NAVIGABILITY ALONG THE NATURAL CHANNEL OF THE GILA RIVER

(From the confluence with the Salt River to the mouth at the Colorado River near Yuma, Arizona)

Hydrologic, hydraulic and morphologic assessment
by

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EXECUTIVE SUMMARY

In accordance with a request from Helm and Kyle, Ltd., the navigability of the natural channel of the Gila River was assessed using hydraulic geometry methods where hydrologic information is projected into the past. The assessment is for the reach from the confluence with the Salt River to the mouth at the Colorado River. The purpose is to determine if this 188-mile reach of the Gila River was susceptible to navigation at the time of Arizona statehood (February 14, 1912) in its ordinary and natural condition. This report is being prepared for proceedings before ANSAC.

The natural flow condition is given in the following test for determining navigability (From Defenders of Wildlife v. Hull, 199 Ariz. 411,426, 18 P.3d 722 (App. 2001)):

> [31] paragraph 55. We hold that, to prove navigability of an Arizona watercourse under the federal standard for title purposes, one must merely demonstrate the following: On February 14,1912, the watercourse, in its natural and ordinary condition, either was used or was susceptible to being used for travel or trade in any customary mode used on water. See The Daniel Ball, 77 U.S. (10 Wall.) at 563, 19 L.Ed. 999.

The assessment used a systematic three-step procedure to describe what we know about the navigability of the Gila River for the natural condition of flow. First, the natural hydrology was defined and expressed in a typical flow-duration curve of daily discharge for the study reach. Channel geometry was then calculated by applying empirical relations that utilize both the flow characteristics from step 1 and sediment characteristics of the Gila River. Finally, navigability was estimated using three independent methods of federal agencies that use information from steps 1 and 2. Published information and standard engineering hydraulic, hydraulic geometry and hydrologic methods were used to accomplish the three steps.

Important hydrologic characteristics are:

- The Gila River drained about 43,500 square miles at the upper end of the study reach and about 58,200 square miles at the lower end. The watershed was hydrologically diverse because of the diversity of climate, geology and topography. The mountainous areas of the north and eastern parts of the watershed typically received more than 20 inches of precipitation per year. The hot-dry southern areas typically received less than 6 inches of precipitation per year. Precipitation fell during two distinct periods--late summer and midwinter. Snow accumulated in the higher mountains and typically melted and ran off in the spring. Much of the runoff for navigation was from the rainfall and snowmelt in the mountainous areas.

- When rain fell onto the land in the Gila River watershed it started moving according to basic principles of hydrology. A portion of the precipitation seeped into the ground to replenish ground water. Some of the water flowed downhill on the land surface as direct runoff and appeared in surface streams that were unaffected by artificial diversions, storage, or other works of man in or on the stream channels. In the Gila River watershed, most of the runoff from storms reached the river channel directly on the land surface via overland flow, flow in rills, creeks and streams. Direct runoff was seasonal because the storms were seasonal and provided runoff for navigation for part of each year.

- The portion of the water that replenished the ground water was very important for the susceptibility of the Gila River to navigation. Under natural conditions the water that replenished the ground water was temporarily stored, and later discharged to the rivers at springs and seeps in the watershed. This base runoff was released from storage during dry periods. Because precipitation, and therefore direct runoff, was seasonal and there are a few months each year with little precipitation, the base runoff provided perennial flow for navigation to the Gila River.

Important hydraulic characteristics under natural conditions at statehood were:

- The Gila River constructed its own geometry and this geometry is computed using established runoff and sediment characteristics of rivers and the runoff and sediment characteristics of the Gila River.

- The natural flow in the Gila River was perennial with a mean annual flow for the 188 mile reach of 2,330 cubic feet per second. The corresponding width, depth and velocity of flow were 300 ft, 4.8 ft and 2.5 ft per second, respectively.

- The computed width-duration relation using this method agreed very well with an independent width-duration relation for surveyed widths of the federal land surveys.

Important navigability characteristics were:

- The depth and current (velocity) of the Gila River flow were important: too little depth and too much velocity limited navigability. Most of the time flow depth was sufficiently great and flow velocity was sufficiently small for navigability along the Gila River.

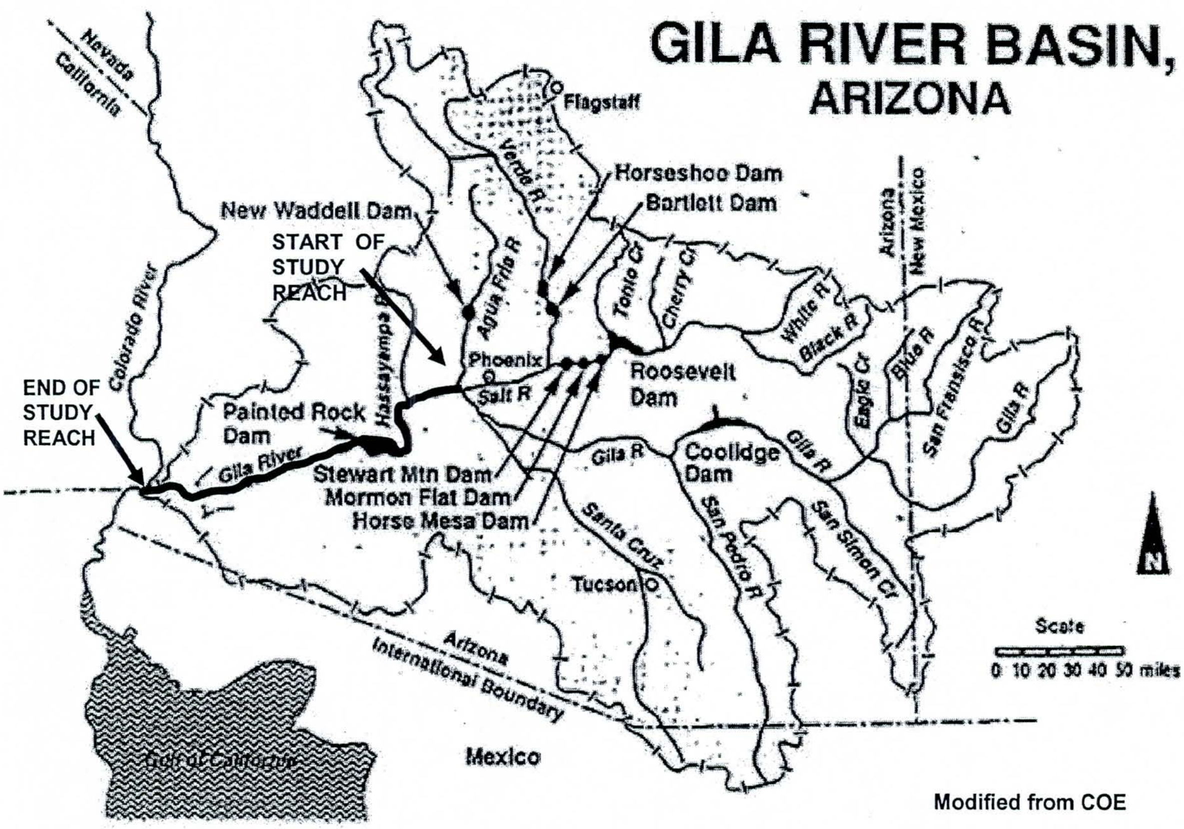
- Navigability was independent of undesirable conditions such as temporary braiding of the river channel following floods, low flow from severe droughts and flow variability because these characteristics are related to how the river might have been used for navigation rather than the navigability.

Conclusion:

Based on all the hydrologic and hydraulic information, data and analysis contained in this report, it is the author's opinion that the natural channel of the Gila River, from the confluence with the Salt River to the mouth at the Colorado River, was susceptible to navigation at the time of Arizona statehood in its ordinary and natural condition.

1. INTRODUCTION

This report and analysis are in response to a request by John Helm, Esq. and Sally Worthington, Esq. that I assess the navigability of the Gila River for natural conditions, at the time of Arizona statehood for presentation to ANSAC. This analysis is based on (1) my knowledge and expertise concerning hydrology, hydraulics and fluvial processes, in general, and the application of this knowledge to the Gila River in central and western Arizona, in particular, (2) the documents that John Helm and Sally Worthington provided me, (3) published reports by the U. S. Geological Survey and other Federal agencies, and (4) federal definitions of navigable and natural flow. The 188 mile reach of the Gila River from the confluence with the Salt River to the mouth at the Colorado River is shown in Figure 1.1.



SITE	MILE	AREA DRAINED (sq. mi.)
Gila River at Salt River	188	43,000
Gila River at mouth	0	58,200

Figure 1.1 Watershed and selected characteristics of study reach.

The natural flow condition is given in the following test for determining navigability (From Defenders of Wildlife v. Hull, 199 Ariz. 411,426, 18 P.3d 722 (App. 2001)):

> [31] paragraph 55. We hold that, to prove navigability of an Arizona watercourse under the federal standard for title purposes, one must merely demonstrate the following: On February 14,1912, the watercourse, in its natural and ordinary condition, either was used or was susceptible to being used for travel or trade in any customary mode used on water. See The Daniel Ball, 77 U.S. (10 Wall.) at 563, 19 L.Ed. 999.

1.1 General approach

The ability to navigate on a river encompasses many factors such as the amount of flow in the river channel, the width and depth of flow in the channel, the type of vessel and the purpose of the travel. Obviously, there must be a minimum depth of water in the channel because even the draft of a canoe will be a few inches. There are other factors of an economic and commercial nature that may be less obvious. These non-hydraulic factors, while important to the actual performance of navigation, are not included in this assessment of navigability.

The hydraulics of vessels and the flow in any river such as the Gila River limit navigability. A vessel, in order to move, must overcome frictional resistance forces. These forces are related to the shape, draft and the size of vessel and the velocity and depth of flow in the river. The squat of a vessel is the increased draft caused by the motion of the vessel. Also, the resistance force is related to the ratio of the draft to channel depth. Thus, there are several fundamental hydraulic and hydrologic factors that should be evaluated.

To make a reliable evaluation of navigability, the anthropegenic impacts such as the many rock dams used along the Gila River and its tributaries to divert water for irrigation by settlers should be considered because the diversion of flow may have affected the navigability. Diversion since about 1860 has altered discharge and sediment characteristics in the Gila River (An example is given in Appendix A.). Therefore, published observations and measurements of channel size and shape made after about 1860 can be of little value because the base flow and the morphology of the river changed as a result of this diversion of base flow from the river. The hydraulic geometry method (See for example Leopold and Maddock (1953), U. S. Corps of Engineers (1990), Wahl (1984) and Osterkamp (1980)), that overcomes the problem of settler-induced changes to estimate natural flow and channel morphology, is used for this analysis.

Parameters included in this study, that are also in accordance with guidelines in U. S. Army Corps of Engineers Engineering Manual EM 1110-2-1611, are: (a) Frequency and duration of river flow based on existing USGS reports and records, (b) general channel width, depth, and velocity during low and mean annual flows, and (c) general composition of the bed and banks and general sediment characteristics of the river. An additional parameter, the minimum specific tractive force suggested by the U. S.

Geological Survey (Langbein, 1962), is also a useful means of quantifying the historic navigability of the Gila River.

How can the navigability of the Gila River be reliably assessed for natural flow prior to 1860? There are few known direct observations of the flow and of the morphology of the river. There were no measurements of streamflow by the U. S. Geological Survey (USGS) until 1888. There were no aerial photographs or detailed topographic maps of the river channel. There have been significant extrinsic changes to the hydrology and morphology of the Gila River from human intervention. There were also intrinsic changes inherent in the river system such as changes in channel width and location and vegetation cover along the channel. There are only a few available recorded observations of the river hydraulics and morphology made by explorers. However, there are many surveyed channel widths by federal land surveyors that provide very useful supportive information. Also, the USGS has made hydrologic studies, which included tree-ring analysis to estimate past streamflow, of the natural flow in the Gila River watershed. The technique known as hydraulic geometry also allows us to make extrapolations of known information on channel morphology from the present into the past.

1.2 Purpose and scope

The purpose of this report is to assess the navigability along the natural Gila River at the confluence with the Salt River to the mouth on February 14, 1912 when Arizona became a state. At statehood, Indians and settlers were diverting large quantities of water from the Salt and Gila Rivers and Roosevelt Dam was already completed on the Salt River. The natural condition of flow that existed before settlers arrived and diverted and stored water for irrigation was used for this analysis of navigability. This assessment is based on the natural hydrologic, hydraulic and morphologic conditions related to navigability because under the Defenders of Wildlife test, navigability is based on natural and ordinary conditions.

The study was performed in three basic steps.

> **Step. 1**: Estimate the amount and temporal distribution of natural flow for the Gila River at the confluence of the Salt River to the mouth of the river near Yuma, Arizona.
>
> The natural hydrology for the Gila River from the Salt River to Yuma is based largely on published reports of natural hydrology for rivers in Central Arizona by the U. S, Geological Survey.
>
> **Step 2:** Estimate the natural hydraulic characteristics of the river channel that are related to navigation.

The natural size and shape of the Gila River channel are based on published hydraulic geometry relations for deformable alluvial channels. Diversion and regulation since about 1860 have altered discharge and sediment characteristics in the Gila River. Since the settlers, observations and measurements of channel size and shape may be unreliable because the base flow and the morphology of the river changed as a result of this diversion of base flow and sediment from the river. Therefore, it is necessary estimate the size and shape of the river channel before about 1860 when the flow was natural. Sediment-hydraulic geometry (morphology) relations for alluvial channels were used to calculate natural channel size and shape of the Gila River.

Step 3: Define if the Gila River was navigable between the confluence with the Salt River and the mouth.

Navigability along the Gila River is evaluated using the natural hydrology, hydraulics and morphology of the channel determined in steps 1 and 2. Two relatively simple methods developed by the U.S. Department of the Interior were used. A third method that uses the physical conditions defining navigability was also used. This third method of description and comparison developed by the USGS (Langbein, 1962), is based upon the specific force required to propel a vessel.

This report presents the results of a quantitative estimate of the navigability of the Gila River below the confluence with the Salt River based largely on USGS reports and stream gage records. Several USGS reports on the flow characteristics of the Gila River, the use of hydraulic geometry to estimate channel geometry and the assessment of the navigability of rivers formed the basis of the reported analysis. Information in other reports by federal agencies, mostly on navigation, also was used.

Other supportive information that provided hydrologic and hydraulic evidence included field notes for surveys along the Gila River in the late 1800s by the predecessor agencies of the U. S. Bureau of Land Management. These original federal land surveys provided 122 useful channel widths at surveyed section boundaries throughout the study reach. A few recorded observations of channel conditions along the Gila River were also obtained from US Corps of Engineers (1995). Channel characteristics shown on old USGS topographic maps also provided limited hydraulic and morphologic evidence.

2. HYDROLOGY

The mountainous areas of the northeastern part of the Gila River (Figure 1.1) watershed typically receive more than 20 inches of precipitation per year with 30 inches or more in a few of the higher areas. Much of the desert area of the western part of the watershed receives less than 6 inches of precipitation in a normal year. Precipitation falls during two distinct periods —late summer and midwinter. Summer precipitation is mostly from thunderstorms and much of the midwinter precipitation in the high mountains of the watershed is snow. Very little of the precipitation in the arid parts of the watershed ran off to the Gila River. Under natural conditions less than about 5 percent of the precipitation on the entire watershed ran off. Most of flow in the lower 188 miles of the Gila River (study reach) was from snowmelt in the high mountains typically in late winter and spring. Another important part of the total runoff for navigability was the water that replenished the ground water, was temporarily stored, and later discharged to the streams in the watershed (Figure 2.1).

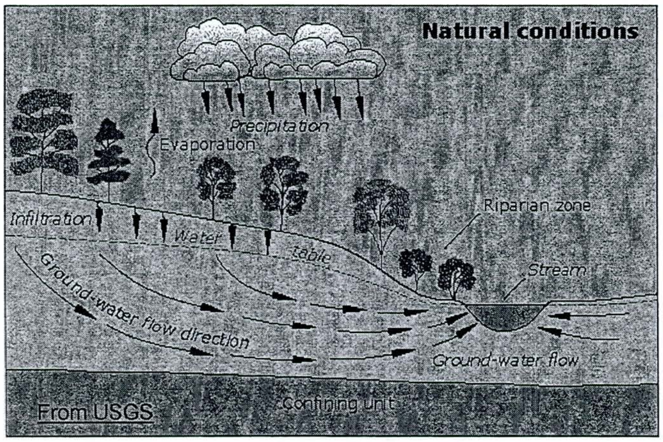


Figure 2.1 Sketch showing ground water under natural conditions.

2.1 Total, direct and base runoff

When rain or snow falls onto the land in the Gila River watershed it starts moving according to hydrologic principles. A portion of the precipitation seeps into the ground to replenish ground water, a portion is lost to evapotranspiration (See Glossary), and some of it flows downhill as direct runoff. Runoff is either direct runoff or base runoff. Base runoff is precipitation that seeps from the ground into uncontrolled streams and rivers. The remainder of the runoff is direct runoff. The total runoff is simply the sum of the direct and base runoff. Whether runoff of the Gila River watershed is direct or base is important for the assessment of navigability.

The portion of the water that replenishes the ground water is very important for the navigability of the Gila River. Under natural conditions the water that replenished the ground water was temporarily stored in many aquifers throughout the watershed. The stored groundwater was later discharged to the streams in the watershed as base runoff during dry periods. Because precipitation, and therefore direct runoff, was seasonal and there are a few months each year with little precipitation, the base runoff provided perennial flow to the Gila River.

2.2 Estimate of natural flow in the Gila River

The natural flow in the study reach of the Gila River was governed largely by the climate of the watershed. The distribution of high flows was governed by the physiography and plant cover of the Gila River watershed. The distribution of low flows (base flow) was controlled chiefly by the geology of the watershed. Base flow in the study reach was the composite of ground water drainage from many parts of the watershed. Much of the base flow in the mountains was from limestone and sandstone aquifers. Many alluvial basins that are traversed by the streams were filled with water, and this ground water drained to the streams under natural conditions. Thus, the low-flow end of the flow-duration curve (Searcy, 1959) reflects the effect of geology on the ground-water runoff to the river and its tributaries (Figure 2.2).

A flow-duration curve was used for this study to define the percent of time the natural mean daily discharge was exceeded during a typical or average year. The curve was defined as follows (See Table 2.1 and Figure 2.2): First, the basin accounting method for natural stream base flow developed by Freethey and Anderson (1986) was used to estimate the 90th percentile of daily discharge, the median discharge and the average(mean) annual natural streamflow for the Salt and Gila Rivers estimated by the USGS (Thomsen and Eychaner (1991) and Thomsen and Portello (1991)) were then combined, and the flow duration relation was estimated using the base, median and mean flow values. The general shape of the flow-duration relations of upstream tributaries gaged by the USGS (Pope and others, 1998) was used to shape the flow-duration curve. A flow-duration relation, that shows average flow values, is commonly used by hydrologists to show the availability of water as a percentage of time.

Table 2.1 Estimated mean, median and base flow for natural conditions along the study reach of the Gila River

Site	Mean annual flow	Median (Q_{50}) flow	Base (Q_{90}) flow
At confluence With Salt River	1,685,000 ac-ft (2,330 cfs)	1,265,000 ac-ft (1,750 cfs)	213,000 ac-ft (290 cfs)
At mouth near Yuma	1,685,000 ac-ft (2,330 cfs)	1,265,000 ac-ft (1,750 cfs)	123,000 ac-ft (170 cfs)

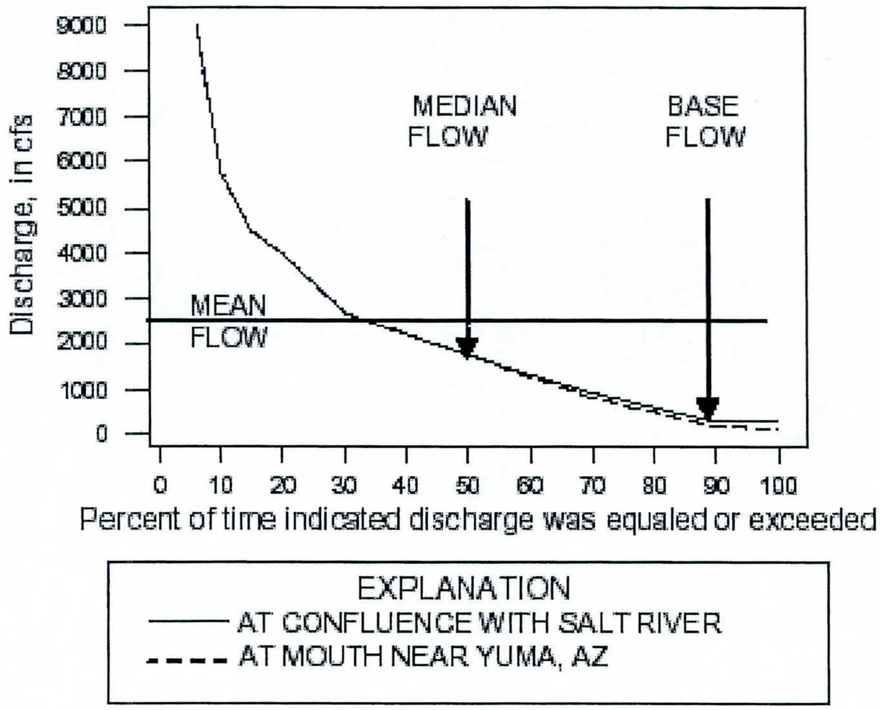


Figure 2.2 Flow-duration relations for natural flow at ends of the study reach.

2.2.1 Base flow

The base flow was computed by applying the basin accounting method for natural stream base flow for ground-water systems (basins) upstream of the study reach. This accounting method was developed by Freethey and Anderson (1986) for natural hydrologic conditions that existed before man's activities. Streamflow amounts for each of the basins were cumulated to estimate the 90th percentile of daily discharge (see for example Lins and Slack (1998) and Wirt and Hjalmarson (2000)). Freethey and Anderson (1986) showed a net loss of base flow for the basins crossed by the Gila River in the study reach. The cumulated loss of 120 cfs in this arid region produced the decrease of base flow from 290 cfs to 170 cfs from the confluence with the Salt River to the mouth near Yuma (Table 2.1).

Freethey and Anderson (1986) show large volumes of ground-water stored in the basins upstream and along the study reach. Because of the large amount of stored ground water that supplied the natural base flow, the base flow may not have varied greatly from one year to the next.

2.2.2 Mean and median annual flow

According to Thomsen and Eychaner (1991) the mean annual natural flow of the Gila River upstream from the Gila River Indian Reservation was 500,000 acre-feet and the median annual flow 380,000 acre-feet. A USGS numerical model was developed to simulate ground-water flow, stream-aquifer connection, and evapotranspiration for purposes of evaluating predevelopment hydrologic conditions on the reservation. The model showed recharge by infiltration from the Gila River, 94,000 acre-feet per year; and discharge to surface flow in the western third of the reservation, 29,000 acre-feet per year, with a net loss of 65,000 ac-ft per year. Thus, the mean and median natural flow leaving the reservation was 435,000 and 315,000 ac-ft per year, respectively. The average annual discharge of the Salt River upstream of the Salt River Indian Reservation was estimated by the USGS to be 1,250,000 acre-feet and the median annual discharge 950,000 acre-feet (Thomsen and Portello, 1991). These estimates are also based on recorded data with adjustments for results of tree-ring studies and estimates of upstream diversions and reservoir evaporation. Losses of runoff in the Salt River within the reservation were not significant (Thomsen and Portello, 1991).

The mean and median annual discharge at the confluence of the Gila and Salt Rivers are estimated by combining average annual predevelopment streamflow for Salt and Gila Rivers, based on estimates by the USGS (Thomsen and Eychaner (1991) and Thomsen and Portello (1991)). The average predevelopment (natural) annual discharge is the sum of 1,250,000 and 435,000 ac-ft or 1,685,000 ac-ft (2,330 cfs). The estimated median annual flow is the sum of 950,000 and 315,000 ac-ft or about 1,265,000 ac-ft (1,750 cfs) (See Table 2.1). The median daily discharge is the flow value at 50% of the time. About half of the days in a typical year have less daily discharge and the other half have more daily discharge. The 50% duration flow for the Gila River is about 1,750 cfs.

For this study of the natural hydrology along the Gila River, the tributary inflow to the study reach below the confluence with the Salt River is assumed to offset runoff losses to evapotranspiration along the Gila River. Based on runoff data given in Krug, Gebert and Graczyk (1989), the average annual runoff to the study reach from the Hassayampa River, Centennial Wash and other tributaries (a combined area of more than 15,000 square miles) was about 100 cfs. This amount of runoff is less than 5 percent of the mean annual flow at the confluence with the Salt River (Table 2.1) and about equal to the loss of base flow in the reach between the Salt River and Yuma (Table 2.1). Because the tributary inflow was small and offset losses to evapotranspiration along the reach, the mean and median annual runoff are assumed constant to the mouth of the Gila River.

2.2.3 Flow duration relation

The flow-duration relations (Figure 2.2) for the Gila River are cumulative frequency curves that show the percent of time specified discharges were equaled or exceeded during a given period. The flow-duration curve does not show the chronological sequence of flows. Rather, it combines in one curve the flow characteristics of the Gila River throughout the range of discharge, without regard to the sequence of occurrence. It represents the distribution of average natural flow of the Gila River for the year and is useful for the assessment of navigability. The duration graph represents mean daily rates of discharge that are arranged in order of magnitude. This display simplifies general assessment of navigability because it represents long-term average flow conditions.

2.3 Discussion and summary of the natural hydrology

When settlers arrived in the 1860s and occupied land along the rivers, they built many diversion dams with canals for irrigation of crops. The early rock diversion dams worked satisfactorily for base flow but higher flows were difficult to control and typically washed out the dams. By the time of statehood, February 14, 1912, Roosevelt Dam had been constructed and even high flows were being impacted by settlers. For a more detailed history of the diversion dams see Thomsen and Eychaner (1991), Thomsen and Porcello (1991) and Halpenney, L. C. and others (1952).

The hydrology for natural (pre-settler) conditions of the Gila River below the confluence with the Salt River was defined using published USGS information (Freethey and Anderson (1986), Thomsen and Portello (1991) and Thomsen and Eychaner (1991)). A flow-duration relation for natural flow was computed using the published information. The flow-duration relation is used to assess the amount of time a particular amount of mean daily discharge can be expected in the study reach of the Gila River.

It is my opinion, based on this analysis, the natural flow of the Gila River was perennial across the desert of central Arizona to the Colorado River. During the typical year the base flow was at least 290 cfs in the upper reach below the confluence with the Salt River and at least 170 cfs at the mouth of the Gila River. The difference in base flow through the reach is mostly because of losses of inflowing water to evapotranspiration. During a typical year the mean annual flow was about 2,330 cfs below the confluence with the Salt River. Flow typically was at least 1,750 cfs for 50% of each year.

3. HYDRAULIC GEOMETRY AND HYDRAULICS

Rivers with natural alluvial channels like the Gila River along the study reach construct their own geometries. This hydraulic geometry of the Gila River is related to the water flow and sediment characteristics. The amount of flow, computed in the previous section of this report, is the principal control of channel size and the sediment characteristics largely determine channel shape (Osterkamp (1980), Hey (1978), Schumm (1960) and Osterkamp and Hedman (1982)).

Two important natural parameters of the main channel are depth and velocity because too little depth and too much velocity limits navigability. Width is also an important parameter partly because width was commonly measured. For example, the original federal land surveyors of the General Land Office identified, measured and recorded channel width of the Gila River along the study reach and a few explorers also recorded observations of width. Also, channel width of main channels can be reliably estimated from flow characteristics (Leopold and Maddock (1953), U. S. Corps of Engineers (1990), Schumm (1968) and Osterkamp (1980)). The depth and velocity of the natural alluvial channel of the Gila River are related to channel width.

Channel characteristics for the more common flows of the Gila River are important for the assessment of navigability. For example, about 70% of the time the flow is less than the mean annual flow (Figure 2.2). In terms of using a vessel on the Gila River, the lower flows such as the base runoff, may limit navigability for at least part of a typical year. While base runoff is a rather small portion of the mean annual runoff, base runoff is all or a large amount of the total runoff at least 30 percent of the time. Therefore, the low, medium and average flow conditions of the river are examined.

Channel size and shape along the study reach of the Gila River are estimated using the mean annual flow of 2,330 cfs as the formative or dominant discharge (independent variable) of the channel property (dependent variable) width. This permits estimates of the channel dimensions (the width for example shown in Figure 3.1) to be made along the Gila River on the basis of the discharge characteristic. The approach infers that the discharge characteristic to be estimated is related directly to the formative discharge of the Gila River but does not require precise identification of that formative discharge.

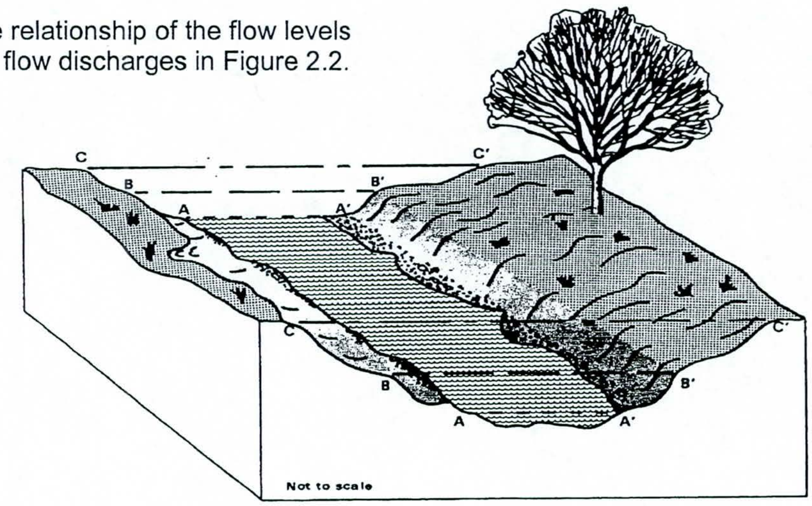
Along rivers like the Gila, functions for width and mean annual discharge are:

$$W = aQ^{b} \qquad \text{Equation 3.1}$$

where width (W), the dependent variable, is related to mean discharge (Q), the independent variable, the value of the exponent (b) varies with the tractive sediment load of the stream and (a) is a constant.

A. Main channel showing width of average annual flow(C-C'), width of median daily flow(B-B'), and width of base flow(A-A').

Note the relationship of the flow levels and the flow discharges in Figure 2.2.



B. Cross section of channel showing width of flow (W), depth of flow(d) and mean depth of flow(D).

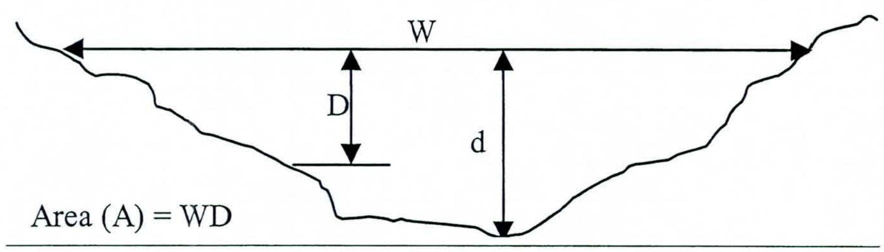


Figure 3.1 Sketches showing general characteristics of river channel

The lowest value of b, about 0.45, is associated with silt-clay bed channels in which essentially no sediment is moved by traction (Osterkamp, 1980). The exponent increases to about 1.0 for some braided stream channels in which large amounts of sediment are moved tractively. With increasing armoring (courser rock along wetted perimeter) of a channel, the value of b decreases, reaching a minimum of about 0.50 for turbulent alpine streams that have low sediment discharge (See Appendix B for armoring).

Channel material characteristics along the study reach, given in soil survey reports of the U. S. Natural Resource Conservation Service are used for this study. The study reach typically is stratified sand and silt with some clay and gravel. In addition to the finer grained sediments, lenses of gravel with some cobbles and a few small boulders have been observed in cut banks along the study reach by the author (Appendix B). The present alluvial deposits along the river are clues to past (natural) sediment conditions.

The geometry (simplified here to the channel width) of an alluvial stream channel primarily is the integrated resultant of all rates of water and sediment discharge conveyed through the channel. The effects of water and sediment variables cannot be completely separated to evaluate the influence that each exerts on channel width. In order to examine the manner in which channel widths vary with sediment properties, it is necessary to generalize width-discharge relations. Sediment characteristics then can be regarded as modifications or complications of those relations (Osterkamp, 1979a). A summary relation of width, W, in feet, and mean discharge, Q, in cfs (Osterkamp, 1979b) follows:

$$W = aQ^{0.50} \qquad \text{Equation 3.2}$$

According to Osterkamp (1979b and 1980), the equation for sand-bed and silt-bank channels is:

$$W = 3.36\, Q^{0.59} \qquad \text{Equation 3.3}$$

Following a moderate flood, much of the fine bed and bank material may be washed away and the width-mean discharge relation (equation 1) might be described by the following equation:

$$W = 3.24\, Q^{0.62} \qquad \text{Equation 3.4}$$

Channel widths from hydraulic geometry and other bed and bank material are shown in Table 3.1. Maximum channel widths occur when fluvial sediment is principally medium- to coarse-grained sand. Narrowest, most stable channels occur when an increased percentage of sediment finer than sand imparts a cohesiveness, or when sediment coarser than sand causes an armoring effect.

Using Osterkamp's equations, estimates of channel width along the natural channel of the Gila River, corresponding to the mean annual flow of 2,330 cfs, were from 250 to

396 feet (Table 3.1). The channel is widest where the bed and banks are sand. The channel is narrowest where there is more silt and clay and also where there is more armoring from coarser gravel. The average width, based on the five likely channel bed materials, is about 300 ft.

Table 3.1.—Summary of width estimates along the Gila River below the confluence with the Salt River using hydraulic geometry.

Bed material	a	b	W (feet)	Source
medium silt-clay	3.01	0.57	250	Osterkamp (1980)
low silt-clay	3.11	0.58	279	same as above
sand with silt banks	3.36	0.59	326	same as above
sand with sand banks	3.24	0.62	396	same as above
gravel	3.70	0.55	263	same as above

Depths of water for the main channel along the Gila River are related to flow characteristics and channel roughness, slope and width. The corresponding depth of flow for natural conditions is estimated using channel conveyance-slope characteristics and rating curve characteristics (Rantz and others, 1982).

Manning's discharge equation is widely used for conditions of channel control to compute flow ratings (Rantz and others, 1982). The typical natural channel, like the natural channel of the Gila River, is approximately parabolic in shape. Using techniques of Burkham (1977) the following equation results:

$$Q = (1.49/n)\,(0.67d)^{5/3}\,W\,S_o^{\,1/2} \qquad \text{Equation 3.5}$$

Where d = depth of water above channel invert, S_o = energy gradient, and *n* = roughness coefficient.

For the study reach, n = .035 (Thomsen and Hjalmarson, 1991), W is from 250 to 396 ft, S_o = channel bed slope = 0.001 and 0.0005 for the upper and lower parts of the study reach, and Q = 2,330 cfs.

The natural channel depths computed by rearranging Equation 3.5 and solving for d are shown in Table 3.2 (See Appendix C).

Table 3.2.—Estimated depth of water for mean annual discharge.

Note: Slope of 0.001 is for upper part of the study reach and slope of 0.0005 is for lower part of study reach to the mouth.

Reach	W(feet)*	slope	d(feet)	Remarks
upper	250	0.0010	4.81	
upper	279	0.0010	4.50	
upper	326	0.0010	4.10	
upper	396	0.0010	3.65	
upper	263	0.0010	4.67	
upper	300	0.0010	4.31	Average
lower	250	0.0005	5.92	
lower	279	0.0005	5.54	
lower	326	0.0005	5.04	
lower	396	0.0005	4.49	
lower	263	0.0005	5.74	
lower	300	0.0005	5.31	Average

*See Table 3.1.

The width-duration curves for the upper and lower parts of the study reach show that the channel width is between about 200 and 300 ft about 60 percent of the days in a typical year (Figure 3.2). At least 90 percent of the time the channel width in the study reach is more than 170 ft.

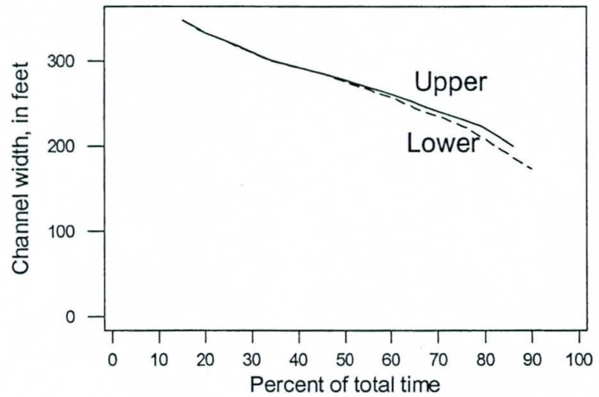


Figure 3.2 Natural channel width-duration curves for upper and lower part of the study reach.

The Manning equation was used to estimate mean channel velocity for the upper and lower parts of the study reach (Table 3.3) and Figure 3.3. At least 80 percent of the time the mean velocity is less than about 3 ft/s (Figure 3.3)

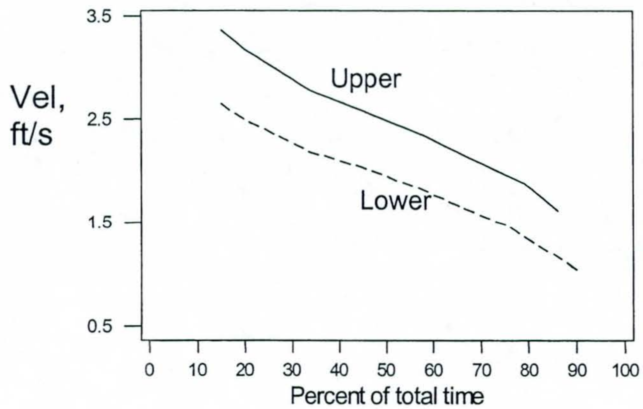


Figure 3.3 Velocity-duration curves for upper and lower parts of study reach.

Channel depth-velocity curves shown in Figure 3.4, and the data shown in Table 3.3 are related to navigability along the watercourse (Langbein, 1962) described in the next section of this report.

Table 3.3. Flow velocities corresponding to flow depths for upper and lower parts of the study reach of the Gila River

Depth (ft)	Mean Velocity (ft/s) Upper	Lower
1.5	1.33	1.04
2.0	1.61	1.27
2.5	1.87	1.47
3.0	2.11	1.66
3.5	2.34	1.84
4.0	2.56	2.02
4.5	2.77	2.18
5.0	2.98	2.34
5.5	3.17	2.50
6.0	3.36	2.65

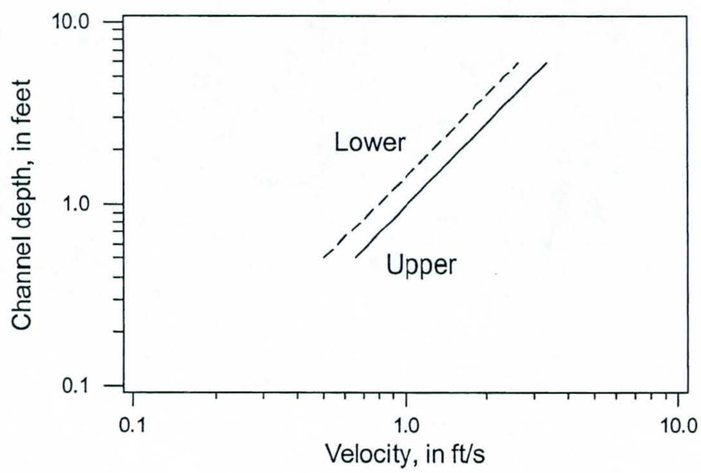


Figure 3.4 Relations of depth versus velocity for upper and lower parts of study reach.

Computed channel widths and the width-duration relation (Figure 3.2) are compared with the measured channel widths of the original land surveys by the federal land surveyors (Appendix D). There is good agreement between channel widths computed using this hydraulic geometry method and the surveyed widths, corrected for channel skew at section boundaries, of the federal land surveys (Figure 3.5). The close agreement between the estimated widths (Curve C) and the surveyed widths (Curve A) (See Table DI for widths) confirms that this assessment of navigability is reliable.

Computed channel widths and depths of the hydraulic geometry method were also compared with channel widths and depths estimated using old USGS topographic maps (Appendix E) and observations of explorers (Appendix C).

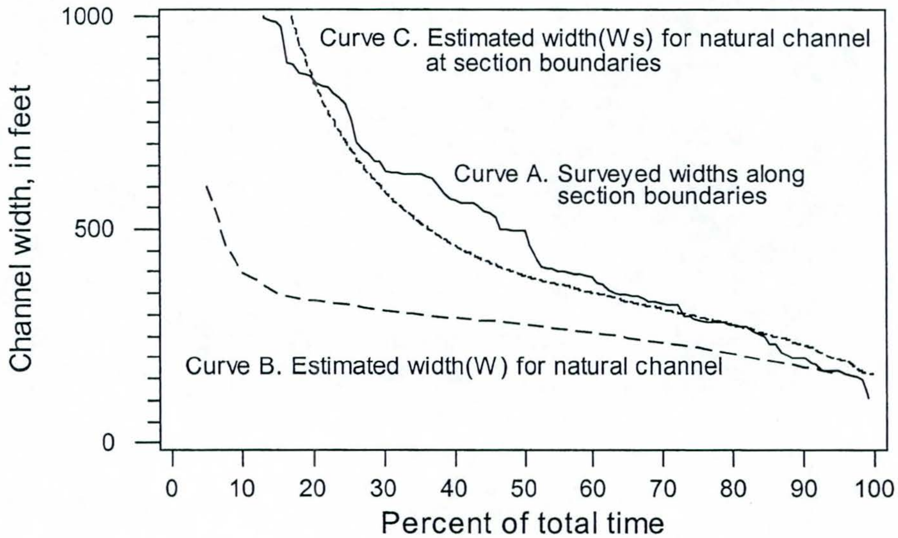


Figure 3.5 Width-duration curves for study reach between the confluence with the Salt River to the mouth near Yuma, Arizona.

The hydraulic geometry method is based on studies of many natural channels and allows us to make projections of known information on channel morphology from the present into the past. For the study reach, there is reasonable agreement between the computed relations of channel width and depth and the three observations of channel width and depth by explorers. The computed minimum natural-channel depth for base flow of 1.6 ft was about the same for the hydraulic geometry and multiple channel (channel conveyance-slope) methods based on the morphology gleaned from the old USGS topographic maps. There is very good agreement between the width-duration relation computed using this method and width-duration relation for the surveyed widths of the federal land surveys.

4. NAVIGABILITY

Navigability along the Gila River is evaluated using the natural hydrology and hydraulic geometry of the natural channel in the study reach. Three methods of assessing instream flows are used. Two relatively simple methods developed by the U.S. Department of the Interior mostly for modern recreational boating are used. To avoid any possible arbitrary assessment of navigability, a third more engineering oriented method developed by the USGS based on the physical conditions defining navigability was also used.

The first method is a rule of thumb rating of navigation difficulty by Jason M. Cortell and Associates Inc. of Waltham Mass (U. S. Bureau of Outdoor Recreation, 1977). This method is easy to use and was developed for the Bureau of Outdoor Recreation of the U. S. Dept. of the Interior in July 1977.

The second method is also easy to use and is based on hydraulics of a single channel cross section that is representative of channel conditions. These navigation requirements (*Instream Flow Information No. 6*) were developed by R. Hyra (1978) for the Fish and Wildlife Service of the Dept. of the Interior. Channel depth and width requirements are defined for types of watercraft such as rafts and rowboats.

The third method uses a standard of comparison developed by the U. S. Geological Survey (Langbein, 1962) for several rivers. This method, that uses the channel velocity and depth from the hydraulic geometry relations of the previous section, is based on the minimum tractive force required for upstream and downstream navigation. The tractive force of the Gila River is compared with a limiting tractive force required for commercial navigation on several rivers.

4.1 Bureau of Outdoor Recreation Method

The use of small watercraft, that includes canoes, kayaks drift boats and rafts, is rated in terms of flow criteria based on an International River Classification scale. A minimum stream flow condition is used to rate the difficulty of using these watercraft in rivers. Six classes of white water are used and Class I is the easiest for navigability. Class 1 is generally for white water streams have a gradient in excess of 10 feet per mile and a flow in excess of 500 cfs. The classes are subjectively described as follows (U. S. Bureau of Outdoor Recreation, 1977);

Class I - Very Easy. Waves are small and regular, passages are clear. Obstacles are sand bars, bridge piers, and riffles.

Class II - Easy. Rapids of medium difficulty with clear, wide passages.

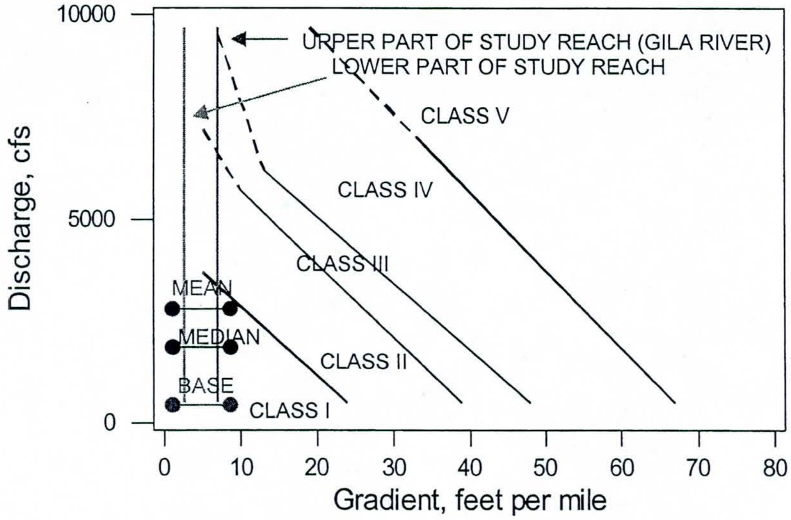
Class III - Medium. Waves are numerous, high, and irregular. Passages are clear but narrow and require expertise in maneuvering.

Class IV - Difficult. Long rapids with powerful waves and many obstacles are present. Passages are difficult to see and powerful, precise maneuvering is required.

Class V - Very Difficult. Rapids are long and very violent, following each other almost without interruption. The riverbed is extremely obstructed with large drops and violent currents.

Class VI - Extraordinarily Difficult. The difficulties of Class V carried to the extreme of navigability.

The discharge and gradient of the study reach is well within Class I and the use of watercraft is considered very easy (Figure 4.1). The maximum gradient in the upper



MODIFIED FROM: (U. S. Bureau of Outdoor Recreation, 1977)

Figure 4.1 River discharge and gradient showing navigation difficulty.

reach is about 7 ft./mile and the gradient in the lower reach is about 2.6 ft/mile. At least 90 percent of a typical year (328 days) the mean daily flow is less than 7,000 cfs (Figure 2.2) and the corresponding rating is Class II or easy. Only about 2-3 weeks of a typical year is rated difficult or more (Class IV to VI). Most of the time the instream flow of the Gila River was at or near optimum conditions for recreation boating according to the rating method by the U. S. Bureau of Outdoor Recreation (1977).

4.2 Fish and Wildlife Service Method

The U.S. Fish and Wildlife Service (Hyra, 1978) developed a method of assessing streamflow suitability for recreation that is applied to the Gila River. The single cross section technique is very simple to use and results in an assessment of the minimum flow recommended for a particular watercraft activity. The characteristics of the hydraulic geometry sections for the upper and lower parts of the study reach are used. Hyra (1978) presents minimum depth and width requirements for canoes, kayaks, drift boats and row boats and power boats (See Figures 4.2A and 4.2B). The minimum width and depth requirements are met nearly all the time in the study reach.

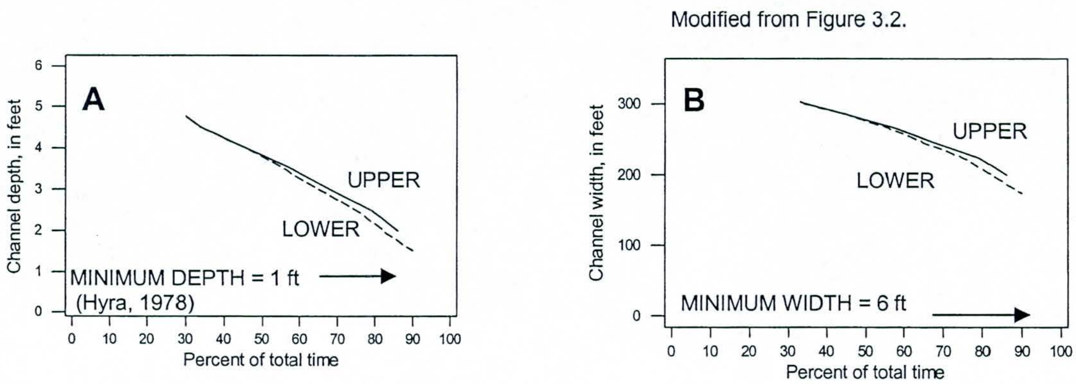


Figure 4.2 Smallest acceptable depth and width of recreational craft at upper and lower parts of the study reach.

The smallest acceptable depth of 1 ft. for the small watercraft (Hyra, 1978) is also less than the channel depth for hypothetical worst-case flow condition (multiple channels) for the Gila River (See Appendix E). A minimum velocity is not considered necessary for this method (Hyra, 1978).

4.3 U. S. Geological Survey Method

This method of description and comparison developed by Langbein (1962), is based upon the specific force required to propel a vessel upstream. The physical characteristics of a natural river such as discharge, gradient, depth, and velocity markedly affect the navigability of any river by diverse craft. Langbein's method uses the natural conditions of a river such as the Gila River to assess if the flow conditions were favorable or unfavorable for two-way commercial navigation by diverse shallow-draft watercraft. Under Arizona law it is not necessary to prove you could go up but it was possible. A report by the Chesapeake Research Consortium, Inc. (Power and Wolman, 1975) for the U. S. Corps of Engineers that used Langbein's method, a recognized technique, to evaluate potential navigability of the Shenandoah River was examined.

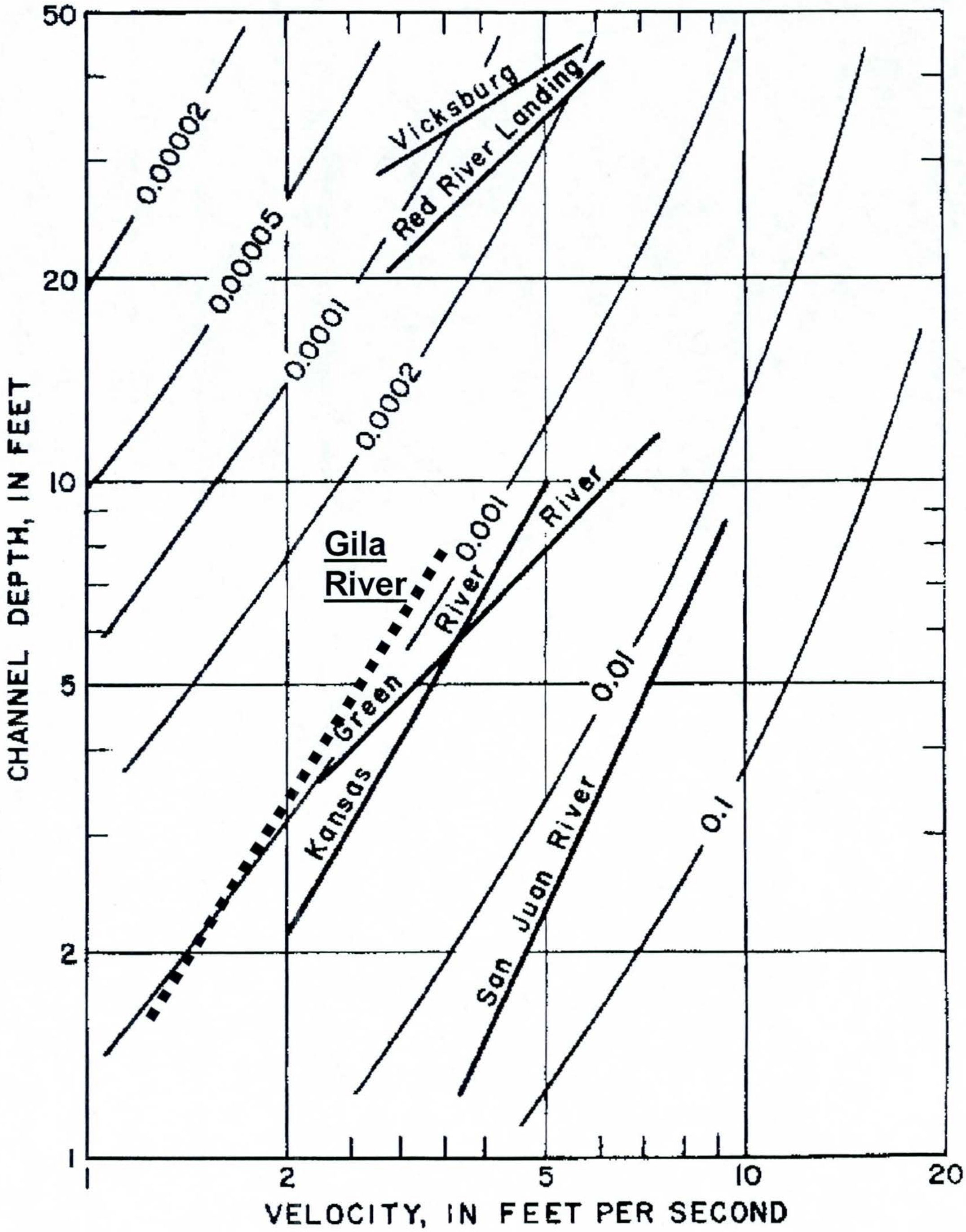
Fortunately for this study of the Gila River, Langbein's method is for *"rivers in their approximate native state"*. Also, this method uses the hydraulic geometry of rivers (Section 3 of this report) and the hydraulic geometry of commercial vessels. Langbein's (1962) method considers hull resistance, shallow water drag, slope drag, squat and other characteristics of vessels. The hydraulic geometry of the river and vessel are combined for the assessment of navigability of the Gila River.

The computed minimum specific tractive force for the study reach of the Gila River is shown in Figure 4.3 and Table 4.1. According to Langbein (1962), in regard to data for the several rivers in Table 4.1 and Figure 4.3, "...these data for the several rivers in relation to what is known of their use for navigation indicates that rivers with specific tractive forces above 0.002 are not used for navigation. ......Thus, to navigate rivers that require tractive forces near or more than this amount would require most of the developed energy to be expended to breast the current rather than for transport. Within the range from 0.002 to 0.001, navigation is usually limited to ferry or short-run operations. Major navigation appears to be associated with rivers that require tractive forces less than 0.001." Langbein further states that river tractive forces of about 0.001 and 0.002 are near the maximum feasible for commercial navigation.

Table 4.1 Tractive force for several rivers by Langbein(1962, page 23) and the Gila River

River and location	Commercial use[1]	Minimum specific tractive force required for two-way navigation
Mississippi River at Vicksburg, Miss.	A	0.00015
Tombigbee River at Columbus, Miss	A	.0002
Red River at Arthur City, Tex	B	.001
Gila River below Salt River to mouth, Arizona	**C**	**.001**
Missouri River at Williston, N. Dak.	B	.001
Green River at Green River, Utah	B	.002
Yellowstone River near Sidney, Mont.	B	.002
Missouri River at Bismark, N. Dak.	B	.002
Kansas River at Bonner Springs, Kans	B	.002
Red River at Terral, Okla	C	.005
Rio Grande at Bernalillo, N. Mex	C	.02
San Juan River near Bluff, Utah	C	.02

[1] A, a commercial waterway of the U. S.; B, ferry and other short-run navigation; C, no known commercial navigation



Modified from Figure 13 of Langbein (1962)

Figure 4.3 Depth-velocity curves for the study reach of the Gila River and for several other rivers in relation to minimum specific tractive force required for navigation.

This USGS method of navigability assessment of the Gila River that is based on standards for commercial navigability clearly shows the Gila River was navigable. The estimated tractive force of the Gila River is about 0.001 and this value is well below the limit for feasible navigation and near the lower limit for feasible commercial navigation using 1962 standards.

4.4 Summary

The three Federal methods show the Gila River along the study reach was navigable.

Although under Arizona law it is not necessary to prove upstream navigability was possible, the USGS assessment showed it was possible.

5. SUMMARY AND CONCLUSION

Assessment of whether the natural channel of the Gila River was navigable involves taking known hydrologic and geomorphic information and relationships from the present and projecting this information into the past. The three-step method is based of the fact that rivers construct their own geometry and this geometry can be estimated using hydrologic and hydraulic principles.

The assessment used published information and data and was performed in three steps using standard engineering/hydrologic methods. The first step was the definition of the runoff for the Gila River using hydrologic techniques. A flow-duration relation for the river was estimated using the base, median annual and the mean annual runoff. The second step utilized hydraulic geometry techniques to estimate the width, depth and velocity for the natural flow in the study reach. There is a predictable relation between the channel geometry, type of sediment and the mean annual amount of natural flow. Finally, navigability was assessed using the physical characteristics of the natural channel of the Gila River such as discharge, gradient, depth, sediment and velocity. The three methods of Federal agencies showed the Gila River was navigable from the confluence with the Salt River to the mouth at the Colorado River.

At the time of statehood the runoff in the study reach was impacted by many upstream diversions for irrigation and storage behind Roosevelt Dam on the Salt River. Diversions along the Gila River and tributary streams reduced the amount of downstream water and sediment flow and thus influenced many downstream river functions in the study reach after about 1860. This method takes into account the anthropogenic impacts.

There is very good agreement between the surveyed channel widths by the federal surveyors and the estimated widths of this assessment. Accounts of a few channel widths and depths documented by explorers and from old USGS topographic maps also agreed with the estimated channel widths and depths. The close agreement between the estimated and surveyed widths confirms this assessment of navigability is reliable.

It is my opinion the Gila River, from the confluence with the Salt River to the mouth at the Colorado River, was susceptible to navigation at the time of statehood (February 14, 1912) in its ordinary and natural condition. Evidence relied upon to form this opinion is in this report and in the references for this report.

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7. GLOSSARY (Mostly from Langbein and Iseri, HTML Version 1995)

HYDROLOGIC DEFINITIONS FOR THIS STUDY OF NAVIGABILITY

Acre-foot. A unit for measuring the volume of water, is equal to the quantity of water required to cover 1 acre to a depth of 1 foot and is equal to 43,560 cubic feet or 325,851 gallons. The term is commonly used in measuring volumes of water used or stored.

Armoring. The natural process of forming an erosion resistant layer of relatively large particles on the surface of the streambed.

Anabranch. A diverging branch of a river which reenters the mainstream.

Average discharge. In the annual series of the Geological Survey's reports on surface-water supply—the arithmetic average of all complete water years of record whether or not they are consecutive. Average discharge is not published for less than 5 years of record. The term "average" is generally reserved for average of record and "mean" is used for averages of shorter periods, namely, daily mean discharge.

Bank. The margins of a channel. Banks are called right or left as viewed facing in the direction of flow.

Base flow. See Base runoff.

Base runoff. Sustained or fair weather runoff. In most streams, base runoff is composed largely of groundwater effluent. (Langbein and others, 1947, p. 6.) The term base flow is often used in the same sense as base runoff. However, the distinction is the same as that between streamflow and runoff. When the concept in the terms base flow and base runoff is that of the natural flow in a stream, base runoff is the logical term. (See also Ground-water runoff and Direct runoff.)

Braiding of river channels. Successive division and rejoining (of river flow) with accompanying islands is the important characteristic denoted by the synonymous terms, braided or anatomizing stream. A braided stream is composed of anabranches.

Cfs-day. The volume of water represented by a flow of 1 cubic foot per second for 24 hours. It equals 86,400 cubic feet, 1.983471 acre-feet, or 646,317 gallons.

Cfsm (cubic feet per second per square mile). The average number of cubic feet of water per second flowing from each square mile of area drained by a stream, assuming that the runoff is distributed uniformly in time and area.

Channel (watercourse). An open conduit either naturally or artificially created which periodically or continuously contains moving water, or which forms a connecting link between two bodies of water. River, creek, run, branch, anabranch, and tributary are some of the terms used to describe natural channels. Natural channels may be single or braided (see Braiding of river channels) Canal and floodway are some of the terms used to describe artificial channels.

Direct runoff. The runoff entering stream channels promptly after rainfall or snowmelt. Superposed on base runoff, it forms the bulk of the hydrograph of a flood.

Discharge. In its simplest concept discharge means outflow; therefore, the use of this term is not restricted as to course or location, and it can be applied to describe the flow of water from a pipe or from a drainage basin. If the discharge occurs in some course or channel, it is correct to speak of the discharge of a canal or of a river. It is also correct to speak of the discharge of a canal or stream into a lake, a stream, or an ocean. (See also Streamflow and Runoff.)

Drainage basin. A part of the surface of the earth that is occupied by a drainage system, which consists of a surface stream or a body of impounded surface water together with all tributary surface streams and bodies of impounded surface water.

Drainage divide. The rim of a drainage basin. (See Watershed.)

Evaporation. The process by which water is changed from the liquid or the solid state into the vapor state. In hydrology, evaporation is vaporization that takes place at a temperature below the boiling point.

Evapotranspiration. Water withdrawn from a land area by evaporation from water surfaces and moist soil and plant transpiration.

Flow-duration curve. A cumulative frequency curve that shows the percentage of time that specified discharges are equaled or exceeded. (See Searcy, 1959.)

Gaging station. A particular site on a stream, canal, lake, or reservoir where systematic observations of gage height or discharge are obtained. (See also Stream-gaging station.)

Ground water. Water in the ground that is in the zone of saturation, from which wells, springs, and ground-water runoff are supplied. (After Meinzer, 1949, p. 385.)

Ground-water runoff. That part of the runoff which has passed into the ground, has become ground water, and has been discharged into a stream channel as spring or seepage water. See also Base runoff and Direct runoff.

Hydrologic budget. An accounting of the inflow to, outflow from, and storage in, a hydrologic unit, such as a drainage basin, aquifer, soil zone, lake, reservoir, or irrigation project.

Hydrologic cycle. A convenient term to denote the circulation of water from the sea, through the atmosphere, to the land; and thence, with many delays, back to the sea by overland and subterranean routes, and in part by way of the atmosphere; also the many short circuits of the water that is returned to the atmosphere without reaching the sea.

Hydrology. The science encompassing the behavior of water as it occurs in the atmosphere, on the surface of the ground, and underground. The science that relates to the water of the earth.

Infiltration. The flow of a fluid into a substance through pores or small openings. It connotes flow into a substance in contradistinction to the word percolation, which connotes flow through a porous substance.

Irrigation. The controlled application of water to arable lands to supply water requirements.

Meander. The winding of a stream channel.

Overland flow. The flow of rainwater or snowmelt over the land surface toward stream channels. After it enters a stream, it becomes runoff.

Percolation. The movement, under hydrostatic pressure, of water through the interstices of a rock or soil, except the movement through large openings such as caves

Precipitation. As used in hydrology, precipitation is the discharge of water, in liquid or solid state, out of the atmosphere, generally upon a land or water surface.

Reservoir. A pond, lake, or basin, either natural or artificial, for the storage, regulation, and control of water.

Return flow. That part of irrigation water that is not consumed by evapotranspiration and that returns to its source or another body of water. The term is also applied to the water that is discharged from industrial plants. Also called return water.

Riparian. Pertaining to the banks of a stream.

Runoff. That part of the precipitation that appears in surface streams. It is the same as streamflow unaffected by artificial diversions, storage, or other works of man in or on the stream channels.

Specific tractive force. Ratio of the force exerted on a vessel in motion to its weight.

Stream. A general term for a body of flowing water. In hydrology the term is generally applied to the water flowing in a natural channel as distinct from a canal. More generally as in the term stream gaging, it is applied to the water flowing in any channel, natural or artificial. Streams in natural channels may be classified as follows:

- Relation to time.
  - Perennial. One which flows continuously.
  - Intermittent or seasonal. One which flows only at certain times of the year when it receives water from springs or from some surface source such as melting snow in mountainous areas.
  - Ephemeral. One that flows only in direct response to precipitation, and whose channel is at all times above the water table.
- Relation to space.
  - Continuous. One that does not have interruptions in space.
  - Interrupted. One which contains alternating reaches, that are either perennial, intermittent, or ephemeral.
- Relation to ground water.
  - Gaining. A stream or reach of a stream that receives water from the zone of saturation.
  - Losing. A stream or reach of a stream that contributes water to the zone of saturation.
  - Insulated. A stream or reach of a stream that neither contributes water to the zone of saturation nor receives water from it. It is separated from the zones of saturation an impermeable bed.
  - Perched. A perched stream is either a losing stream or an insulated stream that is separated from the underlying ground water by a zone of aeration.

Streamflow. The discharge that occurs in a natural channel. Although the term discharge can be applied to the flow of a canal, the word streamflow uniquely describes the discharge in a surface stream course. The term "streamflow" is more general than runoff, as streamflow may be applied to discharge whether or not it is affected by diversion or regulation.

Transpiration. The quantity of water absorbed and transpired and used directly in the building of plant tissue, in a specified time. It does not include soil evaporation.

Underflow. The downstream flow of water through the permeable deposits that underlie a stream and that are more or less limited by rocks of low permeability.

Watershed. The divide separating one drainage basin from another and in the past has been generally used to convey this meaning. Drainage divide, or just divide, is used to denote the boundary between one drainage area and another. Used alone, the term "watershed" is ambiguous and should not be used unless the intended meaning is made clear. As used in this report, watershed refers to the entire drainage of the Gila River and basins refers to internal areas of the "watershed".

Water table. The upper surface of a zone of saturation. No water table exists where that surface is formed by an impermeable body.

APPENDIX A. BASE FLOW IN 1905

The effect of the many diversion dams along the rivers in the Gila River watershed is shown by the hydrographs of daily discharge for gages at Bartlett, Roosevelt and Coolidge dam sites (Figure 1.1) and the gage on the Gila River near Dome (Figure A1-A). The total gaged flow of the three tributary streams was 649 cfs on October 27, 1905 (Figure A1-B). Mostly because of settlers' diversions, there was no flow at downstream gage 09520500 on October 27, 1905.

Also, it is important to realize that the base flow of the Gila, Salt and Verde Rivers at USGS streamflow gages 09469500, 09500500 and 09510000 was also reduced by upstream diversions for irrigation in 1905.

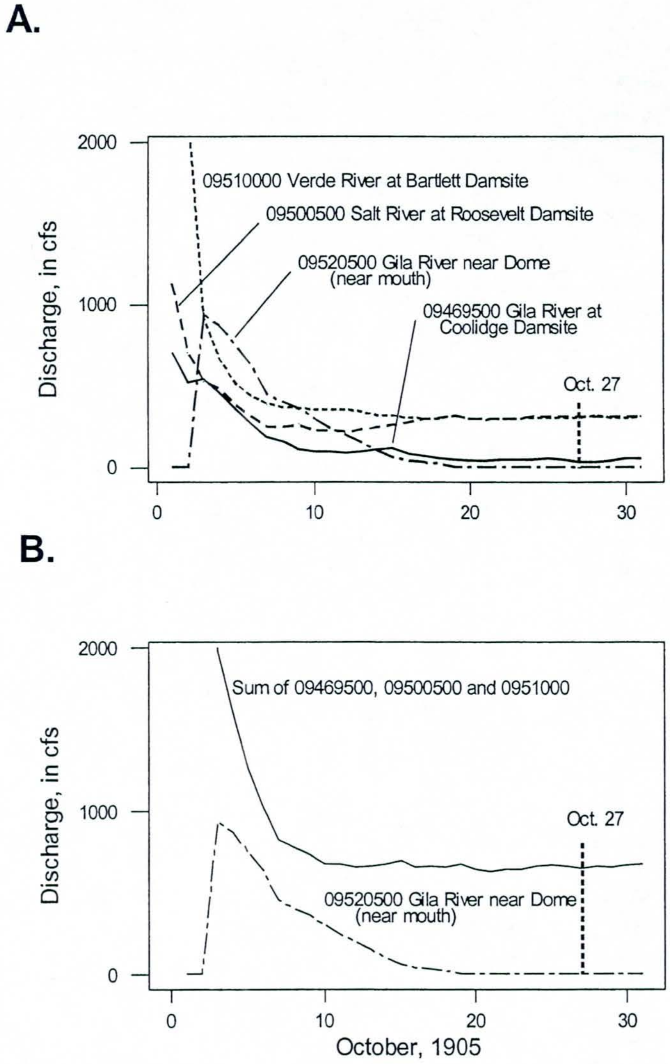


Figure A1. Hydrographs of mean daily discharge for October, 1905.

APPENDIX B. MATERIAL AND VEGETATION ALONG THE CHANNEL

The Gila River in the study reach is a sand-bed channel that is formed in sediment transported by the river and its tributaries. There is a wide range of size and shape of these fluvial sediments. The sediment is composed of rock particles from the watershed that are transported down the river to the Colorado River. Large floods transport larger particles such as boulders while smaller particles are also transported by much lesser flows. Rock particles become rounded and smaller because of abrasion as they are moved downslope. In general, the particle size of the river sediment is smaller downstream. However, there are large particles along the entire study reach partly because of large floods from the headwaters and partly because of boulder-, cobble- and gravel-transporting tributaries all along the Gila River. Thus, under natural conditions the typical channel sediment was sand but there was also both finer and coarser particles throughout the study reach.

Following large floods that destabilize the natural channel, the main channel reformed and the resulting size of the channel was related to the mean flow. As the channel reformed, finer sediment particles were washed away leaving larger particles along the bed and banks. Examples of this armoring effect are shown later in this Appendix. Present sediment provides clues of past sediment conditions.

B1. Vegetation

The banks may have been covered with vegetation based on early accounts of explorers and settlers (Appendix C). Trees along the channel banks would tend to stabilize the banks and narrowing of the main channel probably resulted. Thus, trees tended to stabilize the banks but the bare banks were rather stable in order for the trees to sprout and grow. Evidence of the trees that once lined the channel in the study reach has not been directly observed by the author.

B2. Additional soil characteristics

Much of the soil that formed in floodplain alluvium follow (U.S. Soil Conservation Service Reports (three reports)):

Gadsden Series: The Gadsden series consists of very deep well drained soils formed in stratified stream alluvium. Cadsden soils are on flood plains and have slopes of 0 to 3 percent. Mean annual precipitation is about 6 inches and the mean annual air temperature is about 71 degrees F.

Rock fragments - Averages less than 35 percent

Texture: Clay, silty clay, clay loam, silty clay loam; some soil profiles have strata (less than 2 inches) of coarser textures.

Glenbar Series: The Glenbar series consists, of very deep, well drained soils that formed in stratified stream alluvium. Glenbar soils are on flood plains and alluvial fans and have slopes of 0 to 3 percent. The mean annual precipitation is about 7 inches and the mean annual air temperature is about 71 degrees F.

Texture: Stratified clay loam. silly clay loam, loam. silt loam (averages I8 to 55 percent clay): some pedons have thin strata of contrasting textures.

Indio Series: The Indio series consists of very deep, well or moderately well drained soils formed in alluvium derived from mixed rock sources. Indio soils are on alluvial fans, lacustrine basins and flood plains and have slopes of 0 to 3 percent.

Rock fragments: less than 3 percent gravel and/or few small shell fragments.

Texture: stratified very fine sandy loam, loam, silt loam, silt (less than 18 percent clay and less than 15 percent fine and coarser sand).

Ripley Series: The Ripley series consists of very deep. well drained soils that formed in alluvium from mixed rock sources. They are on flood plains and alluvial fans. Slopes are 0 to 2 percent. Mean annual precipitation is about 5 inches and the mean annual air temperature is about 72 degrees F.

Texture: upper part of the control section is silt loam, silt or very tine sandy loam with less than 18 percent clay and less than 15 percent sand coarser than very fine sand-
Holtville Series

Holtville Series: The Holtville Series consists of deep, well drained soils formed in mixed and stratified alluvium. Holtville soils are on flood plains and basins and have slopes of 0 to 2 percent. The mean annual precipitation is about 4 inches and the mean annual temperature is about 76 degrees F.

Kofa Series: The Kofa series consists of very deep well drained soils that formed in stratified alluvium from mixed sources. Kofa soils are on flood plains and have slopes less than I percent.

Rock fragments - less than 15 percent in the upper part and as much as 65 percent in the sandy lower part.

Texture: Clay, silty clay, with thin strata of silty clay loam or silt textures.

Vint Series: The Vint series consists of very deep, somewhat excessively drained soils formed in stratified stream alluvium. Vint soils are on flood plains and have slopes of 0 to 5 percent. The mean annual precipitation is about 7 inches and the mean annual air temperature is about 71 degrees F.

Rock fragments - Usually nongravelly, but some pedons average as much as 15 percent

Texture: Dominantly loamy fine sand or fine sand, with thin strata of coarser or finer textures

Gilman Series: The Gilman series consists of very deep well drained soils that formed in stratified stream alluvium. Gilman soils are on flood plains and alluvial fans and have slopes of 0 to 3 percent. The mean annual precipitation is about 7 inches and the mean annual air temperature is about 71 degrees F.

Rock fragments - Less than 35 percent gravel

Texture: Loam, very fine sandy loam, silt loam: some have minor strata of finer or coarser textures.

Lagunita Series: The Lagunita series consist of very deep, excessively drained soils that formed in stratified stream alluvium from mixed sources. Lagunita soils are on flood plains and have-slopes of 0 to 5 percent. The mean annual precipitation is about 4 inches and the mean annual air temperature is about 72 degrees F.

Rock fragments - Mainly less than 15 percent gravel by volume.

Texture: Stratified loamy sand, sand, coarse sand, and loamy coarse sand.

A small sample of soils in the area adjacent to floodplains, that reflect tributary input to the floodplain, follow:

Carrizo series: The Carrizo series consists of very deep, excessively drained soils formed in stratified alluvium from mixed sources. Carrizo soils are on flood plains and alluvial fans, fan aprons and fan terraces and have slopes of 0 to 9 percent.

Rock fragments: averages 35 to 80 percent gravel, cobbles or stones.

Texture of the fine earth: coarse sand, sand. loamy coarse sand or loamy sand and is modified by stones, cobble, and/or gravel.

Estrella series: The Estrella series consists of very deep well drained soils that formed in stratified mixed alluvium. Estrella soils are on alluvial fans and have slopes of 0 to 5 percent. The mean annual precipitation is about 7 inches; and the mean annual air temperature is about 71 degrees F.

Rock fragments - Less than 35 percent in any one horizon

Texture: Loam, sandy loam, sandy clay, sandy clay loam, clay loam

B3. Recent photographs of larger bed and bank sediment.

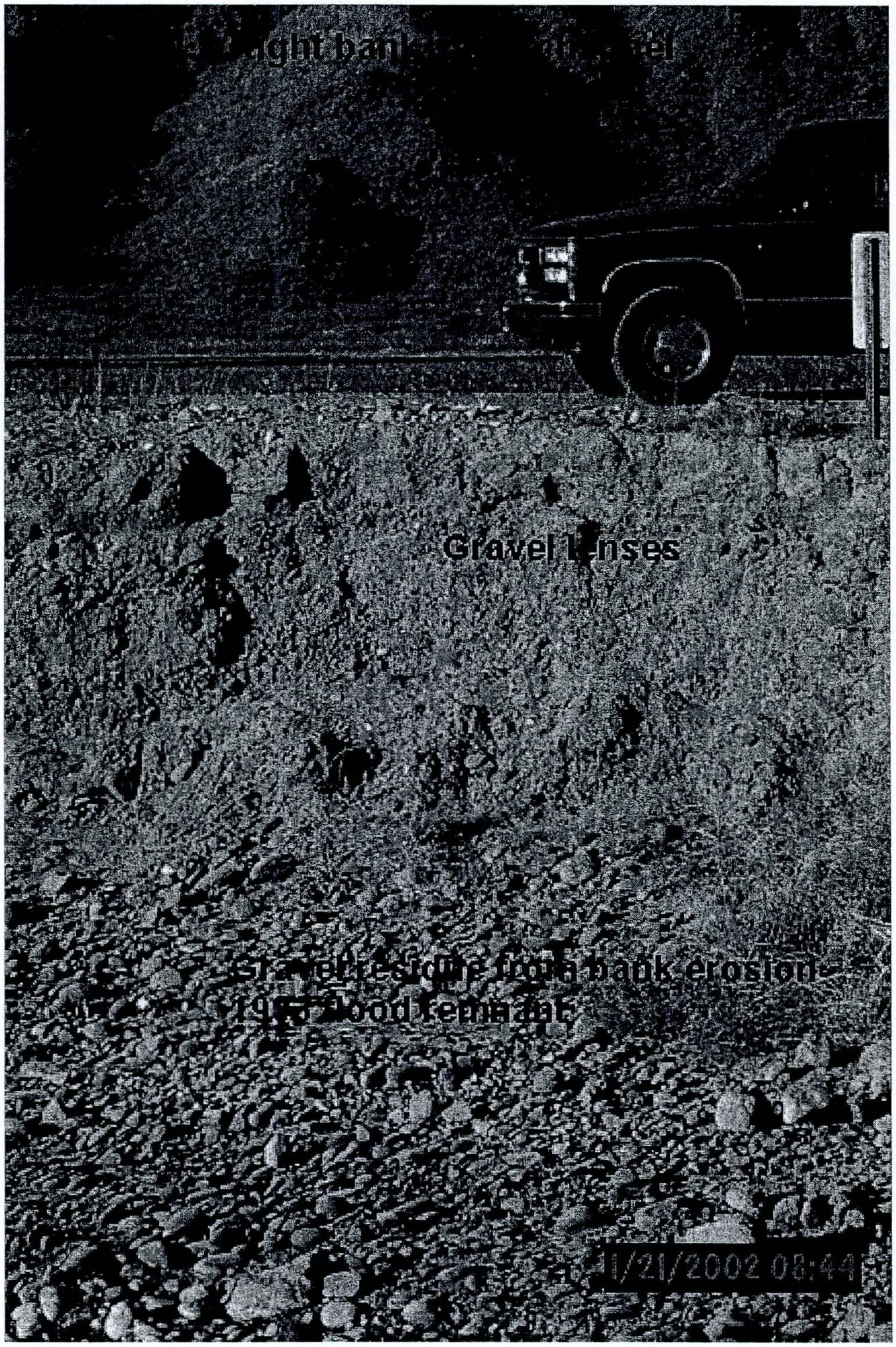


Figure B1. Bed and bank sediment at site 154.8 miles above the mouth in upper part of reach.

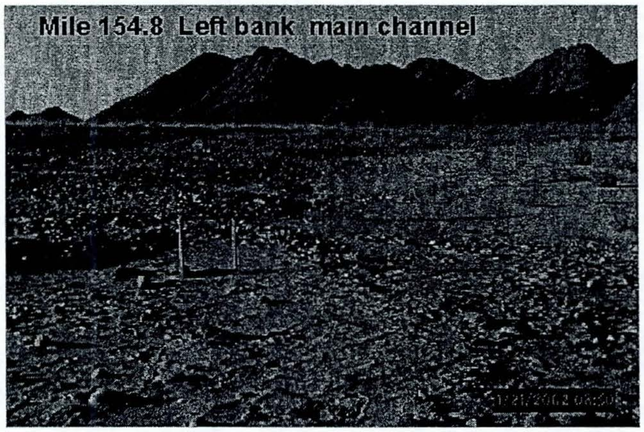


Figure B2. Left bank of main channel at mile 158.4. Frame is 1.5 ft x 1.5 ft.

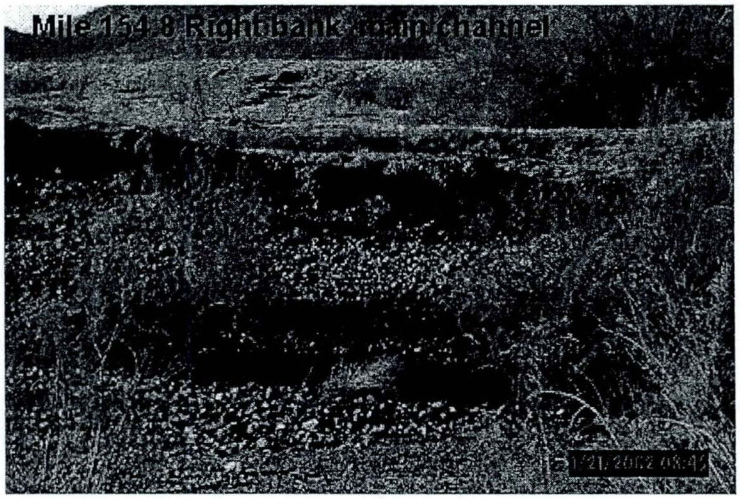


Figure B3. Right bank of main channel at mile 158.4.

The localized armoring shown in Figures B1-B3 is built as the non-moving coarser particles segregate from the finer material. The finer material is transported downstream and the coarser particles are gradually worked down into the bed, where they accumulate in a sub layer. Fine bed material is lifted up through this coarse sub layer and carried downstream with other material in transit. As sediment movement and channel forming progresses, an increasing number of non-moving particles accumulate in the sub layer and "armor" the bed surface. The channel is formed when fines can no longer be eroded from the underlying bed,

An armor layer sufficient to protect the bed against moderate discharges can be disrupted during high flow, but may be re-established as flows diminish.

Figure B4. Left bed at mile 158.4 (string grid is 1 inch x 1 inch-typical).

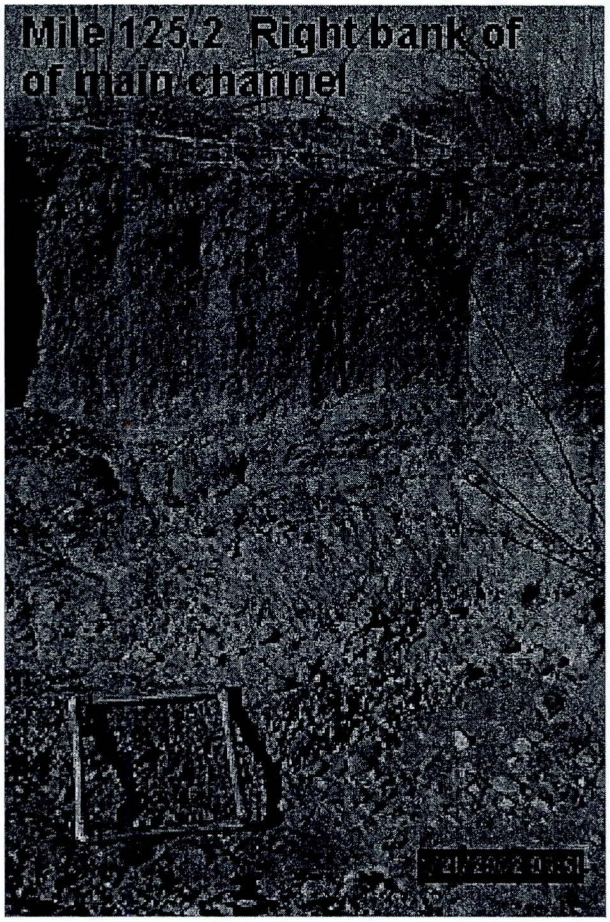
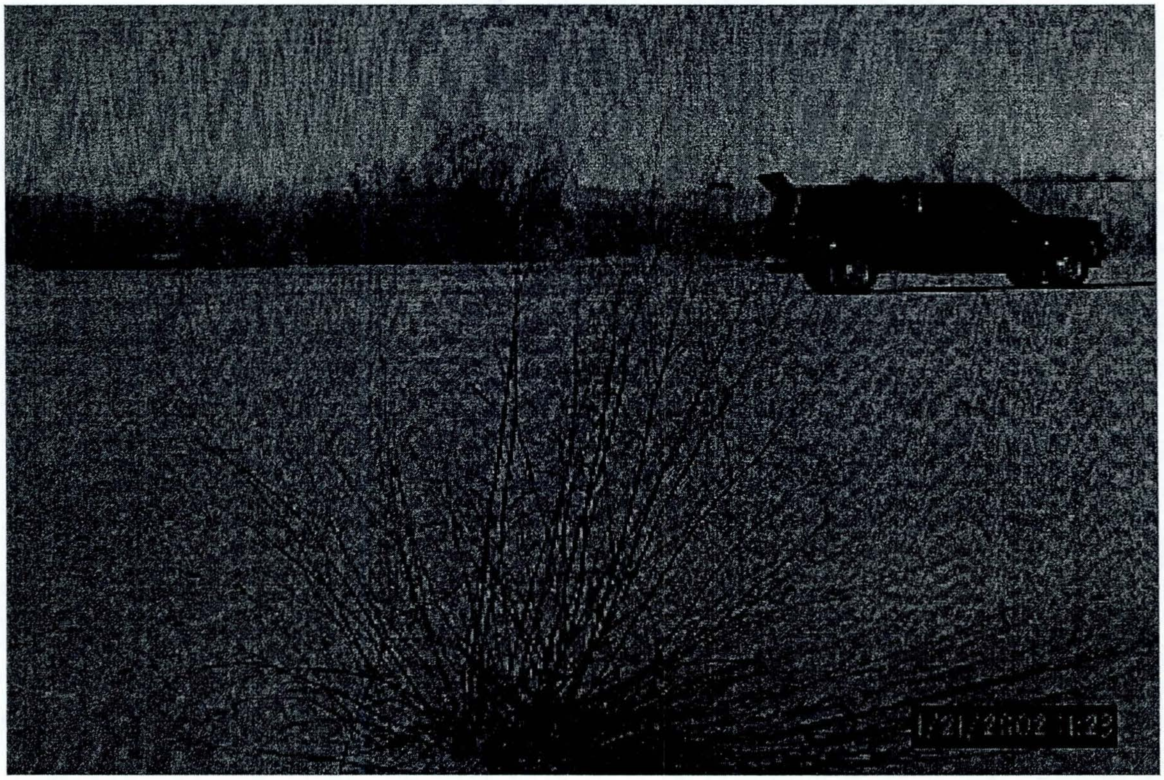
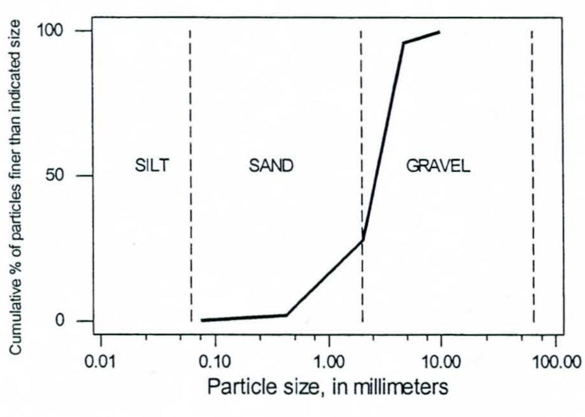


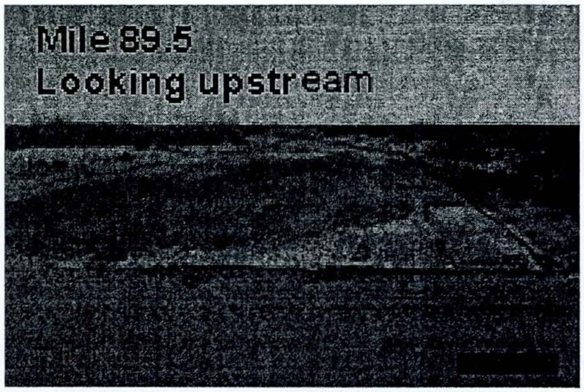
Figure B5. Right bank at mile 125.2 (orange frame is 1.5 ft x 1.5 ft-typical all photographs).



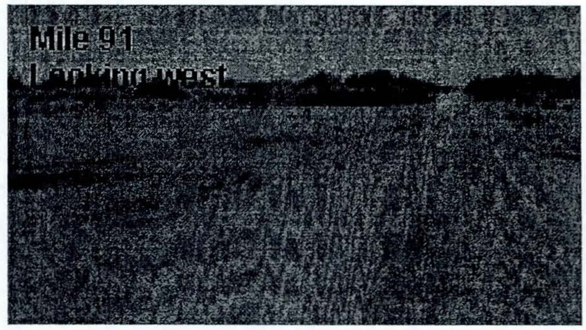


NOTE: Channel from here to the mouth is affected by levees and other manmade changes. Only a rough estimate of the natural channel material can be made for the lower 91 miles of the Gila River. The bed sediment that presently is visible is mostly silt and sand but there are areas of small-rounded gravel as shown above. A few scattered rounded cobbles were observed by the author.

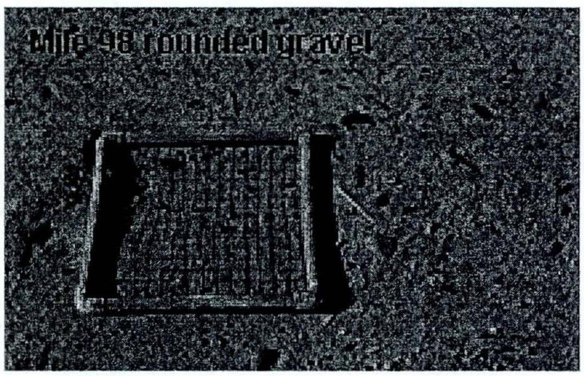
Figure B6. Bed material at Gila River 91 miles above mouth near middle of study reach.



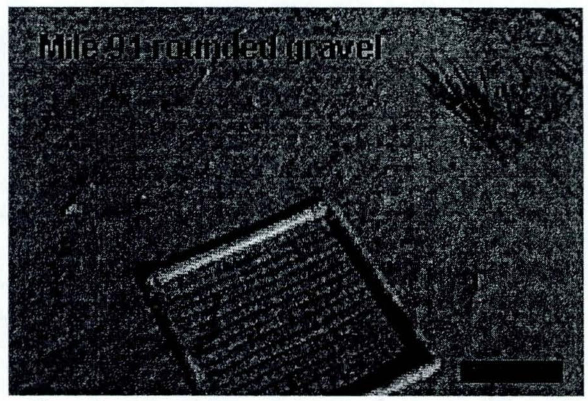
Looking upstream at main channel



Bank in background is manmade



Bed sediment with some gravel



Sandy gravel area.

Figure B7. Bed material at Gila River 89.5, 91 and 98 miles above mouth.

APPENDIX C. ACCOUNTS BY EXPLORERS OF NATURAL CHANNEL WIDTH AND DEPTH AND VEGETATION ALONG BANKS

The COE (1995) published several measurements or observations of channel width and depth of the Gila River as follows:

YEAR	WIDTH*	REMARKS*
1746	----	Willows and cottonwoods along Gila River below confluence with Salt River. Here the eye is regaled with creeks, marshes, fields of reed grass and an abundant growth of alders and cottonwood.
1775-1776		On the banks of the Gila are cottonwoods, willows, and mesquites.
1826-1827	200 yards	At confluence with Salt River.
1846-1847	60-80 yards	At Gila bend. Average depth of 3 ft.
1846-1848	150 yards	3-4 ft. deep.
1847	150 yards	3-4 ft. deep in places.
1849	<100 yards	Narrow at this point and flow rate is 6 miles/hr.
1849	----	River spread over large extent of ground forming several channels.
1856	150 ft.	Near mouth. Depth is variable.

* The accuracy and precision of the widths and depths is unknown.

The above pairs of channel widths and depths for 1846-1847, 1846-1848 and 1847 are shown on the following Figures C1 and C2. The relations are for the bed material shown in Table 3.1. The observations by explorers are of limited value because (1) the amount of flow in the Gila River was unknown and (2) the precision of the values is unknown. The explorer's accounts plot on each side of the width-depth and width-mean depth relations, suggesting some agreement with the hydraulic geometry relations. The dashed lines (Figures C1 and C2) represent the reported range of channel width or depth shown in the above table. These accounts are interesting but the usefulness is uncertain.

Figure C1. Relations between channel depth and width showing observations by explorers

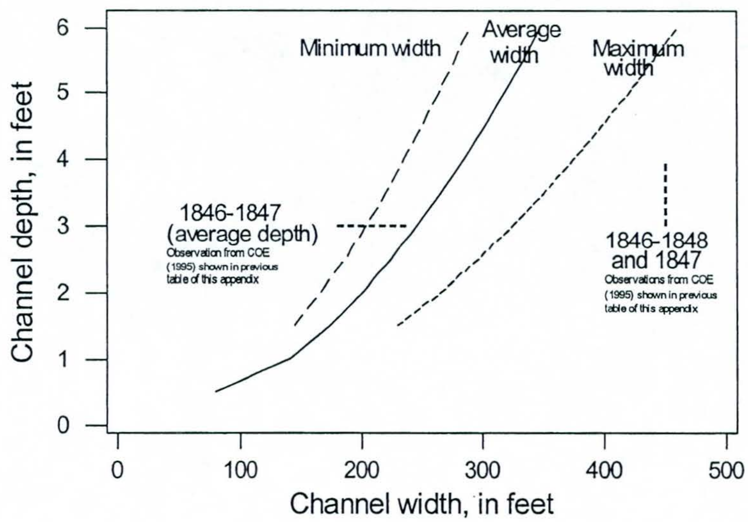
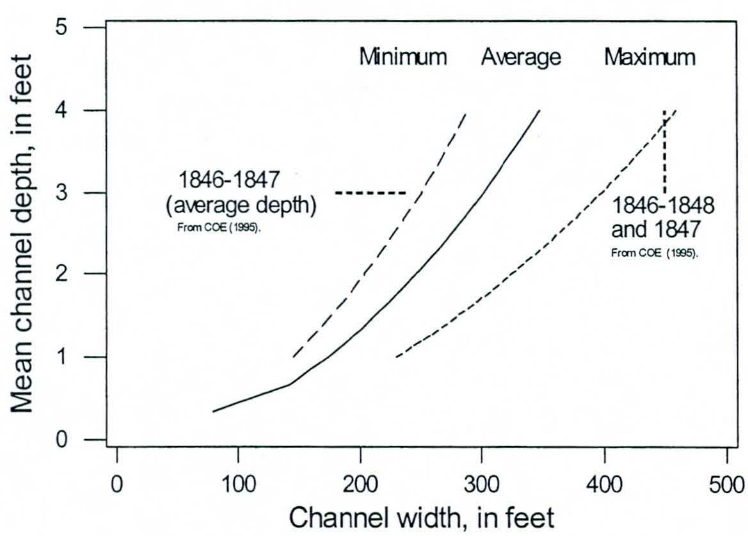


Figure C2. Relations between mean channel depth and width showing observations by explorers



APPENDIX D. CHECK OF ESTIMATED CHANNEL WIDTHS ALONG THE STUDY REACH

Estimated channel widths of the width-duration relation (Figure 3.2) are checked using surveyed widths along section boundaries from the original federal land surveys by the General Land Office. Land surveys were along section lines and crossings of the Gila River were identified and recorded. Distances and channel width along the section lines were surveyed using standards of the time (distance was measured with 66 ft long chain). Channel widths were recorded at all or nearly all crossings of the Gila River. Where the river channel intersected the section line at 90 degrees (perpendicular) the chained width was equal to the true width of the Gila River channel. Where the intersection of the river was not at 90 degrees, the measured width was greater than the true channel width. For example, if the angle of incidence was 45 degrees, the surveyed width for the particular discharge in the river at the time was 41 percent greater than the true channel width. Where the angle of incidence of the Gila River channel at a section line was small, the recorded width was considerably greater than the true width.

The surveyed channel widths of the original federal land surveys (Table D1) were of the channel width along the surveyed section boundaries. The width-duration relation for the surveyed channel width is shown by curve A in Figure 3.5. These surveyed widths (Ws) were equal to or greater than the true channel width (W) as defined by the following sketch of the angle of incidence (θ), in plan view, and the corresponding continuous probability density function.

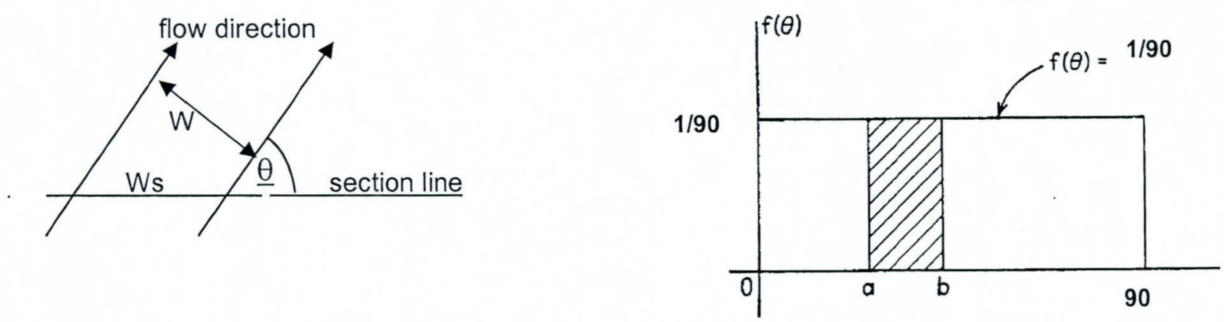


Figure D1. Angle of incidence of channel at section line and continuous probablity density function.

The relation between the surveyed width and the true width is:

$$Ws = W \text{ cosecant } \theta$$

where θ is any angle between 0 and 90 degrees.

The density function, that is a constant, is

$$f(\theta) = \frac{1}{90}, 0 \leq \theta \leq 90^0$$

Table D1. Channel widths at section boundaries along the Gila River below the confluence with the Salt River.

The sorted widths(Ws),in feet, shown below are from the original federal land surveys by the General Land Office

104	145	152	158	161	165	165	165	165
180	185	198	198	198	205	211	231	231
247	255	261	271	271	274	276	284	284
284	284	287	290	296	297	321	323	323
327	330	330	337	343	343	348	348	350
356	371	374	387	393	396	396	398	400
400	407	409	410	436	462	495	496	496
502	502	528	537	541	555	562	562	562
567	572	583	601	620	623	628	628	628
628	633	633	635	660	660	675	686	703
754	797	809	820	835	836	845	859	864
867	888	892	977	985	990	996	1031	1043
1094	1112	1123	1137	1196	1376	1399	1399	1435
1665	1716	1942	2079	2453				

Note: Widths >1,000 ft not plotted in Figure 3.5.
Channel width was measured with surveyor's chain and many bank locations were recorded to 0.01 chain or 0.01 x 66 ft/chain = 0.7 ft.

Since θ must be between 0 and 90 degrees, the probability P that an observed angle θ is between say, a and b, is proportional to the difference, b – a, such that

$$P = \frac{(b - a)}{90^0}$$

The values of a and b are between 0 and 90 and b is greater than a for this explanatory example.

The width-duration relation for the lower reach shown in Figure 3.2 is about the same as curve B, Figure 3.5: curve B includes the larger and smaller widths that are not shown in Figure 3.2. This relation (curve B) was modified to represent the effects of the angle of incidence as described above (Figure 3.5, curve C). Curve C was determined by (1) dividing curve B into 10 equal intervals of time (i.e., 0-10%, 10-20%,.........,90-100%), (2) multiplying the corresponding channel width at the midpoint for each interval by the cosecant of θ for 1 degree intervals from 0 to 90 degrees, (3) tabulating the resulting computed widths in order of magnitude, (4) determining the probability of each value and (5) plotting the values. The resulting Curve C represents the typical distribution of natural channel width at the section boundaries.

The computed width-duration relation at the section boundaries (curve C) compares favorably with the width-duration relation for the 122 widths surveyed between 1867 and 1892 (curve A). Curves A and C are comparable but curve A is for a short period of 26 years and curve C is estimated for natural conditions. Also, the surveyed channel widths (curve A) were impacted by diversions of settlers. Thus, width-duration curve A is an average curve for a 26-year period after settlers and before statehood and width-duration curve C is the average curve for natural conditions. The close agreement of curves A and C (Figure 3.5) confirms that the hydrologic and hydraulic geometry methods used for this assessment of navigability are reliable and also shows the effect of the diversions (1867-1892) are small.

The small impact of diversions during the late 1800s is also suggested by Burkham (1972). Burkham found the channel size and geometry of the Gila River in Safford Valley were about the same for 1846-1904.

APPENDIX E. CHANNEL WIDTH AND DEPTH FROM USGS TOPOGRAPHIC MAPS.

Estimates of the size and shape of the main channel were obtained for several cross sections from available old USGS topographic maps. Three channel cross sections that depict navigability characteristics for the study reach were selected. Because of the small map scale and large contour intervals, the resulting hydraulic estimates are approximate. Manning's equation (Barnes (1967), Thomsen and Hjalmarson (1991) and Jobson and Froehlich (1988)) was used to compute the hydraulic characteristics of the cross sections.

The following USGS maps that were used to assess the channel hydraulics are listed below. All maps except the Yuma Quad. are 15 minute series (Scale 1/62,500). The Yuma Quad is a 30 minute series (Scale of the Yuma Quad. is 1/125,000).

Name of map	Date of survey or map
Yuma, CA & AZ	1902-03
Fortuna, AZ	1902-03 & 1925-26.
Laguna, AZ	1955
Welton, AZ	1926
Sentinel, AZ	1950
Mohawk, AZ	1926
Stoval, AZ	1950
Dendora Valley, AZ	1951
Aztec, AZ	1926-27
Woolsey Peak, AZ	1951
Cotton Center, AZ	1951
Arlington, AZ	1962
Buckeye, AZ	1958
Avondale, AZ	1946
Phoenix, AZ	1903,04,12
Mesa, AZ	1903,04,13
Maricopa, AZ	1952
Gila Butte, AZ	1903,04,14
Gila Butte, AZ	1952
Sacaton, AZ	1904-06

Two sites represent typical main channels at the upper and lower ends of the study reach (Figures E1 and E2, respectively). The third site, depicted on the 1951 Cotton Center map, may represent a worst-case condition for navigability where the river was composed of two anabranches. This possible worst-case condition is of limited use because the topography is based on aerial photography of 1947, photos that were taken some 80 to 90 years after the settlers arrived, and therefore are not likely to represent natural conditions. The channel geometry for the three channels was used because it was the earliest available. The computed flow depths at base flow are about equal to or more than the depths for the hydraulic geometry method. Depth-discharge relations for the three sites follow.

Figure E1. Depth-discharge in the main channel at cross section 5 miles below Gillespie Dam. From topographic maps.

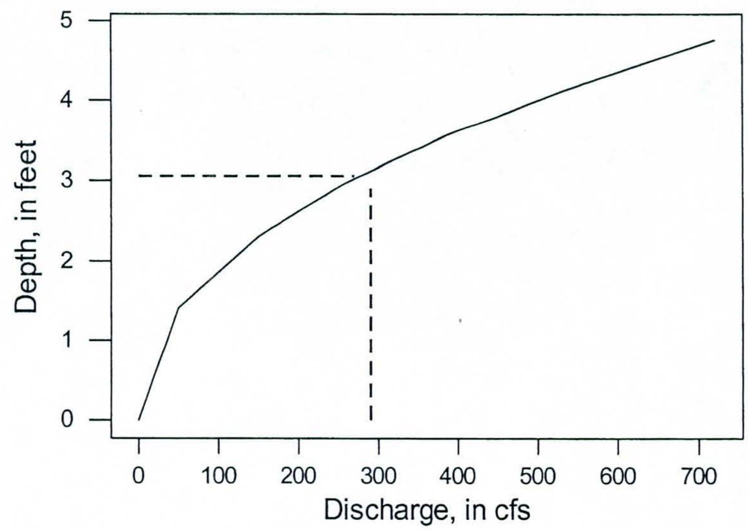


Figure E2. Depth-discharge in the main channel at cross section nr Yuma (Represents section in Yuma area estimated from topography)

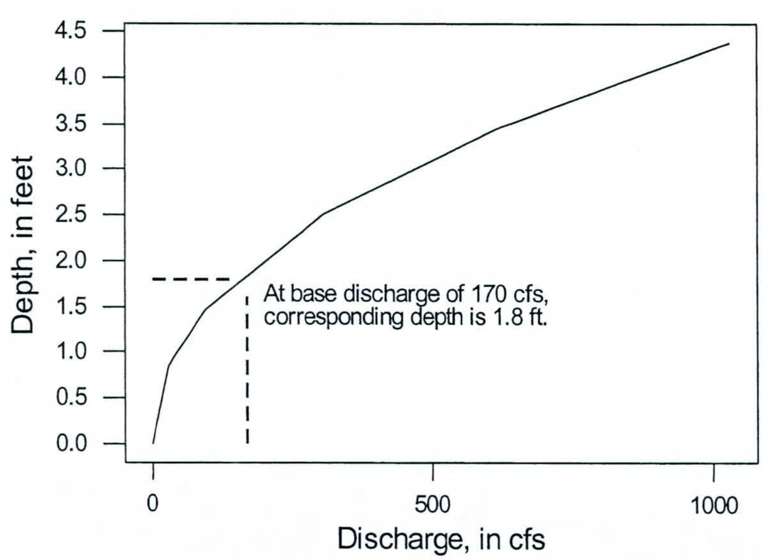


Figure E3. Depth versus total discharge for three channels located 3.5 miles below Gillespie Dam