire chronology of
aerial photographs indicates that much of this erosion occurred during the sustained streamflow releases of 1980, 1993 and 1995 (see Figure 4). Several figures are included in this report that highlight progressive changes in key reaches at roughly decadal or bi-decadal intervals over the 42 year period and thus help to supplement the mapping.

Methods of Map Preparation

In preparing the maps, the aerial photographs were analyzed stereoscopically and distinct channel features were identified and outlined on mylar overlays. Ultimately, a continuous strip of the river from Alamo Dam to Lake Havasu (approximately to the bridge crossing at Highway 95) was mapped this way. These photo mapping was then transferred to the appropriate 7.5 minute USGS topographic quadrangle.

This method of manually transferring line work based on photos to geodetically corrected base maps is handicapped by the effects of distortion in the aerial photographs. This problem was particularly pronounced in some broad reaches of the river characterized by few distinct landmarks. In these instances, xerographic reduction of the overlays to the approximate map scale was performed with some success. In other instances, the photos were scanned and subjected to very simplified computer manipulation in Adobe Photoshop™ so as to try to “rubber-sheet” the photos to the base map using scaling, skewing, and rotating routines. Figures in this report that show aerial photograph comparisons were prepared in this way. Any subsequent study of the morphological evolution of the Bill Williams River should take advantage of recent advances in GIS modeling and computerized photo matching to precisely illustrate the time series of channel change (Hilmes and Liebermann, 1996).

In the photo analysis, greatest emphasis was placed on the 1953 photos for establishing the fluvial geomorphic framework of the river. This was because of the exceptional clarity and large-scale (~1:18,000) of these photos, the fact that most of the higher surfaces have remained largely intact due to the altered flow regime, and subsequent increases in the density of riparian vegetation that have reduced the relative precision of photo interpretation in some areas.

Explanation of Mapping

The 1953 aerial photographs were used to characterize the pre-dam geomorphology of the Bill Williams River channel. The clarity of these photos, the lack of post-dam riparian vegetation growth, and the general lack of agricultural development made these photos the
best choice for this purpose. Because of the influence of flow reductions by Alamo Dam, the
Bill Williams River has generally occupied a far smaller width of the canyon thus effectively
abandoning many of the active, high-flow related alluvial surfaces present in 1953.
Therefore, much of the geomorphology peripheral to the lowest surfaces in 1953 remains to
this day—although considerable lateral erosion of some abandoned surfaces has occurred.
The mapping of the 1953 photos establishes the geomorphic framework for evaluation of
subsequent, principally post-dam changes in channel geometry and pattern.

There are four dominant alluvial surfaces along the Bill Williams River. In some areas,
six levels are recognizable in the aerial photographs. These two additional levels have been
classified for the purposes of this report as subdivisions of two of the main group members.
Each of the surfaces has been delineated on the basis of the following criteria: topographic
position (i.e. elevation-based hierarchy), vegetation density, and lateral position relative to
other surfaces and channel boundaries. The last criteria applies to areas that have been
designated as likely fine-grained flood deposits along the perimeter of the channel.

Generally, the first two criteria are the most important for differentiating alluvial
surfaces. They also are positively correlated in most instances—the relative density of
vegetation increases with elevation of the surface. This is a simple consequence of the
frequency of inundation by flood flows along the river. The higher surfaces are inundated
less frequently than the lower surfaces. (Note, these generalizations only apply to the pre­
dam situation). There are important exceptions to this generalization. In areas characterized
by significant amounts of riparian vegetation (typically in areas where subsurface flow
resurfaces, e.g. at the downstream end of the alluvial valleys), the lowest surface may have
the highest density of vegetation. In these instances, topographic position as well as the type
of vegetation are means of differentiating the surfaces.
Map Units - 1953.

Yr: Lowest alluvial surface, water present; inundation frequency very high
Yrv: Same as above, but with relatively dense coverage of riparian vegetation
Y1: Lowest dry alluvial surface; completely devoid of vegetation; inundation frequency is high
Y1a: Slightly higher surface entirely devoid of vegetation. Characterized by small scarp separating it from bounding Y1 or Y2 surfaces.
Y2: Highest surface that is completely or nearly completely devoid of vegetation; inundation frequency moderate to high
Y2a: Slightly higher surface with some vegetation present; frequency of inundation is moderate to high
Y3: Next highest alluvial surface, relatively dense, mature vegetation present; infrequently inundated
Y4: Mixed unit comprising the highest alluvial surface and fine-grained alluvial deposits located along the perimeter of the main channel typically in small re-entrants and niches. Generally, Unit Y4 represents fine-grained flood deposits of varying elevations relative to the main channel. Most Y4 deposits are restricted in spatial extent and were deposited by the largest floods prior to the construction of Alamo Dam.

Map Units - 1995.

Yr: Portion of river channel inundated by 1995 flood. Vegetation sparse or absent. Yrv denotes low, inundated areas characterized by relatively dense vegetation.
Y1: Inundated area with moderate density of vegetation. Flood waters appear to be continuous through these areas, although they are topographically higher than Yr areas. Y1v denotes areas with higher vegetation densities.
Y1a: Highest Inundated surface with highest density of vegetation. Flood waters appear as discontinuous channels separated by bars. In some areas, the vegetation density precludes the assessment of the extent of flood waters.

Study Reaches

For the sake of simplifying the following discussion, the length of the river has been
subdivided into a series of generally distinct subreaches. The subreaches were selected to represent the predominant trends in the morphology of the system. They are differentiated as follows: (1) Alamo Gorge, (2) Reid Valley, (3) Rankin Valley, (4) Pipeline Canyon, (5) Third Gorge, (6) Planet Valley, (7) Havasu Canyon, and (8) the Havasu Delta. Figure 6 is a location map showing the boundaries of each of these reaches.

**Alamo Gorge - 5.5 miles.**

The Alamo Gorge is a spectacular narrow chasm that begins at the base of Alamo Dam. The river follows this gorge for approximately 5.5 miles, at which point it enters the distinctly wider Reid Valley reach. Based on information provided in U.S. Geological Survey surface water reports, the upper portion of Alamo Gorge was once referred to as Striped Canyon, and it was there where several of the historical extreme discharge estimates were made. Because it is so narrow and the mobility of the channel is so limited, this reach was not analyzed for the present study.

**Reid Valley - 2 miles.**

Reid Valley is a roughly semi-circular alluvial valley approximately 1.5 miles wide by 2.5 miles long. It is the first in the series of alluvial valleys that are separated by narrow gorges along the length of the Bill Williams River. It is bounded on the north by the Rawhide Mountains, and the south by the Buckskin Mountains. The valley is occupied by Lincoln Ranch, which has been in operation since at least 1953. Through Reid Valley, there is a high, wide floodplain surface along the south bank where the agricultural activity is concentrated (Figure 7). The north bank of the river is bounded by steep tributary alluvial fans and bedrock slopes of the Rawhide Mountains. The southern edge of the floodplain grades into fine grained distal alluvial fan deposits formed below the mouths of numerous narrow sandstone gorges draining the Buckskin Mountains. It is likely that much of this surface has been isolated from all but the largest floods on the BWR during the past 100 years. Agricultural modification of the floodplain makes it difficult to discern the boundary between the distal fan deposits and the river floodplain, but it is at this contact where the maximum limit of flooding
<table>
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<td>3-Second Gorge</td>
</tr>
<tr>
<td>4-Rankin Valley</td>
</tr>
<tr>
<td>5-Pipeline Canyon</td>
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</table>

**Figure 6.** Locations of study reaches along the Bill Williams River. Reaches are described in the text.
Figure 7. Aerial photo comparison, Reid Valley: 1953-1995
by the BWR is likely to exist.

The map showing cumulative channel changes over the period 1953-1995 (Plate 1) indicates that the primary mechanism of channel change through Reid Valley has been channel narrowing and incision. Several extensive areas designated as Y2 (moderate to high frequency of inundation) have been largely abandoned by the river. Some lateral erosion of the higher surfaces has clearly occurred, but the most recent large release of flow from Alamo Dam was mainly restricted to a limited portion of the low flow channel present in 1953.

**Second Gorge - 1.25 miles.**

This short gorge spans the reach between Reid Valley and Rankin Valley. It is a relatively narrow reach bounded by steep bedrock walls of the Rawhide and Buckskin Mountains. Relatively high-standing alluvial surfaces in this reach are restricted to the inner portions of channel bends, and small embayments along the perimeter of straight sections of the river. Channel change in the second gorge has been minimal. In general the most obvious change is an overall increase in the density of vegetation on the higher surfaces.

**Rankin Valley - 3.25 miles.**

Rankin Valley is the second alluvial valley along the Bill Williams River. The Rankin Valley reach is characterized by a relatively wide alluvial valley that coincides with a prominent westward bend in the river. Through much of the valley the river is bounded by alternating wide alluvial surfaces on either side of the river. Along the northern edge of the river is a broad, relatively low floodplain surface that was likely to have been inundated relatively frequently by pre-dam streamflows. However, only small threads of flow have inundated portions of this surface since the dam was emplaced. This surface coincides with the outer edge of the distinct westward bend of the river and is partially bounded on its south side by a relatively large bedrock island. On the south side of the river is a similar, but slightly higher surface where agricultural activity has been concentrated. This surface was less prone to flooding prior to the construction of the dam, although the photos suggest that inundation of much of the surface was likely during the largest floods.

**Pipeline Canyon - 2.5 miles**

Pipeline Canyon is an irregular canyon reach characterized by a short series of
intermittent broad alluvial reaches of restricted lateral and longitudinal extent. The low-flow channel of the Bill Williams River shifted from the south bank to the north bank in the middle portion of this reach between 1953 and 1995. The protracted, large post-dam flow releases of 1993 and 1995 contributed to locally significant changes in the channel position near the western edge of Figure 8. As a consequence of these shifts, abandoned bars and alluvial terraces were eroded laterally. Vegetation density has increased noticeably through most of this reach. This, coupled with narrowing associated with the abandonment of low terraces has stabilized the channel position in most of the valley.

**Third Gorge - 5.5 Miles**

The Third Gorge is a relatively wide canyon bounded by steep bedrock walls. Beyond Pipeline Canyon, the gorge trends towards the southwest for about 1 mile and then abruptly bends to the north. Upon reaching the volcanic edifice of Black Peak, the river abruptly bends to the west and enters Planet Valley. Geomorphic change in the Third Gorge reach has been controlled by lateral shifts in channel position. Channel narrowing by means of abandonment of low terraces has not been a dominant process in the Third Gorge. In fact, the 1995 dam release discharge covers the entire width of the channel at several points through this reach. The higher alluvial surfaces that remain in this reach have been appreciably trimmed back through lateral erosion associated with channel migration.

**Planet Valley - 6.5 miles**

The east-west-trending Planet Valley is the longest and widest alluvial valley occupied by the Bill Williams River (Figure 9). It is bounded on its north and south sides by high-standing dissected surfaces of relict Pleistocene and late Tertiary alluvial fan surfaces and intervening late Holocene alluvial fans emanating from the Buckskin Mountains on the south and from diverse, distant mountain source areas on the north.

Perhaps the most dramatic changes in the Bill Williams river floodplain during this century have occurred in Planet Valley. This is due almost entirely to flow reduction by Alamo Dam, but has also been spurred by relatively intensive agricultural development of the floodplain beginning sometime between 1953 and 1964. Prior to flow regulation, moderate to large magnitude streamflow events occupied extensive tracts of the Planet Valley. Low flows
Figure 8. Aerial photo comparison, Pipeline Canyon: 1953-1995
Figure 9. Aerial photograph comparison, Planet Valley: 1953-1995
Figure 10. General Land Office survey map of western Planet Valley, February 1916
appear to have consistently remained restricted to the southern edge of the valley through most of its length. This pattern has been in place since at least the extremely large flood on January 19, 1916 which was reportedly 175,000 cfs (from Striped Canyon near Alamo). Interestingly, the earliest available General Land Office Map from this area is based on surveys performed between November 1915 and February 1916, thus bracketing the event. The GLO map of the Planet Valley area is shown in Figure 10. Note the clear demarcation of the low flow channel along the southern margin of the valley and the classification of the remaining valley area to the north as the “high water channel”. Photographic comparisons provided in Figure 9 illustrate the pace of the eventual abandonment of this portion of the valley by all but tributary streamflows.

As the BWR approaches Havasu Canyon (discussed below) its historical tendency has been to veer back toward the center of the valley. Near the entrance to the gorge, perennial surface water reappears and a thick stand of large riparian trees is present. As is evident in Figure 11 and in the geomorphic mapping, this area has been relatively thickly vegetated since at least 1953. It is very likely that much of this particular stand of vegetation had been repeatedly altered, if not largely destroyed by the extremely large flood events in the late nineteenth and early twentieth centuries. The 1953 photos post-date a moderate flood in 1951 (August 29: 65,100 cfs at Alamo) (Figure 3) and the effects of this event are almost certainly reflected in the variable density and age structure of the vegetation. The preceding largest flood was in 1939 (September 6: 73,000 cfs at Planet) and it was followed by a long sequence of low to moderate discharge events in the winter of 1940-1941. All of these events are likely to have influenced the distribution of vegetation in this part of the valley.

Between 1953 and 1964, relatively large-scale agriculture began in Planet Valley and was accompanied at first by some rather ineffective attempts to constrain the path of the river (see Figure 9). A series of parallel berms was constructed across the valley bottom perpendicular to flow. It is evident in the 1964 photos that this approach was largely failing and by as late as 1972, the method was abandoned.

Planet Valley was subjected to protracted, high post-dam stream flow events in 1993 and 1995. Considerable lateral erosion resulted, but minimal to no vertical incision of the channel is apparent. The channel remained restricted to the general position established by 1985. The
Figure 11. Aerial photo comparison, Planet Valley (west end): 1953-1995
extent of flooded area in Planet Valley was a mere fraction of the extent subjected to flooding prior to dam construction.

**Havasu Canyon - 4.5 miles.**

Some of the most complicated fluvial geomorphology of the river is present in Havasu Canyon. It begins at the narrow constriction at the west end of Planet Valley, where jagged cliffs of the Bill Williams Mountains and the Buckskin Mountains jut prominently above the relatively low lying terrain around Planet Valley. The beginning of the gorge is very near the site of the old stream gage “at Planet”. The gorge is characterized by an extremely tortuous course with variable width. Complex assemblages of alluvial surfaces are present throughout the reach.

**Havasu Delta - 4 miles**

The Havasu Delta reach has experienced the least dramatic change overall in the period 1953-1995. The primary change in this reach, as in Havasu Canyon, is an overall increase in vegetation density (Figure 12). Near the end of the reach changes in vegetation density and in the channel geomorphology have been tempered by the influence of changes in the level of Lake Havasu. Note that in the 1953 photos and on Plate 1, Lake Havasu is near its maximum level. In the 1995 photos the lake level is considerably lower.

**DELINEATION OF ORDINARY LOW AND HIGH WATER MARKS**

To aid the Arizona Navigable Stream Adjudication Commission in its evaluation of the Bill Williams River, the ordinary low and high watermark boundaries were mapped for the Bill Williams River. Several qualitative and quantitative procedures have been developed to delineate high and low watermark boundaries. For this investigation, information gathered from field checks, aerial photographs and topographic maps was utilized to delineate the low and high watermark boundaries on the Bill Williams River. The time frame chosen for this delineation is 1995, the date of the youngest set of aerial photographs of the Bill Williams River area that we were able to obtain.

The ordinary low watermark, per ARS § 37-1101, is defined as “the line on the banks of a watercourse created when the water recedes at its regularly recurring lowest stage in normal
Figure 12. Aerial photo comparison, Havasu Delta Reach: 1953-1995
years without reference to unusual droughts.” Though this definition is fairly straightforward when used to describe rivers with a baseflow, ambiguity arises when applying such a definition to the Bill Williams River because it is intermittent or ephemeral in the many of its reaches. First, physical markers on the landscape left by low flows tend to be quickly erased by periodic high flows. Second, even if there were a statistical definition of the ordinary low watermark based on hydrological records, much of the Bill Williams River is not gaged. For these reasons, we consider that low watermark boundaries exist only in the reaches in which there was water at the time the most recent aerial photographs were taken. Along all of the Bill Williams River, the low watermark boundaries were too close together to draw separately, so one line was drawn. The approximate position of the low-flow channel along the river as of April 1995 is depicted in Plates 1 and 2 (Appendix A).

The ordinary high watermark is defined as “that line on the bank established by the fluctuations of water and indicated by physical characteristics such as a clear, natural line impressed on the bank, shelving, changes in the character of the soil, destruction of terrestrial vegetation, the presence of litter and debris, or other appropriate means that consider the characteristics of the surrounding areas.” (33 CFR, Part 328.(e)). We mapped high watermark boundaries using defined channel banks, channel surfaces cleared of vegetation, and changes in vegetation type. Current high-water mark boundaries are most readily defined by the extent of the river channel that was inundated by the 1995 flood. The high-flow channel or channels are shown by the extent of map unit Yr in 1995 on Plates 1 and 2. Note that these areas do not encompass the entire extent of the 1995 flood, but rather the channel areas that were inundated. Thus, low terraces and bars that experienced shallow inundation in 1995 are not included within the ordinary high-water marks.

CONCLUSIONS

The Bill Williams River and its principal tributaries, Big Sandy River and Santa Maria River, form a large, rugged, and diverse watershed that drains most of west-central Arizona. The BWR below the confluence of the Big Sandy and Santa Maria rivers consists of a series of narrow bedrock gorges and much wider alluvial reaches. Completion of Alamo Dam in 1968 profoundly altered hydrology and geomorphology of the BWR. Natural flow conditions on the BWR prior to 1968 were extremely variable. Sustained flows typically were moderate
in the winter months and intermittent in the dry months, but days with no flow were rare. A number of large floods occurred from 1891 to 1953, including the largest estimated peak discharge for a basin of this size in the lower Colorado River basin. There is a progressive decrease in flood peak discharge estimates from 1891 to 1968, however, which suggests that the early flood discharges may have been systematically overestimated. Since the completion of Alamo Dam, flood peak discharges have been much lower. Even during the extremely wet winters of 1993 and 1995, peak discharges downstream of Alamo Dam never exceeded 7,000 cfs. Total flow volumes are similar in the pre-dam and post-dam record, however, and this has resulted in much longer sustained flood flows. In addition, the number of days with no flow has increased substantially.

The absence of large floods on the BWR since the completion of Alamo Dam has also impacted the geomorphology of the river. Analysis of repeat aerial photography indicates that the BWR has eroded laterally into low terraces along its banks since Alamo Dam was completed. Most of this erosion occurred during prolonged periods of stream flow in 1980, 1993, and 1995. Because no moderately large floods have occurred since dam construction, many of the pre-dam channel areas that were formerly devoid of vegetation now sustain moderate to dense riparian vegetation. Changes have been most dramatic in the broad alluvial reaches, which were occasionally entirely inundated by large floods prior to dam construction.

REFERENCES


Appendix A

MAPS SHOWING CHANGES IN THE CHANNEL GEOMORPHOLOGY OF THE BILL WILLIAMS RIVER, ARIZONA 1953-95

by P. Kyle House

(MAPS IN POCKET)
A stage-discharge rating curve is a graphical plot that shows the relationship between the monitored water level at a gaging station (the stage) and the corresponding flow rate (the discharge). The establishment of a reliable stage-discharge relationship is essential at all river gauging stations when continuous-flow data are needed from the continuous stage record.\(^1\) While stage-rating curves most often are used to convert stage data to discharge values, the curves also can be used to do the reverse. Stage-discharge rating curves are provided in this report so that the Arizona Stream Navigability Commission may determine the water heights that correspond to the discharge values given in earlier chapters. A brief description of the meaning and use of stage-discharge rating curves, and examples of curves developed for the Bill Williams River, are provided below.

The stage-discharge relationship is dependent on the nature of the channel section and the length of channel between the site of the gage and the cross-section where the discharge was measured. Channel conditions in natural rivers tend to change over time; hence, stage-discharge relationships also tend to change over time, especially after flood flows. Typically new discharge measurements are made throughout a range of stages on a regular basis by the hydrologists responsible for maintaining USGS streamflow records. The hydrologists plot the discharge measurements against the corresponding stage measurements on log-log graph paper and draw a best-fit line through the points. Because the data are plotted on log-log paper, the data points tend to group in a more linear fashion that makes relationships more apparent to the hydrologists. If the data were plotted on regular arithmetic graph paper, the data points would group into a curve; hence, the name “rating curve” is given to the hand-drawn line through the data points. Each time new measurements are collected, a new stage-

discharge rating curve is created. That rating curve is then used until the next time new discharge measurements are made.

Figure B-1 is an example of such a stage-discharge plot using a log-log scale created for the Santa Cruz River at Tucson from data gathered during the 1955 to 1961 period. There is a great amount of scatter in the data points’ location; that is, the points do not cluster close together. Such scatter often occurs in data collected from rivers with channels composed of sandy, unconsolidated materials. Rivers with bedrock channels tend to have flows that remain in a fixed location with a fixed channel geometry; therefore, their stage-discharge points plot closer together. In contrast, channels in unconsolidated materials tend to shift their locations and dimensions through such processes as scour and deposition within the channel, and the formation and cut-off of channel meanders. Channel changes may occur even as a hydrologist is taking the discharge measurements (D. Ufkes, USGS-Water Resources Division, Tucson, personal communication, 1996). The change in the slope of the line drawn through the data points in Figure B-1 at the stage height of about one foot indicates that there was a change in the channel control governing the stage-discharge relationship in this reach (i.e. there may have been a change in the slope of the river banks). In rivers where flood flows overfill the channels and spill onto floodplains, there may be another break in the slope of the line at higher discharges because the stage-discharge relationship of the within-bank flow may be very different from the stage-discharge relationship of the floodplain flow.

Once the hydrologist establishes a satisfactory rating curve, a rating table is compiled from values of stage and discharge extracted from the rating curve. Table B-1 provides an idealized version of the rating table used for the gage on the Bill Williams River below Alamo Dam for the period October 1, 1970, to August 12, 1971. For this report, we assembled data from historical rating curves and rating tables archived by the USGS offices in Phoenix, Tucson, and Yuma, as well as from recently developed rating tables stored digitally by the USGS offices in Tucson and Phoenix, and by the U.S. Fish and Wildlife Service office located at the Bill Williams National Wildlife Refuge. Table B-2 lists the data available for the Bill Williams River basin.
Figure B-1. Stage-rating data for the Santa Cruz River at Tucson, Arizona. Data points are plotted on a log-log scale. Discharge measurements were gathered 1955-1961.
Table B-1
Rating Table for Bill Williams River below Alamo Dam
October 1, 1970 to August 12, 1971.
U.S.G.S. Station No. 09426000, Table No. 03

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<th>Gage Height (feet)</th>
<th>Discharge (cfs)</th>
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Table B-2. Time periods of stage-discharge rating data for gages in the Bill Williams River Basin.
[Dates listed below indicate the beginning date of the period for which each rating table was used.]

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<th>Rating No.</th>
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<th>Near Parker</th>
<th>At Planet</th>
<th>Big Sandy River</th>
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1 Rating curve for this period was developed from measurements recorded by a supplemental gage.

2 Rating curve for this period was developed from measurements recorded by both the supplemental gage and the main gage.

* These rating data are located at the U.S. Geological Survey's national archive.
We entered the data from the rating curves and rating tables into a computer spreadsheet. Because it is common for a discharge of zero not to correspond to a stage of zero, we subtracted the stage that corresponds to zero flow from all of the stage values for a given record so that water depth, not stage height, would be compared to discharge. We then plotted the data as curves using an arithmetic scale, rather than as straight lines on a log-log scale, to make the graphs easier to read. Figure B-2 illustrates how the stage-discharge relationships at different gages on the Bill Williams River have changed over time. Figure B-3 provides enlargements of the curves presented in Figure B-2 that better show the stage-discharge relationships for lower stage heights.

The following is an example of how to extract information from the rating curves. Table 2 indicated that the Bill Williams River gage below Alamo Dam experienced a daily discharge mean of 160 cfs for the post-dam period of 1968 to 1995. Figure B-4 contains an enlarged illustration of the rating-curve used for the period October 1, 1970, to August 12, 1971. According to this rating curve, a discharge of 160 cfs would have a corresponding water depth of approximately 2 feet.

The earliest rating tables we retrieved from the USGS date to the 1940's and 1950's. Because of the multitude of channel changes that have occurred on the Bill Williams River, and because of the effects of the Alamo Dam, the reader is advised not to use the 1950's curves to determine the water depths corresponding to earlier discharges presented in this report except to get very rough estimates. Table B-3 provides a comparison of the estimated water depth and discharge values extracted from the stage-rating curves of the gages at Planet, near Alamo, and below Alamo Dam.
Figure B-2. Stage-rating curves for three gages along the Bill Williams River.

A. Stage-rating curve for the Bill Williams River near Alamo.

- RT No. 1. 10/1/56 to 3/16/58
- RT No. 4. 4/14/59 to 8/1/64

The stage values corresponding to zero flow were not available for these rating curves. Hence, water depths could not be provided.

B. Stage-rating curve for the Bill Williams River below Alamo Dam.

- RT No. 3. 10/1/70 to 8/12/71
- RT No. 11. 2/16/95 to present

Zero flow occurred at a stage of 5.5 feet during the 10/1/70 to 8/12/71 period. From 2/16/95 to present, zero flow occurred at a stage of 9.4 feet.
Figure B-2. Stage-rating curves, continued.

C. Stage-rating curve for the Bill Williams River at Planet.

Zero flow occurred at a stage of 3.5 feet during the 2/24/44 to 9/30/46 period.
Figure B-3. Stage-rating curves for low discharges on the Bill Williams River.

A. Stage-rating curves for the Bill Williams River near Alamo.

- RT No. 1. 10/1/56 to 3/16/58
- RT No. 4. 4/14/59 to 8/1/64

The stage values corresponding to zero flow were not available for these rating curves. Hence, water depths could not be provided.

B. Stage-rating curves for the Bill Williams River below Alamo Dam.

- RT No. 3. 10/1/70 to 8/12/71
- RT No. 11. 2/16/95 to present

Zero flow occurred at a stage of 5.5 feet during the 10/1/70 to 8/12/71 period.
From 2/16/95 to present, zero flow occurred at a stage of 9.4 feet.
C. Stage-rating curves for the Bill Williams River at Planet.

--- 2/24/44 to 9/30/48

Zero flow occurred at a stage of 3.5 feet during the 2/24/44 to 9/30/48 period.
Figure B-4. Stage-rating curve for the Bill Williams River below Alamo Dam: Low discharges for the 10/1/70 to 8/12/71 period.

Table B-3. Comparison of stage-rating values for three gages along the Bill Williams River.

<table>
<thead>
<tr>
<th>Discharge (cfs)</th>
<th>Water Depth (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Near Alamo</td>
</tr>
<tr>
<td>10</td>
<td>2.1</td>
</tr>
<tr>
<td>100</td>
<td>3.1</td>
</tr>
<tr>
<td>1000</td>
<td>4.5</td>
</tr>
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