Gila

11-17-05
Mark McGinnis

CONFIDENTIAL
NOTES

THE ABILITY TO NAVIGATE THE GILA RIVER UNDER NATURAL CONDITIONS

BELOW THE CONFLUENCE WITH THE SALT RIVER TO THE MOUTH AT YUMA, ARIZONA

BY
HJALMAR W HJALMARSON, PE

FOR
HELM & KYLE, Ltd

025

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——NOTES——
ANALYSIS OF THE ABILITY TO NAVIGATE THE GILA RIVER UNDER NATURAL CONDITIONS (BELOW THE CONFLUENCE WITH THE SALT RIVER TO THE MOUTH AT YUMA, ARIZONA)

by Hjalmar W. Hjalmarson, PE
For Helm and Kyle, Ltd

My limited research on the history of navigability of the Gila River suggests it was not used on a regular basis for any kind of water transportation of bulk commodities such as furs or covered wagons or people. There are a few historic accounts that suggest the river was used for navigation such as for the transport furs-there was trapping along the river. The navigability is mentioned in the Treaty of Guadalupe Hidalgo and this is presented later in these notes. Clearly, no accounts that the river was developed for navigation were found. An obvious problem is there is little recorded history in this part of the world before about 1850.

There were at least two ferrys(Hayden Ferry on the Salt River and Morgan Ferry downstream on the Gila) that have significance. These ferrys are not considered a form of navigation for this study. Rather, the mere need for the ferries suggests a channel geometry of the river that is typical of natural rivers. Because the appearance of the channel has changed because of human impact such as the several reservoirs, irrigation diversions, introduction of salt cedar vegetation and lowering of gropund-water levels, the need for the ferries suggests a single natural channel rather than the present braided appearing channel. These ferries support the hydraulic geometry relations that were used in this study to simulate the physical characteristics of the natural channel.

To avoid any arbitrary assessment of navigability, the physical conditions defining navigability developed by the USGS were used. The method of description and comparison developed by Walter Langbein, based upon the specific force required to propel a vessel upstream, was used. 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 of analysis suggests that the natural conditions of the Gila River were favorable for upstream commercial navigation by diverse shallow-draft craft.

Win Hjalmarson
12 July 2001

ENGLISH TO METRIC CONVERSION FACTORS

To Convert From To Multiply
By

Length Conversions
Inches
Feet
Miles

Millimeters
Meters
Kilometers

25.4
0.3048
1.6093

Area Conversions
Acres
Acres
Square Miles

Hectares
Square meters
Square kilometers

0.4047
4047
2.590

Volume Conversions
Gallons
Cubic yards
Acre-Feet
Acre- Feet

Cubic meters
Cubic meters
Hectare- meters
Cubic meters

0.003785
0.7646
0.1234
1234

Other Conversions
Feet/mile
Tons
Tons/square mile
Cubic feet/second
Degrees Fahrenheit

Meters/kilometers
Kilograms
Kilograms/square kilometer
Cubic meters/sec
Degrees Celsius

0.1894
907.2
350.2703
0.02832
(Deg F-32) x (5/9)

INTRODUCTION

This report is in response to a request by John Helm, Esq. that I assess the navigability of the Gila River for natural conditions, at the time of Arizona statehood. 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 provided me, (3) published reports by the U. S. Geological Survey and the Federal agencies, and (4) federal definitions of navigable and natural flow. Natural flow of the Gila River is for hydrologic conditions before about 1860.

The "equal footing" doctrine of the U. S. Constitution has had an important effect on the property rights of new States to soil under navigable waters. In Pollard v. Hagan, the U. S. Supreme Court held that the original States had reserved to themselves the ownership of the shores of navigable waters and the soils under them, and that under the principle of equality the title to the soils of navigable water passes to a new State upon admission. States like Arizona, who have not acted on its claim of ownership, may act on this claim. In other words, Arizona could receive ownership of the beds of all navigable rivers on the date of statehood.

The natural flow condition is given in the following federal test for determining navigability:

> [T]hat streams or lakes which are navigable in fact must be regarded as navigable in law; that they are navigable in fact when they are used, or are susceptible of being used, in their natural and ordinary condition, as highways for commerce, over which trade and travel are or may be conducted in the customary modes of trade and travel on water; and further that navigability does not depend on the particular mode in which such use is or may be had - whether by steamboats, sailing vessels or flat boats - nor on an absence of occasional difficulties in navigation, but on the fact, if it be a fact, that the stream in its natural and ordinary condition affords a channel for use for commerce.

In other words, the Gila River is considered navigable if it was used or was susceptible to being used as a highway for commerce at the time of statehood for the natural condition of flow.

The ownership of the bed of the Gila River, downstream of the confluence with the Salt River, depends on the navigability of the river when Arizona became a state on February 14, 1912. If the Gila River was navigable the state of Arizona become the owner of the bed.

APPROACH

The ability to travel by water 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, especially laden with furs, will be a few inches. The velocity of flow is also a consideration because upstream travel can be restricted by high flow velocities. There are other factors of an economic and commercial nature that may be less obvious. Those non-hydraulic factors, while important to the actual performance of navigation, are not important to the general assessment of naviagbility. The question "Was the Gila River capable of being navigated?" must be answered before the economic and commercial factors are considered.

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. In order for a vessel to move upstream, additional energy to raise the vessel is needed. This raising force is known as slope drag. The squat of a vessel is the increase 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 must be evaluated.

The term navigability is assumed to apply to the potential use of the natural channel of the Gila River for navigation without maintanence and structures such as locks, dams, training and stabilization structures and corrective dredging, that are considered in modern feasibility studies of navigation(U. S. Army Corps of Engineers Engineering Manual EM 1110-2-1611). Such customary engineering measures to develop and improve the waterway to provide efficient movement of vessels and minimize delays is beyond the scope of this general assessment. Maintanence and structural improvements are related to how the river might be used for navigation. The initial question "Could the Gila River have been used for navigation?" must be answered first.

Parameters included in this study, in accordance with guidelines in U. S. Army Corps of Engineers Engineering Manual EM 1110-2-1611, are : (a) Frequency and duration of river stages and discharges based on existing USGS reports and records, (b) general channel width, depth, and velocity during low and mean flows, (c) general composition of the bed and banks and general sediment characteristics of the river and changes produced by variations in discharge. 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 navigability of the Gila River.

PURPOSE OF THIS STUDY AND THESE NOTES

The purpose of these notes is to describe the natural hydrologic conditions related to navigation that would have existed along the Gila River below the confluence with the Salt to the mouth on February 24, 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 completed on the Salt River. Abstractions of natural flow at statehood were significant and became more significant after statehood as more dams were built and stored ground-water was pumped from the large aquifers upstream.

The natural hydrology for the Gila River from the Salt River to Yuma is based largely of published estimates of natural hydrology for rivers in Central Arizona by the U. S, Geological Survey. This natural hydrologic condition was used to estimate the navigability of the Gila River.

The river is considered navigable if it was used or was susceptible to being used as a highway for commerce at the time of statehood. The question -- Could the Gila River be considered navigable at the time of statehood had there been no impact of man? –is answered in this report.

BACKGROUND

Federal law governs the legal standard for establishing navigability to determine an equal footing claim. This means that Arizona could have aquired ownership of the beds of navigable rivers on February 24, 1912, the date of statehood. Arizona is presently acting on its title to lands beneath navigable waters within its boundaries.

The federal test for determining navigability

> [T]hat streams or lakes which are navigable in fact must be regarded as navigable in law; that they are navigable in fact when they are used, or are susceptible of being used, in their natural and ordinary condition, as highways for commerce, over which trade and travel are or may be conducted in the customary modes of trade and travel on water; and further that navigability does not depend on the particular mode in which such use is or may be had - whether by steamboats, sailing vessels or flat boats - nor on an absence of occasional difficulties in navigation, but on the fact, if it be a fact, that the stream in its natural and ordinary condition affords a channel for use for commerce.

In other words, the Gila River is considered navigable if it was used or was susceptible to being used as a highway for commerce at the time of statehood. The "natural and ordinary condition" of the river is considered the same as predevelopment hydrologic condition in this report.

Arizona Navigable Stream Adjudication Commission (ANSAC)

At the direction of state legislation a board, the Arizona Navigable Stream Adjudication Commission (ANSAC), was appointed by the governer to identify river reaches that were navigable at statehood. To assist ANSAC determine which streams were navigable a report "Gila River Navigability Study" was written by Arizona State Land Department(SLD). The purpose of the SLD study was to identify, catalogue, gather and evaluate existing available information relating to the Gila River. The report summarizes factual information relating to the navigability of the Gila River as of the time of statehood. The report provides information on the portion of the Gila River located between Solomon and the confluence with the Colorado River. The report does not make a recommendation or draw any conclusions regarding title navigability of the Gila River.

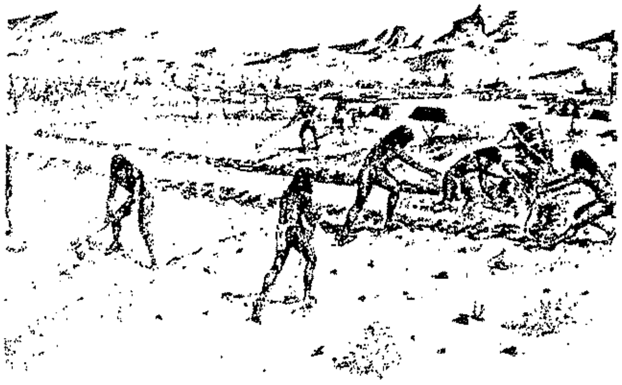
The report consists of several related parts. First, archaeological information for the Gila River relating to river uses is presented to set the long-term context of river conditions and river uses. Second, historical information from the periods prior to and including the time of statehood are discussed with respect to river, modes of trasportation, and river conditions. Third, limited oral history information for the river is also presented. Fourth, historical and modern hydrologic and hydraulic data are summarized to illustrate past and potential flow conditions in the river. Fifth, a review of geologic influences on stream flow and river conditions is presented. Sixth, land use and land ownership information are described and presented in a geographic information systems format. According to the preface of the SLD report, the use of the document is governed by the Arizona State Land Department and the Arizona Navigable Stream Adjudication Commission.

U. S. Geological Survey

The U. S. Geological Survey has published several reports relating to the predevelopment hydrology of the Gila River. Information in the following USGS reports formed the basis of the hydrology analysis: 1) Thomsen and Eychaner(1991), 2) Thomsen and Porcello (1991), and Freethey and Anderson(1986). Several other USGS reports formed the basis of the hydraulic analysis. A few of these reports are: 1) Leopold and Maddock(1953),

History of Water Development

Before the arrival of settlers, the Indians diverted water from the Gila River for the irrigation of cropland. It is easy for the author to imagine some impact of the indian activities on the flow in the Gila River. The indians irrigated a few thousand acres of crops using canals as shown below.



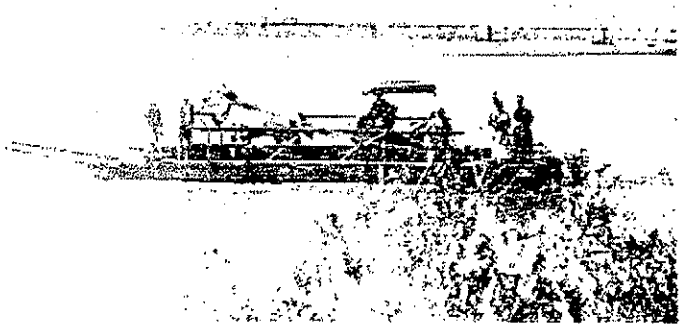
From: Water for the Southwest, American Society of Civil Engineers publication No. 3.

The Treaty of Guadalupe Hidalgo, ending the Mexican War, was signed on February 2, 1848, by Nicholas P. Trist for the United States and by a special commission representing the collapsed government of Mexico. Trist disregarded a recall to Washington, and negotiated the treaty in violation of most of his instructions. The U.S. Senate reluctantly approved the treaty. Reference to navigability along the river Gila is made in the following article of the treaty.

ARTICLE VII

The river Gila, and the part of the Rio Bravo del Norte lying below the southern boundary of New Mexico, being, agreeably to the fifth article, divided in the middle between the two republics, the navigation of the Gila and of the Bravo below said boundary shall be free and common to the vessels and citizens of both countries; and neither shall, without the consent of the other, construct any work that may impede or interrupt, in whole or in part, the exercise of this right; not even for the purpose of favoring new methods of navigation. Nor shall any tax or contribution, under any denomination or title, be levied upon vessels or persons navigating the same or upon merchandise or effects transported thereon, except in the case of landing upon one of their shores. If, for the purpose of making the said rivers navigable, or for maintaining them in such state, it should be necessary or advantageous to establish any tax or contribution, this shall not be done without the consent of both Governments. The stipulations contained in the present article shall not impair the territorial rights of either republic within its established limits.

A photograph of Hayden's Ferry on the Salt River, a major tributary to the Gila River, at Tempe, Arizona in 1895.



Courtesy of Salt River Project.

An illustration of the Gila River near Gila Bend in 1853-56 is shown below. The width of the river appears to be about 300 feet. The banks are lined with trees. Note the swimmers and the woman with the water bucket at the wagon. It is interesting that a similar channel is computed later in this report using hydraulic geometry techniques.

From: U. S. Pacific Railroad Exploration and Surveys, Explorations for a railroad Route from the Mississippi River to the Pacific Ocean—General Report (washington, D. D., 1983-6), plate VI.

Early diversions by settlers and major dams in the Gila River watershed.

DATE	DAM/RESERVOIR	RIVER
1860-80	Diversion dams	All
1911	Roosevelt	Salt
1927	Apache	Salt
1927	Pleasant	Aqua Fria
1928	San Carlos	Gila
1930	Saguaro	Salt
1938	Canyon	Salt
1939	Bartlett	Verde
1949	Horseshoe	Verde
1959	Painted Rock	Gila

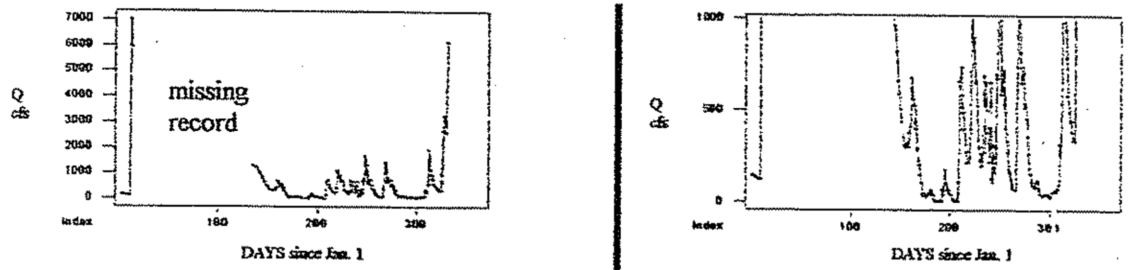
Diversions of streamflow for irrigation of crops increased greatly during the 1860s and 1870s. The base flow was affected the greatest because diversion dams were more effective after high-flow periods of melting snow. Also, high flows would wash out the diversion dams. Thus, the numerous diversions had a large impact on the base flow in the study reach starting in about 1860.

Roosevelt Dam was completed in 1911 on the Salt River followed by several other large dams with reservoirs.. Most of the Gila River in the study reach is now dry, or nearly dry, most of the time. The major reservoirs and many diversions and flood control dams have significantly changed the flow in the Gila River as depicted by the dry river channel shown in the photo of July 23, 1996 near Gila Bend below. The dry channel in the scene is very different from the tree-line river channel depicted in the previous illustration of the Gila River near Gila Bend in about 1853-56

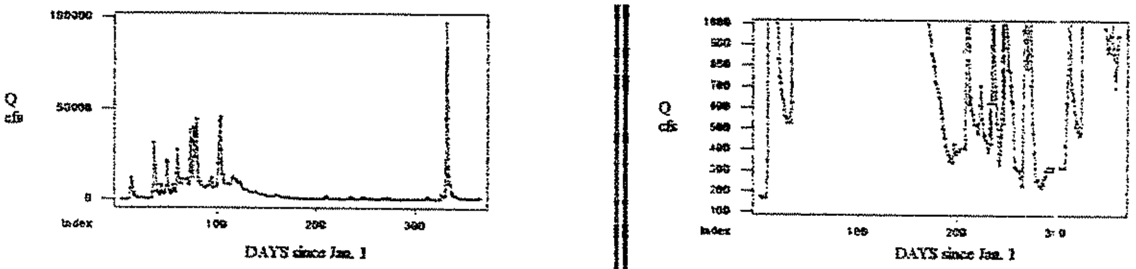
HYDROGRAPHS OF DAILY DISCHARGE, 1905, AT USGS GAGES 09469500, 09500500, 095100000 AND 09520500

Graphs on the left are for total discharge and graphs on the right are for discharge less than 1,000 cfs for the same period. There are many diversions for irrigation along the rivers in the watershed but there are no major storage reservoirs(Roosevelt Dam was not completed until 1911). The effects of the many diversions is evidenced by the periods of no flow at the gage near the mouth(bottom graph). For example, one Oct. 27, 1905 (see day 300 on red line below). the mean daily flow was 31, 313 and 305 cfs at upstream stations 09469500, 09500500 and 09510000(a total of 649 cfs) but there was no flow at station 09520500 near the mouth.

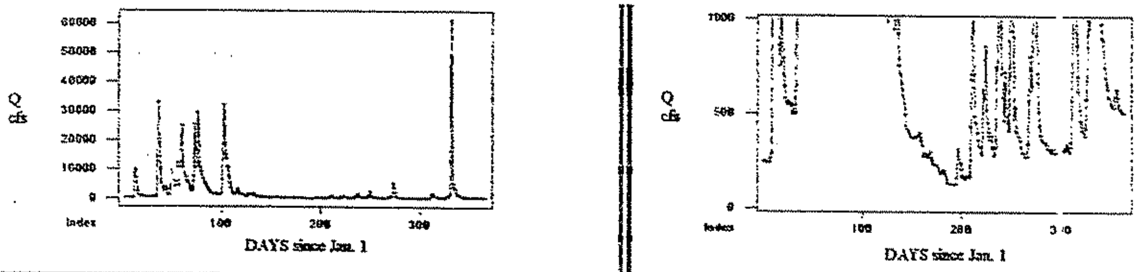
09469500 Gila River at Coolidge Damsite



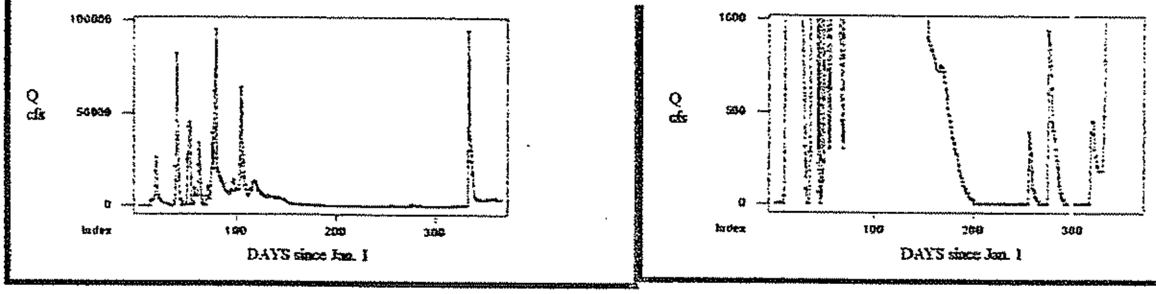
09500500 Salt River at Roosevelt Damsite



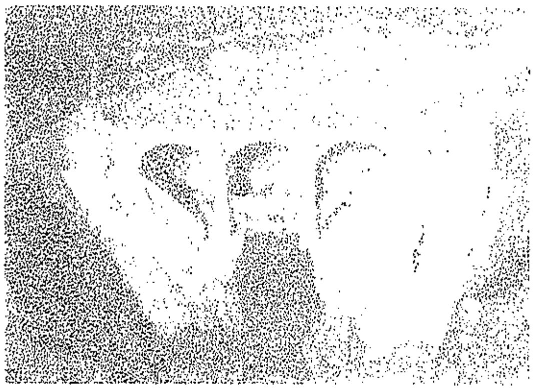
09510000 Verde River at Bartlett Damsite



09520500 Gila River near Dome, Az (near mouth)

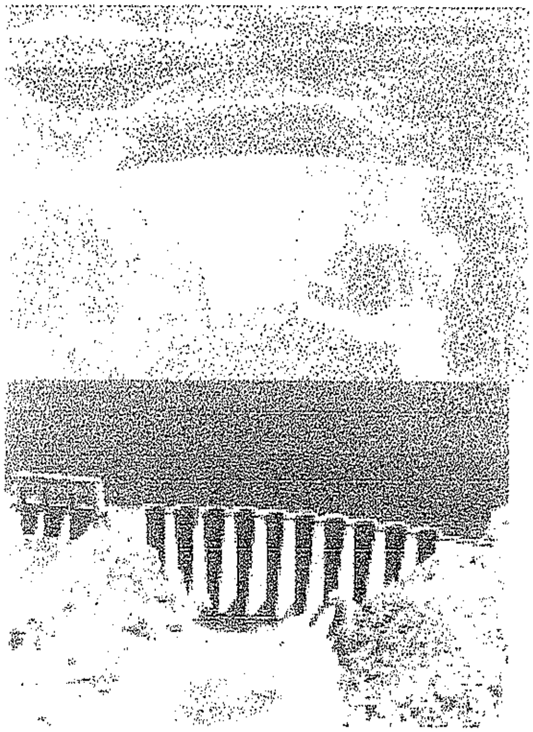


THE DAMS AND RESERVOIRS SHOWN ON THIS PAGE REPRESENT THE LARGE HUMAN IMPACT ON THE NAVIGABILITY OF THE GILA RIVER.



Coolidge Dam on the Gila River

Roosevelt Dam on the Salt River



Bartlett Dam on the Verde River

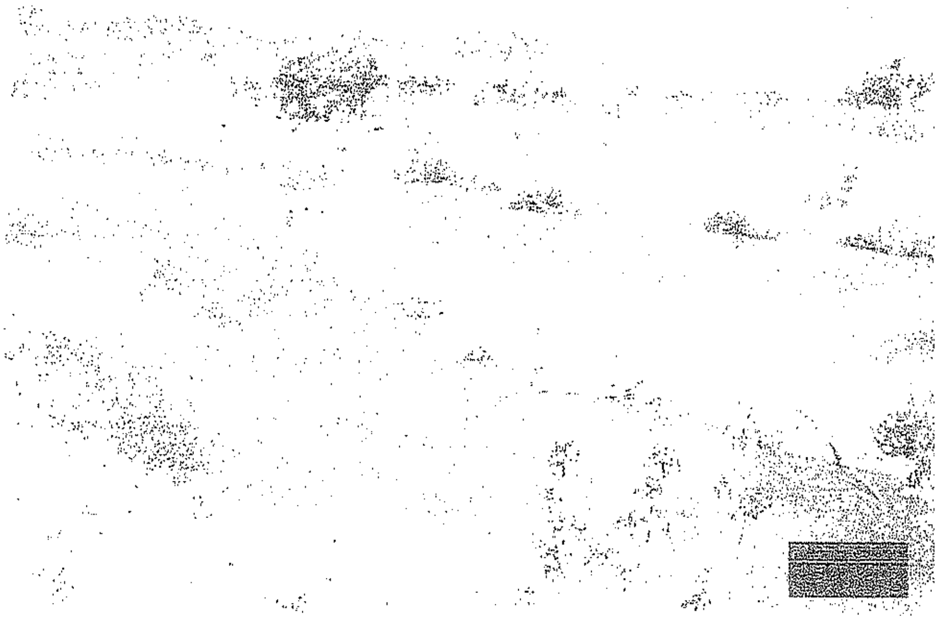
Stewart Mountain Dam on the Salt River

Mormon Flat Dam on the Salt River

Horse Mesa Dam on the Salt River

The appearance of the Gila River may have resembled the Verde River River in the Verde Valley of central Arizona shown below. The Verde River is a tributary to the Gila River. Obviously, because the Verde River is a tributary and smaller than the Gila River, the channel of Gila River was much larger than the channel in the scene below.

When settlers arrived in the 1860s and occupied land along the rivers, they built many diversions for irrigation of crops. Some of the diversions resembled the dam and canal in the scene below. The View is looking upsteream at an earth dam that diverts flow from the Verde River to the canal(yellow arrow) in the foreground.



Water Equivalents

What is a cfs? What is an acre-foot?

1 Cubic Foot = 7.48 Gallons = 62.4 Pounds

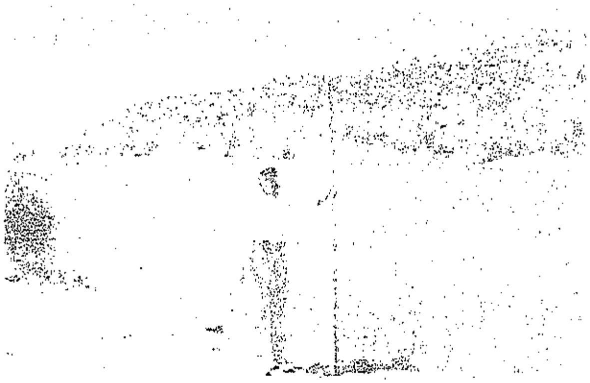
1 Acre-Foot (AF) = 43,560 Cubic Feet
= 325,851 Gallons

1 Cubic Foot per Second (cfs) = 448.83 Gallons per Minute (gpm)

1 cfs for 24 Hours = 1.9835 Acre-Feet
for 1 Year = 723.97 Acre-Feet

In this report a flow in the Gila River of about 300 cfs is used. It is equal to a volume of water 10 feet high and 10 feet wide flowing a distance of 3 feet in one second. It is equal to 2,244 gallons of water flowing each second.

View of Salt River near Roosevelt, Arizona
showing about 300 cfs.



IMPORTANT TERMS

(SEE ALSO GLOSSARY)

Alluvial basin	Much of the Gila River watershed has sharply rising mountains separated by broad alluvial basins. The basins are filled with permeable sediments. These basin-fill deposits form a system of aquifers in central Arizona that once supplied base runoff to the Gila River.
Natural flow	The rate of water movement past a specified point on a natural stream from a drainage area for which there have been no effects of man caused by stream diversion, storage, import, export or return flow. See runoff below.
Navigability	The ability to navigate or travel by water.
Predevelopment	Before about 1860. Considered the natural condition when ground-water systems were in equalibrium—long-term inflow was equal to long- term ourflow and no change in storage occured.
Runoff	The discharge that occurs in a natural channel. Although the term discharge can be applied to the flow of a canal, the word runoff uniquely describes the discharge in a surface stream course. This discharge is not affected by diversion or regulation. Direct runoff is water that flows over the land surface to the stream. Base runoff is ground water discharge that was present throughout the year in the Gila River.
Settler	Mostly people who arrived in the region after the indians.
Tributary	A smaller river(for example the Salt River) or stream that flows into a larger river(the Gila) or stream. Usually, a number of smaller tributaries merge to form a river. Hydrologists tend to think of creeks as small(like Oak Creek at Sedona, Arizona), streams being mid-size, and rivers being the largest.
Watershed	The land area that drains water to a particular river, like the Gila River. Also refered to as the *drainage area*. The watershed of the Gila River encompasses about 58,000 square miles.

SCOPE OF REPORT

This report presents the results of a quantitative estimate of the navigability of the Gila River near Gillespie Dam based largely on USGS reports, USGS stream gage records and topographic maps. Several USGS reports on the flow charactersitics 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 analysis that is presented. Information in other reports by federal agencies mostly on navigation also was used. Focus was on the use of published information and the use of standard engineering and hydrologic methods. Every effort was mas to document results and produce a factual and unbiased report.

Other supportive information included field notes for surveys along the Gila River in the late 1800s by the U. S. Bureau of Land Management, historic descriptions of the Gila River, historic accounts of navigation including the use of ferries and early photographs of the river. Hydraulic conditions along the channel of the Gila River were also obtained from *Historic Descriptions of the River* by the U. S. Bureau of Land Management since 1867(Arizona State Land Department, Gila River Navigability Study-Draft Final Report, September, 1996). Other useful information was in *Historical Overview/River Chronology* of the same report. Channel characteristics shown on old USGS topographic maps also were used.

The time for this estimate of navigability is on or about February 24, 1912, the date of statehood. However, focus is on hydrologic and hydraulic conditions before the settlers arrived in about 1860. These pre-settler conditions are considered the natural condition of the Gila watershed. All available data and information that could be used to improve the analysis were used.

The location of this estimate is for the reach of the Gila River downstream of the confluence with the Salt River to the mouth of the Gila River. Many diversion dams were used by the settles for irrigation upstream of this reach. There were also several diversions for irrigation within this reach. For example, at the site of the present Gillespie Dam, that was built in about 1921, there were previous irrigation diversion dams but these older dams were destroyed by floodwater.

The study was performed in three basic steps as follows:

1. Estimate the amount and temporal distribuation of natural (predevelopment) runoff for the Gila River upstream of Gillespie Damsite at the confluence of the Salt River to the mouth of the river.

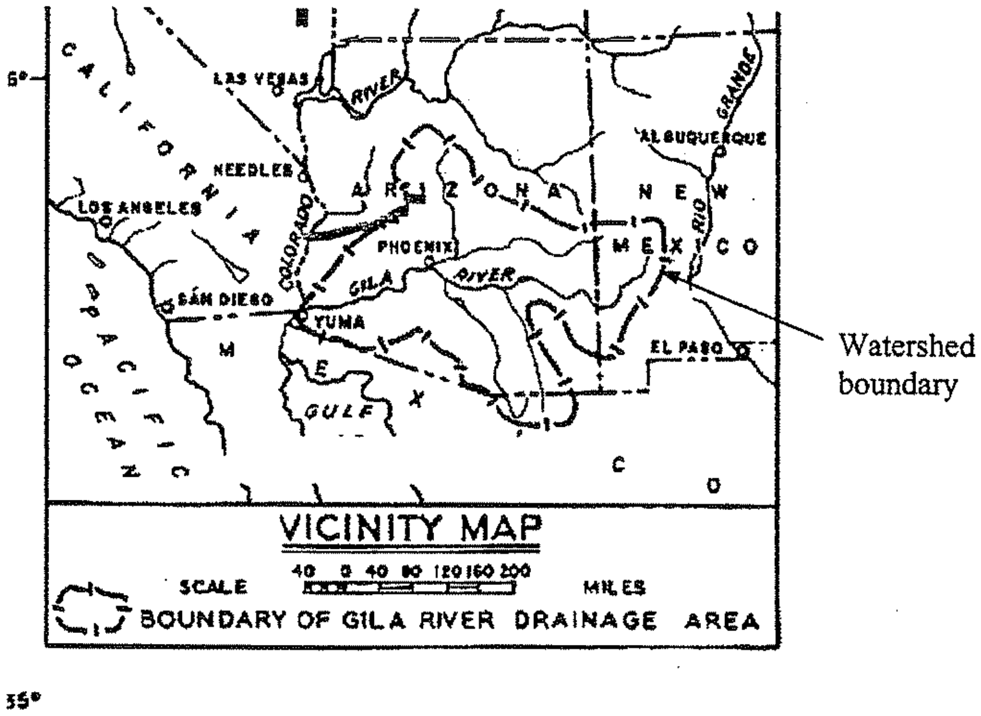
2. Estimate the natural hydraulic characteristics of the river channel that are related to navigaton.

3. Define where and when the Gila River was navigable between the confluence with the Salt River and the mouth.

USGS maps 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

The study reach of the Gila River is about 188 miles long(see blue area on map below). The area of land drained by the Gila River at Yuma is about 58,200 square miles. This area is a considerable portion of the land in Arizona(>50% of 114,004 square miles). The watershed is the land area where precipitation runs off into the Gila River. The boundary or ridge line separating the drainage-basin land from adjacent land is shown on the map below. The drainage basin of the Gila River contains smaller drainage basins of the Verde, Salt, Santa Cruz, San Fancisco and many other rivers and streams.



SITE	MILE	AREA(sq mi)	CHANNEL SLOPE
Salt River	188	43,000	.001
Gillespie Dam	156	49,650	.001
Yuma area	0	57,850	.0005

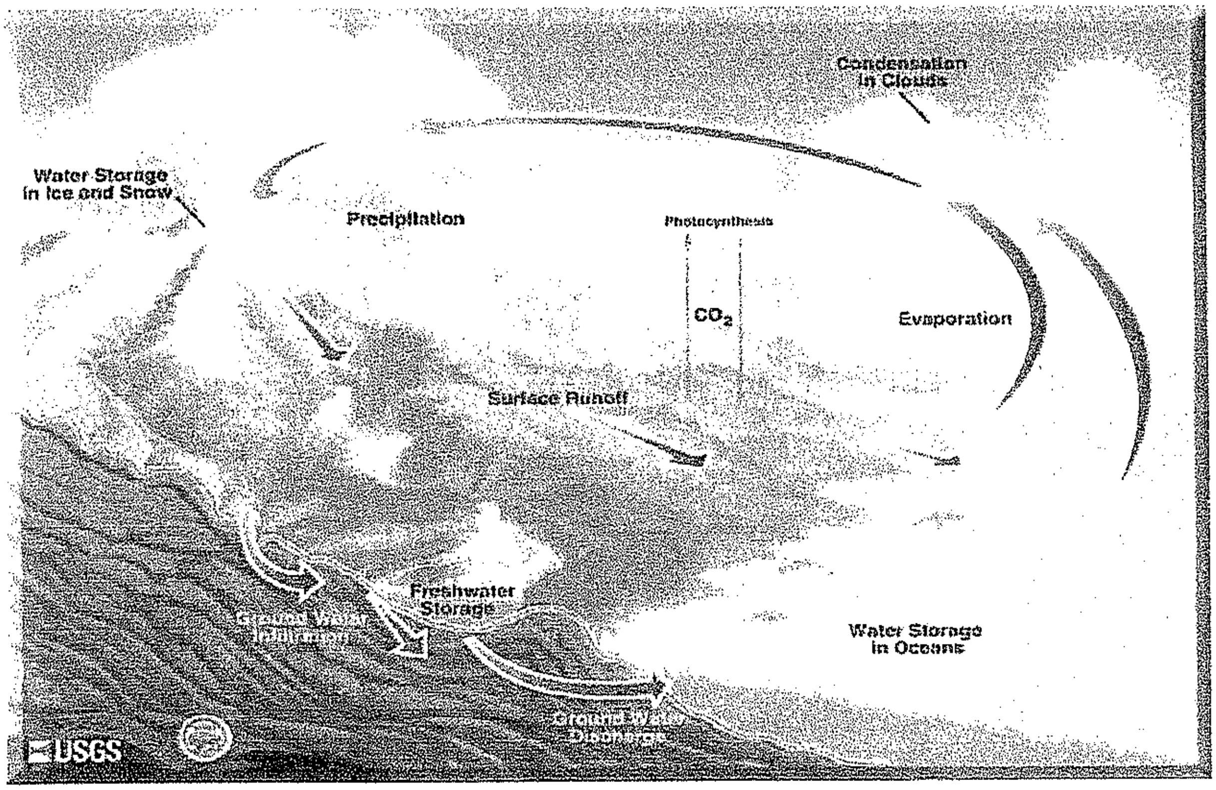
The Gila River drains a large mountainous area of central and eastern Arizona. There is a distinct season of winter snowmelt and spring runoff. There are many headwater springs that supply base runoff during dry periods. Before about 1860(predevelopment) the many alluvial basins that are crossed by the tributary streams were filled with water that supplied base flow to the Gila River.

An understanding of some fundamental principles about hydrology and the Gila River is important.

HYDROLOGY

The science of waters of the earth, their occurrence, distribution, and circulation; their physical and chemical properties; and their reaction with the environment, including living beings.

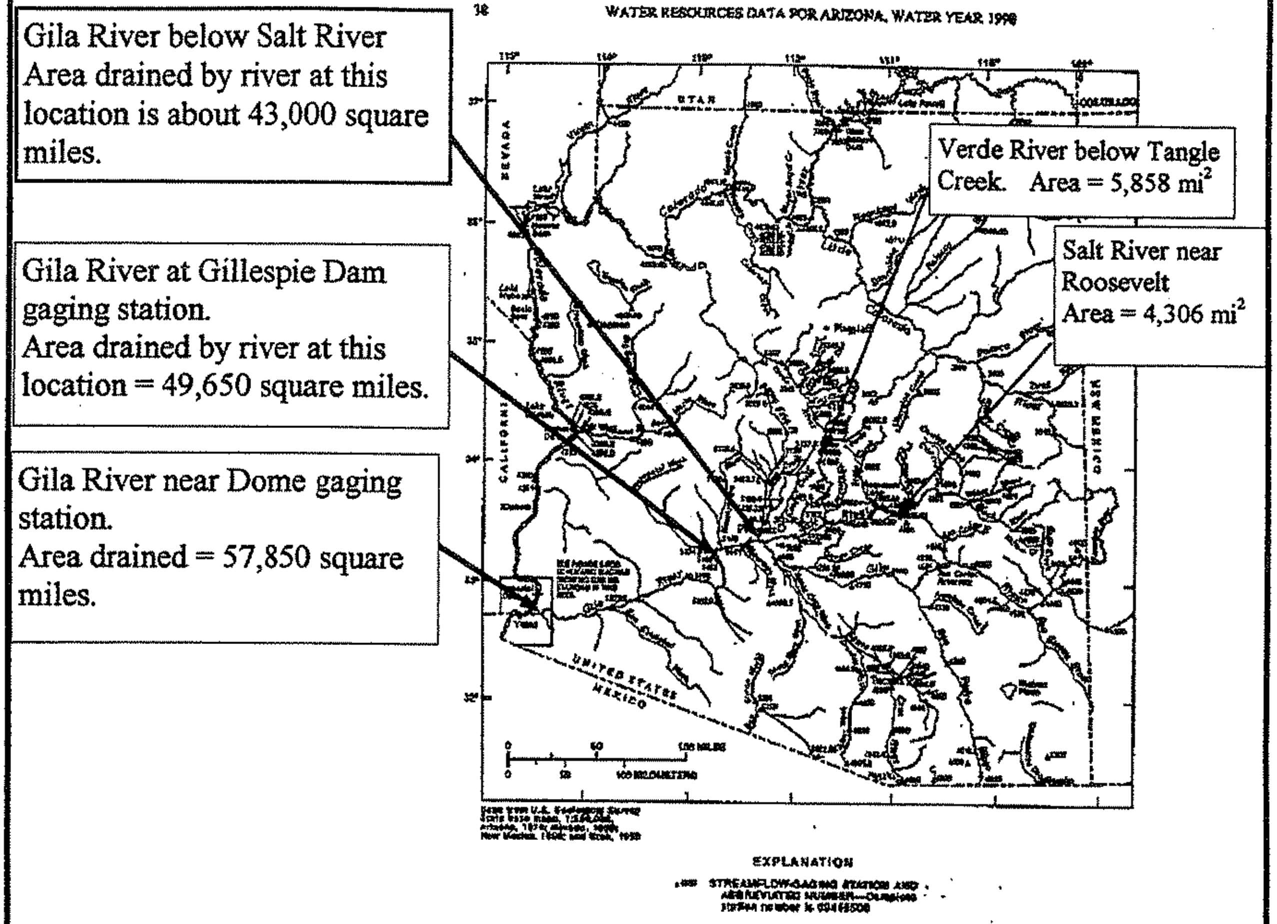
NOTE: Some of the following information is modified from the USGS.



HYDROLOGIC CYCLE

The circuit of water movement from the atmosphere to the earth and return to the atmosphere through various stages or processes such as precipitation, interception, runoff, infiltration, percolation, storage, evaporation, and transportation (See glossary at end of report).

Map of Arizona with streams and rivers, USGS streamflow gages and selected sites discussed in this report on predevelopment hydrology of the Gila River at and below Gillespie Dam.



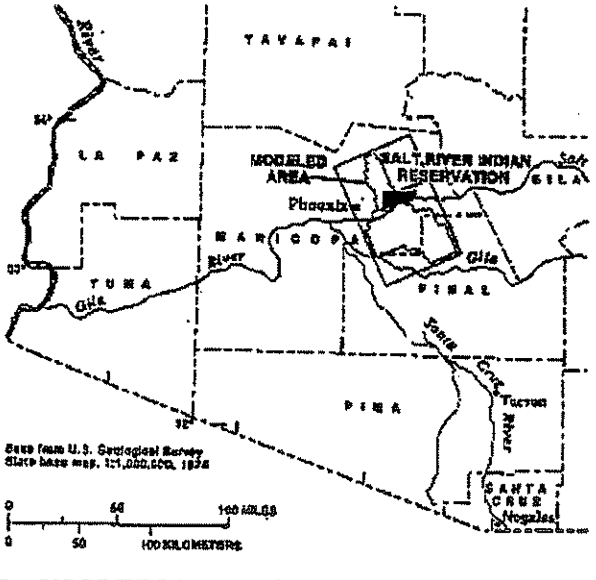
Gila River below Salt River
Area drained by river at this location is about 43,000 square miles.

Gila River at Gillespie Dam gaging station.
Area drained by river at this location = 49,650 square miles.

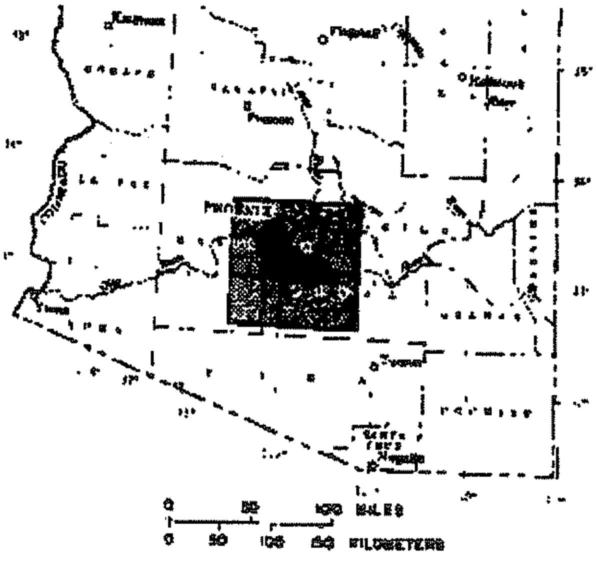
Gila River near Dome gaging station.
Area drained = 57,850 square miles.

Verde River below Tangle Creek. Area = 5,858 mi^2

Salt River near Roosevelt
Area = 4,306 mi^2



See USGS WRI 91-4132 for Salt River Indian Res.



Seee USGS WRI 89-4174 for Gila River Indian Res.

The Gila River

The Gila River of Arizona is nothing more than water finding its way over and under land from a higher altitude to a lower altitude, all because of gravity. When rain falls on the land, it either seeps into the ground or becomes runoff, which flows downhill into tributary rivers such as the Salt and Verde, on its journey towards the Colorado River and the Gulf of California.

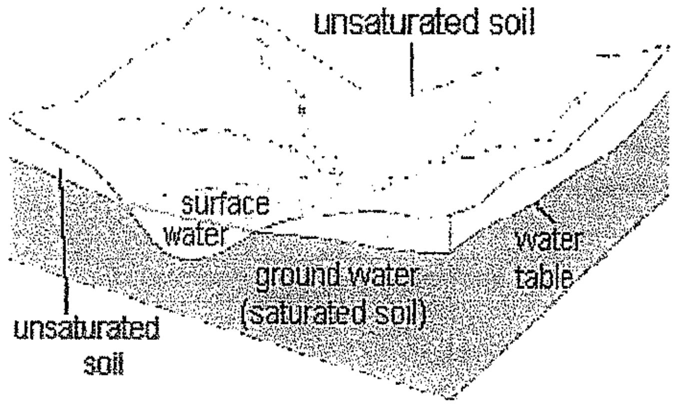
Flowing water finds its way downhill initially as small creeks such as Oak Creek near Sedona, Arizona. As small creeks flow downhill they merge to form larger streams and rivers such as the San Francisco and Salt Rivers. If man has built a dam, like Roosevelt Dam, to hinder a river's flow, the lake that forms is a reservoir such a Roosevelt Lake.

During predevelopment the flowing water was unobstructed by man except for small diversion dams used by indians to irrigate crops.

Water source of the Gila River

The water in the Gila River and it's tributary streams doesn't all come from surface runoff. Rain falling on the land also seeps into the earth to form ground water. At a certain depth below the land surface, called the water table, the ground becomes saturated with water. If a river bank happens to cut into this saturated layer, as most rivers do, then water will seep out of the ground into the river. Examples of ground-water seepage can presently be seen in the Verde River below Granite Creek and in the Salt River a few miles above highway 60.

Look at the diagram below. The earth below the water table, the aquifer (the purple area), is saturated, whereas the earth above (the pink area) is not. The top layer (unsaturated soil/rock material) is usually wet, but not totally saturated. Saturated, water-bearing materials often exist in horizontal layers beneath the land surface. Since rivers, in time, may cut vertically into the ground as they flow (as the river cuts into the purple section in the diagram), the water-bearing layers of rock can become exposed on the river banks. Thus, some of the water in rivers is attributed to flow coming out of the banks. This is why even during droughts there is some water in streams tributary to the Gila River.



Runoff

When rain or snow falls onto the land in the Gila River watershed, it just doesn't sit there -- it starts moving according to the laws of gravity. A portion of the precipitation seeps into the ground to replenish ground water. Some of it flows downhill as runoff.

The portion of the water that replenishes the ground water is very important for the navigability of the river. Under natural conditions the water that replenished the ground water was temporarily stored, and later discharged to the rivers. This base runoff was released from storage during dry periods. Because precipitation is seasonal and there are a few months each year with little precipitation, the base runoff provided perennial flow to the Gila River.

Runoff is that part of the precipitation or snow melt that appears in uncontrolled surface streams and rivers. Runoff may be classified according to speed of appearance after rainfall or melting snow as direct runoff or base runoff, and according to source as surface runoff, storm interflow, or ground-water runoff. For this assessment of navigability and natural hydrology of the Gila River, runoff is either direct runoff or base runoff. Base runoff, as defined by Freethey and Anderson(1986), is precipitation that seeps from the ground into uncontrolled streams and rivers. The remainder of the runoff is mostly surface runoff that may include some runoff from springs at elevations above the saturated zone of the particular ground-water unit. Direct Runoff is precipitation that flows on the land surface into uncontrolled rivers. The total runoff is simply the sum of the direct and base runoff.

The average annual predevelopment runoff for the Gila River near Gillespie Damsite is about 2,330 cfs. Most of this water is direct runoff but a large portion is base runoff. The base runoff below the confluence with the Salt River typically was at least about 300 cfs. The computation of these amounts is discussed later.

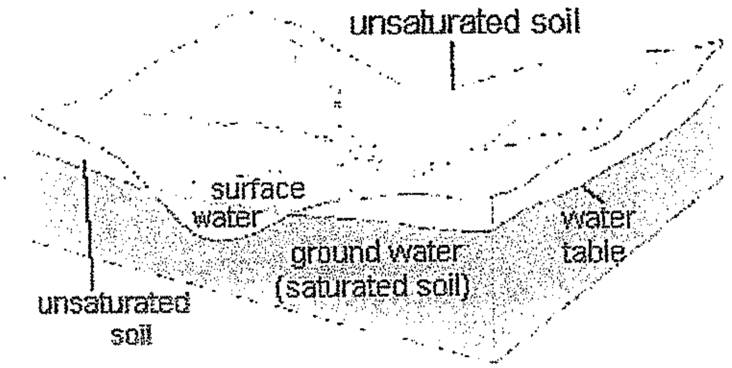
Navigability depends on the amount and distribution of runoff throughout the year. A flow-duration relation is commonly used by hydrologists to characterize mean daily runoff. A flow-duration curve was used to define the percent of time the natural mean daily discharge was exceeded during a typical year. The curve was defined as follows:
(A) The basin accounting method for natural stream base flow developed by Freethey and Anderson (1986) was use to estimate the tenth percentile of daily discharge,
(B) 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 combined, and
(C) The flow duration relation was estimated using the three values from steps A and B and the general shape of the flow-duration relations of upstream tributaries gaged by the USGS(Pope and others, 1998).

The nature of the runoff in the Gila River watershed and how the flow-duration curve was estimated is further described on the following papes.

Ground water in the Gila Watershed

Ground water is the part of precipitation that seeps down through the soil until it reaches rock material that is saturated with water. Ground water slowly moves underground, generally at a downward angle (because of gravity), and may eventually seep into streams and lakes. Many of the natural seeps and springs were from ground water in limestone, sandstone and alluvial basins.

Below is a simplified diagram showing how the ground is saturated below the water table (the purple area). The ground above the water table (the pink area) may be wet to a certain degree, but it does not stay saturated. The dirt and rock in this unsaturated zone contain air and some water and support the vegetation on the earth. The saturated zone below the water table has water that fills the tiny spaces (pores) between rock particles and the cracks (fractures) of the rocks.



Why is there ground water?

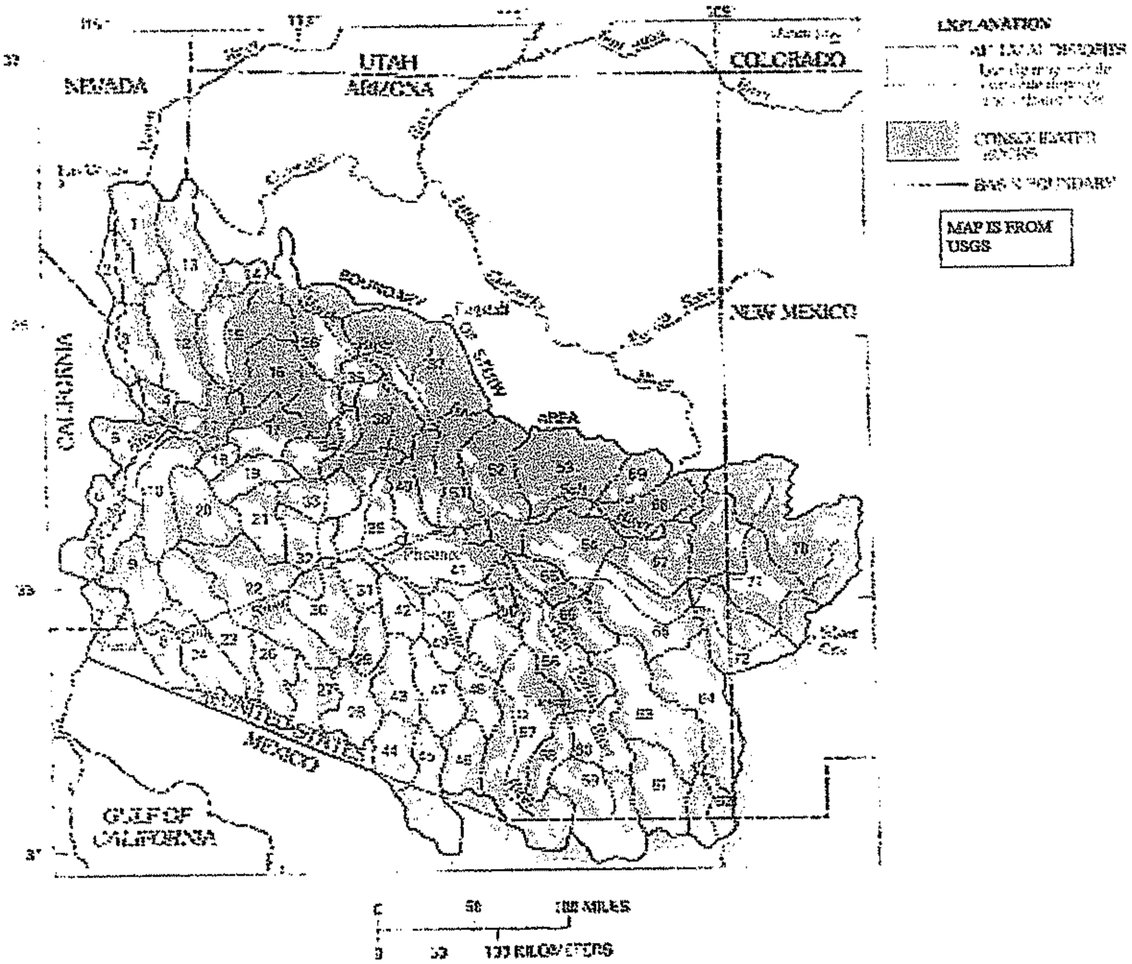
A couple of important factors are responsible for the existence of ground water:

First, gravity pulls water toward the center of the earth. That means that water on the surface will try to seep into the ground below it.

Second, the rocks below our feet commonly are porus. Even gravity has a hard time pulling water downward through dense rock like granite but the earth's bedrock consists of many types of rock, such as sandstone, granite, and limestone. Bedrocks have varying amounts of void spaces in them where ground water accumulates. Bedrock can also become broken and fractured, creating spaces that can fill with water. Also, the alluvial basins of the Gila River watershed are filled with silt, sand, gravel and boulders. This deep alluvium covered wide areas between bedrock mountains and very porus. These deep alluvial aquifers stored and transmited large quantities of ground water before the settlers.

How much was the natural runoff for the Gila River and how was runoff distributed through a typical year?

The basin accounting method for natural (predevelopment) stream base flow developed by Freethey and Anderson (1986) was used to estimate the tenth percentile of daily discharge(Q_{10}). Basins defined by the USGS are shown below:

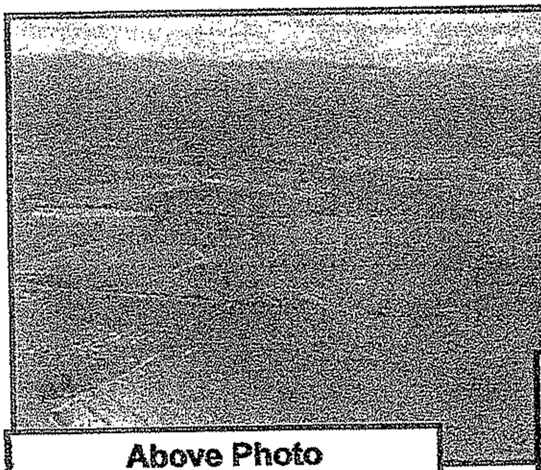


The median discharge(Q_{50}) and the average annual predevelopment streamflow for the Salt and Gila Rivers estimated by the USGS (Thomsen and Eychaner(1991) and Thomsen and Portello(1991)) were combined.

A flow duration relation was estimated using the Q_{10}, Q_{50} and average discharge.

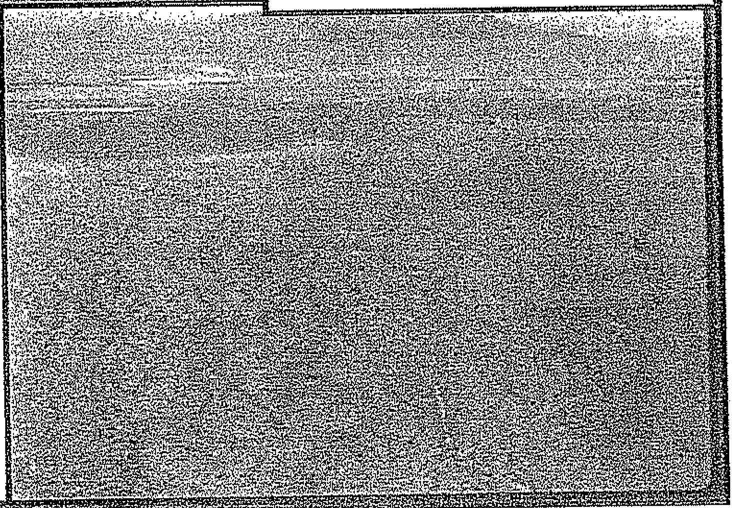
Sample of alluvial basins used for basin accounting by USGS

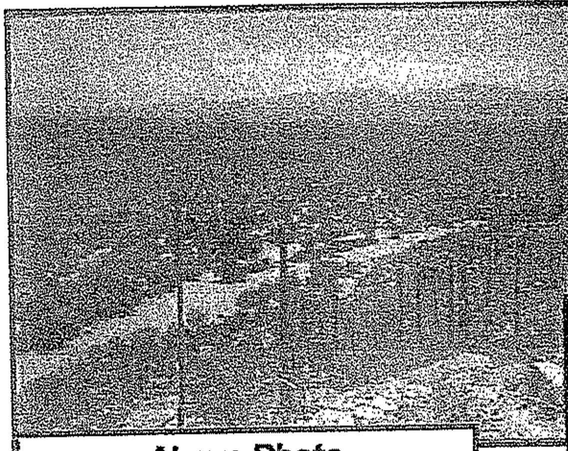
Photographs taken in 1983 by Winn Hjalmarson, PE



Above Photo
Aerial view along Gila River looking across basin 65 with mountains in background. Photo taken during flood recession in 1983 where farmland in center of scene had been flooded.

Below Photo
Aerial view looking north across basin 49 with Picacho Peak and other mountains in background. Farmland in background is along the Santa Cruz River. Mountains are surrounded with alluvium.



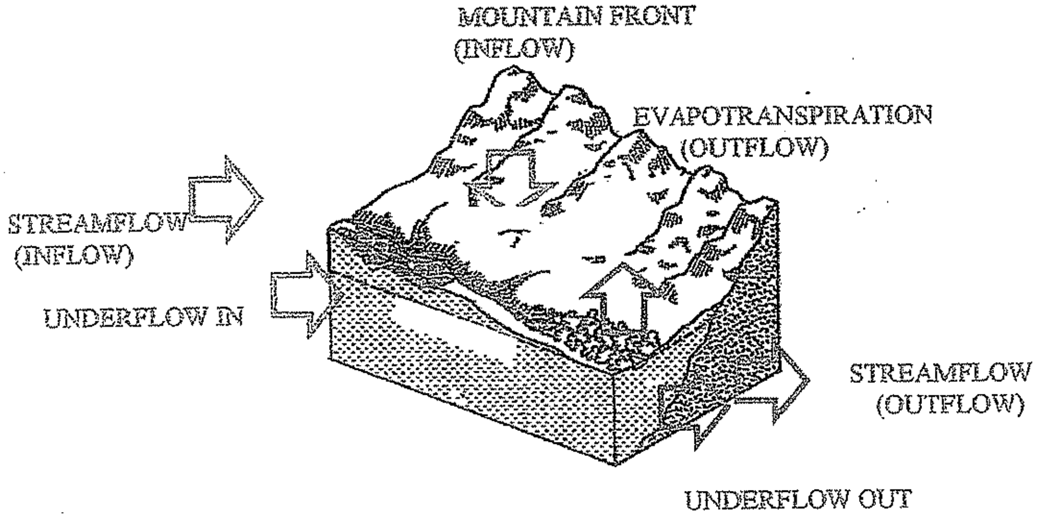


Above Photo
View looking north from west slopes of Tortolita Mtns across alluvial basin 48. Alluvial fan in foreground is area of ground water recharge where floodflow infiltrates the coarse alluvium.

Below Photo
Aerial view looking east across basin 60 with Dragoon Mtns in background. San Pedro River cuts across foreground of scene from the right to the left.

Shetch of typical ground-water basin showing predevelopment components of natural inflow and outflow.

for typical ground-water basins in the Gila River drainage basin.



GROUND-WATER BUDGET
(Used by the USGS)

INFLOW = OUTFLOW

An accounting of the hydrologic components within each ground-water basin.

Before development the basins were in equalibrium and the amount of storage did not change over the long term.

Modified from: Freethey, G. W. and Anderson, T. W., 1986, Predevelopment hydrologic conditions in the alluvial basins of Arizona and adjacent parts of California and New Mexico, U. S. Geological Survey Hydrologic Investigations Atlas HA-664, 1986.

The USGS (Freethey and Anderson, 1986) assessed "the hydrologic conditions that existed prior to man's activities that might have altered the natural hydrologic systems. Prior to development, the ground-water systems were assumed to be in equilibrium-long-term inflow was equal to long-term outflow and no change in storage occurred. The purpose of the USGS report is to summarize the predevelopment hydrologic conditions using available data and hydrogeologic knowledge."

A traditional accounting method of the inflows to, the outflows from, and the storage changes of water in each of the hydrologic units(subareas) in the Gila River watershed and of the predevelopment hydrologic system of the entire area was made. The quantities of inflow and outflow and the volume of water in storage were estimated from field data, numerical modeling, and transfer of selected parameter values from basins for which data were available to basins for which data were not available. Each of the subareas represent, for the most part, separate groundwater systems.

The ground water budget below has two flow components for each subarea that is used for this study (see diagram showing flow components on previous page).

GROUND-WATER BUDGET

INFLOW = OUTFLOW

with the following components

UNDERFLOW IN		(UNDERFLOW OUT
STREAMFLOW IN	=	STREAMFLOW OUT
MOUNTAIN FRONT INFLOW		EVAPOTRANSPIRATION

A simple accounting of the streamflow components along the major streams that traverse the subareas (See pie diagrams on sheets 1-3 of Freethey and Anderson, 1986) yields the base runoff along the Gila River and it's tributaries.

According to Geoff Freethey (e-mail communication of April 10, 2000) the value of each component represents "average" conditions over a multi-year pre-development period.

An accounting of base flow above the USGS Salt River near Roosevelt stream gage indicates the value of base flow corresponds to the annual tenth percentile of daily discharge(Q_{10}) at the gage for the 85 years of record. The tenth percentile of daily discharge is considered by some hydrologists to reflect baseflow conditions for perennial flow streams. The flow at Salt River above the Roosevelt gage is affected by diversion but to a lesser amount than other streams that could be used to evaluate the Freethey and Anderson (1986) amount of base flow. Thus, for predevelopment conditions, the mean daily discharge for 90 percent of the days in a year is expected to be greater than the Freethey and Anderson (1986) average amount of base flow.

Mean, Median and Base Runoff

According to Thomsen and Eychaner(1991) the mean annual 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 flow leaving the reservation was 435,000 and 315,000 ac-ft per year, respectively.

The average predevelopment 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.

The mean and median annual discharge upstream of Gillespie damsite 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 annual discharge is the sum of 1,250,000 and 435,000 ac-ft or 1,685,000 ac-ft. The estimated median annual flow is the sum of 950,000 and 315,000 ac-ft or about 1,265,000 ac-ft(See Table below). For this study of the predevelopment(natural) hydrology along the Gila River, the tributary inflow is assumed to offset runoff losses in the Gila River. The mean and median annual runoff are assumed constant to the mouth of the River at the Colorado River. The effect of this assumption on the assessment of navigation is not significant as will be shown in this report.

Table of estimated flows for natural conditions along the Gila River from below the Salt River

Site	Mean annual		Median(Q_{50})		Base(Q_{10})	
	ac-ft	cfs	ac-ft	cfs	ac-ft	cfs
upper reach	1,685,000	2,330	1,265,000	1,750	213,000	290
lower reach	1,685,000	2,330	1,265,000	1,750	123,000	170

As previously described, the basin accounting method for stream base flow developed by Freethey and Anderson (1986) was used to estimate the base discharge at the Gila River at Gillespie Dam site. The estimated base flow was about 210,000 ac-ft per year. The accounting was used downstream because losses to evapotransipiration are relatively large. Total losses of the base flow, according to the USGS, were 90,000 ac-ft per year leaving about 120,000 ac-ft per year at the mouth near Yuma, Arizona.

The predevelopment average runoff is now defined by the median(Q_{50}), mean and base(Q_{10}). A cumulative frequency curve (flow duration curve) that shows the percentage of time that specified daily discharges are equaled or exceeded can be estimated. The flow duration curves for USGS gages at Verde River below Tangle Creek and Salt River near Roosevelt were use to estimate the shape of the curve. The flow duration curve is shown on the next page followed by a discussion.

The following diagram shows the relation between duration and frequency curves. See USGS Water-Supply Paper 1542-A for more description of flow-duration curves.

The mean discharge is determined as follows: The area under the flow-duration curve is a measure of the discharge available 100 percent of the time. Dividing the area by 100(base of the curve—100 percent of the time) gives the average ordinate which, multiplied by the scale factor, is the mean discharge.

The median discharge or flow is the curve value at 50 percent of the time.

The modal flow is the point of inflection of a flow-duration curve plotted on rectangular-coordinate paper occurs at the modal flow(not used in this study of navigability).

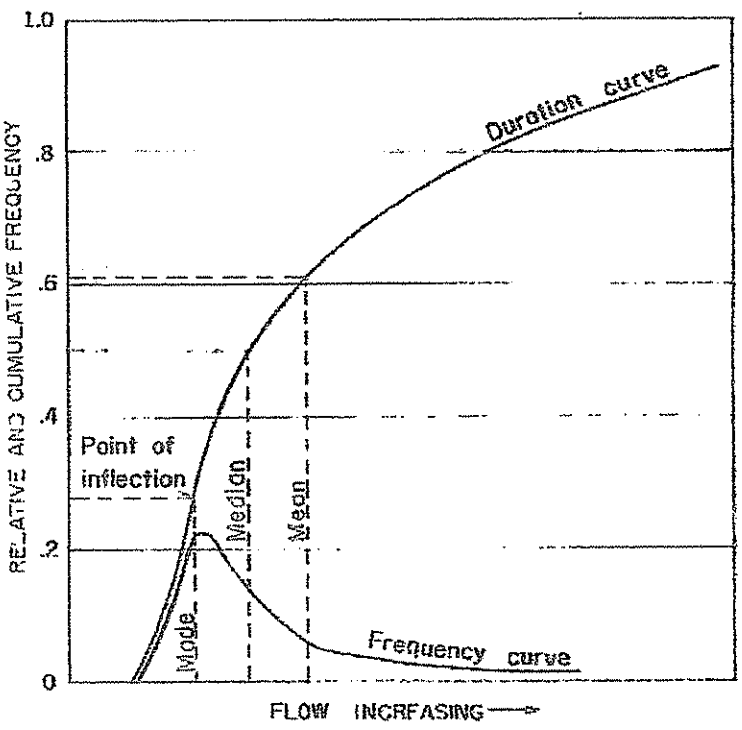
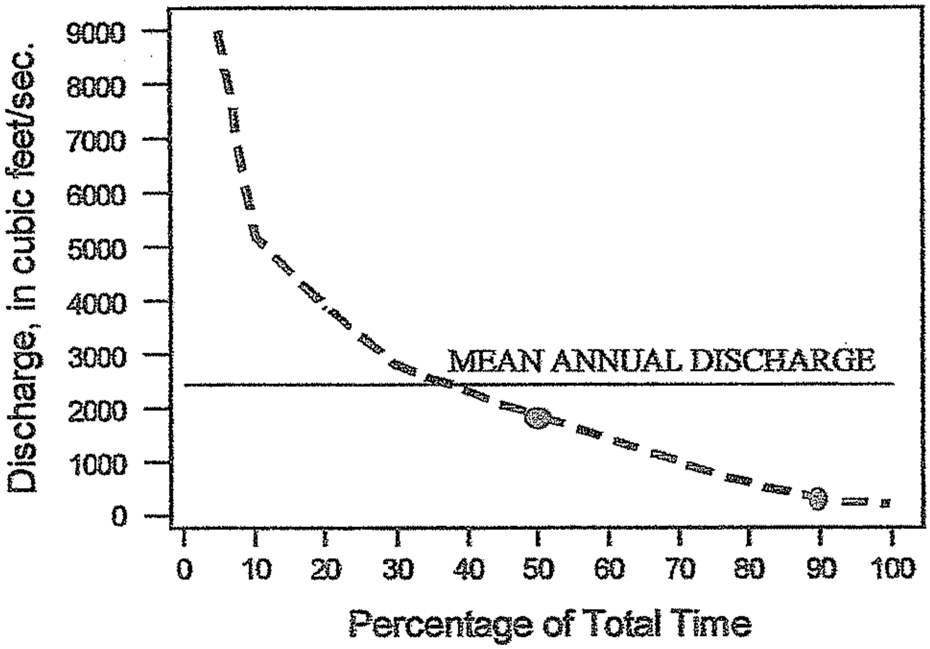


FIGURE 10.—Relation of duration and frequency curve.

PREDEVELOPMENT HYDROLOGY
of
GILA RIVER

DURATION CURVE OF DAILY DISCHARGE AT GILLESPIE DAMSITE



EXPLANATION

● Median daily discharge (from Thomsen and Eychaner, 1991 and Thomson and Porcello, 1991) (Estimated)

● Baseflow discharge (from Freethey and Anderson, 1986)

NOTE

The mean annual discharge is from USGS reports by Thomsen and Eychaner (1991) and Thomson and Porcello (1991). Shape or relation also based on flow duration relations for USGS gages at Salt River near Roosevelt and Verde River below Tangle Creek.

DISCUSSION OF FLOW-DURATION RELATION

The daily rates of discharge have been arranged in order of magnitude in the duration graph. This display facilates general assessment of navigability. The flow-duration curve for the Gila River is a cumulative frequency curve that shows 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 natural flow of the Gila River and is useful for the general assessment of navigability.

See the graphs on the following page for an example of a flow duration curve for a single year. The 1905 hydrograph of daily discharges and the corresponding flow duration graph can be compared.

At the upper end of the reach of the Gila River, the 90% duration is about 290 cfs. This amount of base runoff is from the Gila and Salt Rivers and is based on the alluvial basin water budgets by Freethey and Anderson(1986). Base runoff from the Santa Cruz River is not significant. Base runoff at the mouth of the Gila River was about 170 cfs. The loss along the watercourse of about 120 cfs was mostly because evapotranspiration in the arid region was more than the ground-water recharge from precipitation. It is important to realize that these estimates of base runoff are independent of the estimates in mean and median runoff for this study.

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. This amount is the sum of the median values for the Salt River(Thomsen and Portello, 1991) and the Gila River(Thomsen and Eychaner, 1991). This summation assumes both the Salt and Gila Rivers are hydrologically similar. Days of concurrent discharge are assumed to have the same duration on the curve for each river. The median for the Gila River below the confluence with the Salt clearly is an estimate.

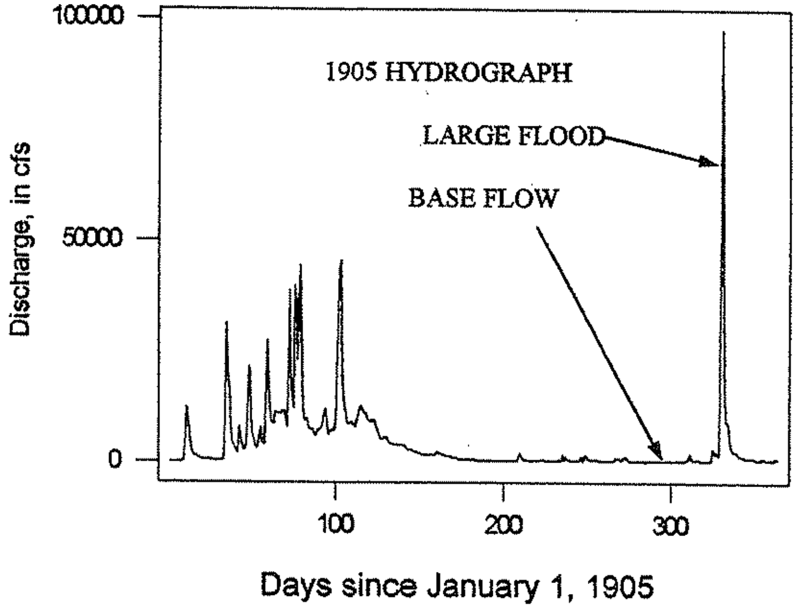
The mean annual flow is represented by a horrizontal line that divides the area under the flow duration curve into equal parts. The area under the entire curve is a measure of the total flow available 100% on the time. The mean value was simply computed by adding the mean values for the Salt River (Thomsen and Portello,1991) and the Gila River (Thomsen and Eychaner, 1991). This method of estimating the natural mean annual flow does not have the limitation discussed above for the estimate of the median flow.

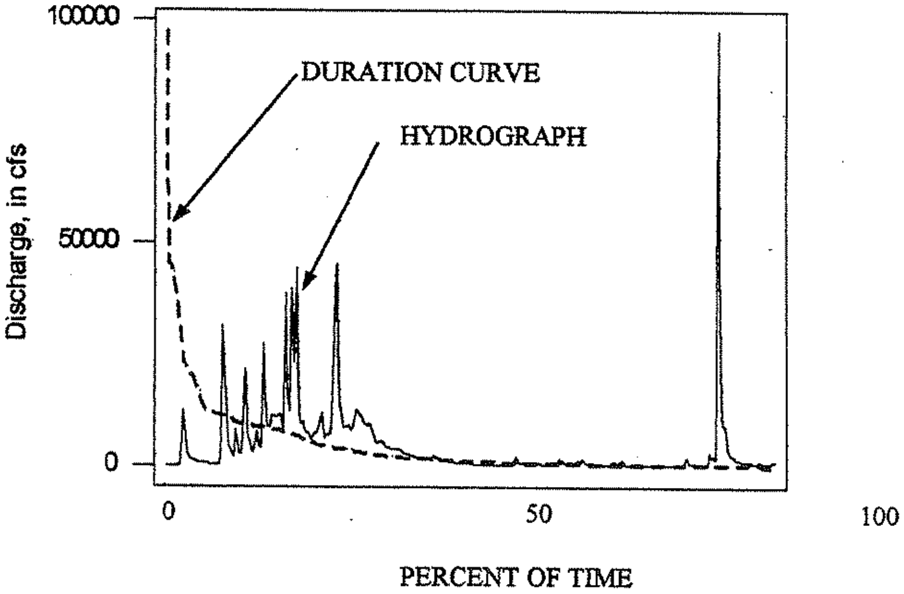
The flow-duration relation was shaped to pass through the 90% and 50% mean daily discharges and to satisfy the requirements of the mean annual flow. The curve can be used to estimate the percent of time that a discharge was equaled or exceeded in the past. The curve represents long-term natural flow of the Gila River and is sufficiently precise to assess the navigability of the Gila River.

EXAMPLE

Comparison of hydrograph of daily discharge and corresponding flow duration graph for 1905 calender year.

USGS gaging station 09500500 Salt River at Roosevelt Damsite, AZ.





The distribution of high flows is governed largely by the climate, the physiography, and the plant cover of the Gila River basin. The distribution of low flows is controlled chiefly by the geology of the basin. Thus, the lower end of the flow-duration curve reflects the effect of geology on the ground-water runoff to the river and it's tributaries. Because of the diverse geology and because many alluvial basins are traversed by the streams, and the ground water in these basins drains to the streams under natural conditions, the low end of the curve is the composite of ground water drainage from a many parts of the basin. Where the stream drains a single formation, the position of the low-flow end of the curve is an index of the contribution to streamflow by the formation. For a complex drainage area like the Gila, the effect of geology on low flow is also complex.

The stored ground water that fed the streams that crossed the many alluvial basins probably had a smoothing effect on the base flow of the Gila River. The base flow may not have varied much from one year to the next or within each year. Such is the situation in the upper Verde River where the base discharge at the USGS Paulden gage is typically from 18-26 cfs. While the high flows of the Gila River were variable, the low flows were less variable because of the large amount of stored ground water that supplied the river during dry periods.

NATURAL CONDITION WHEN THERE WAS NAVIGABILITY: Before about 1860, when the first settlers diverted water for irrigation, a large portion of the precipitation that entered the ground infiltrated to the water tables of the many alluvial basins in the Gila River watershed. Also, a large portion of the precipitation that enters streams and rivers flowed down the Gila River to the Colorado River and into the Gulf of California. PRESENT CONDITION: There are now major dams and reservoirs, many diversions of water from the rivers and major lowering of ground water levels in the alluvial basins of the Gila Rivere watershed. The combined reservoir storage capacity exceeds the natural mean annual runoff and essentially all of the strammflow is diverted from the rivers above the confluence with the Salt River, mostly for irrigation of crops. Little evidence of the natural flow in the Gila River remains.

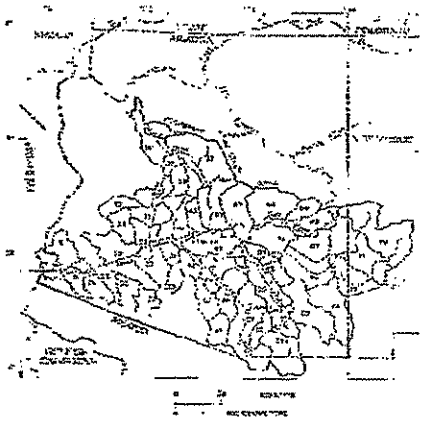
The flow duration curve is considered a reasonable estimate of the typical distribution of daily flow. We can only speculate precisely how the daily discharge varied throughout the year and from one year to the next. There was, and is, a distinct season of high flow as snow in the headwater mountains melts in the spring. There are also dry periods in about September-October and May-June when there typically is little direct runoff. During wet years the flow duration relation would be displaced upward to reflect an increase in daily discharge. Conversely, during dry years the flow duration relation would be displaced downward to reflect a decrease in daily discharge. The precise variation of flow from one year to the next is beyond the scope of this general assessment. A computer model of the Gila watershed might be used if a precise estimate of flow throughout the year is needed. All that is needed for this general assessment of navigability is a typical distribution of daily discharge.

Summary and discussion of the natural hydrology

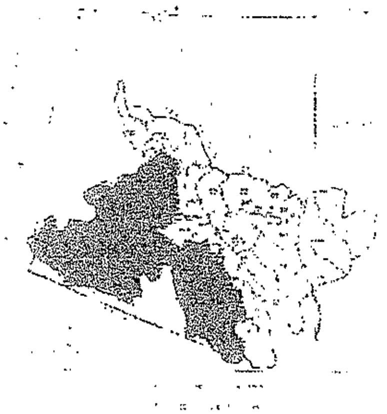
Using published USGS information the hydrology of the Gila River below Gillespie Damsite was defined. A flow-duration relation was estimated using the information. The flow-duration relation is used to assess the amount of time a particular amount of daily discharge can be expected in the river.

Average yearly conditions are used for the natural hydrology. The variation of low water amounts from one year to the next is unknown. Based on the variation of low water (Q_{10} to about Q_{50}) in the larger tributaries upstream a coefficient of variation(average annual discharge/standard deviation) of perhaps 0.25 might be expected. If so, the expected amount of Q_{10} would be within 25%(between about 225 and 375 cfs) of the typical value of Q_{10} at Gillespie Dam. To account for this possible variation from one year to the next, this analysis of the hydrology and the subsequent analysis of the hydraulic conditions related to navigability are conservative so as to not over estimate the amount of navigability.

For example, the ground water basins used for the value of Q_{10} are shown on the map to the right(Freethey and Anderson, 1986). The contribution of runoff from many of these basins in the more arid region was ignored for higher flows shown on the flow duration relation shown on the previous page.

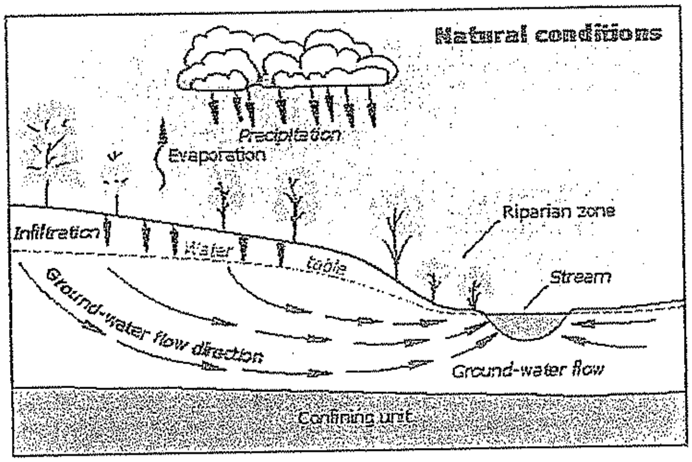


The contribution of runoff to the Gila River for flow more than Q_{10} was not considered for the tributary areas areas shown in red on the map to the right. This area includes the Santa Cruz River, Aqua Fria River, Hassayampa River and Centenial Wash basins that are tribuary to the Gila River upstream of the Gillespie Damsite. By ignoring inflow from the basins in this area the resulting estimate of runoff for navigation is conservatively low. This conservatism is to account for any lack of precision in the estimate of flow characteristics.



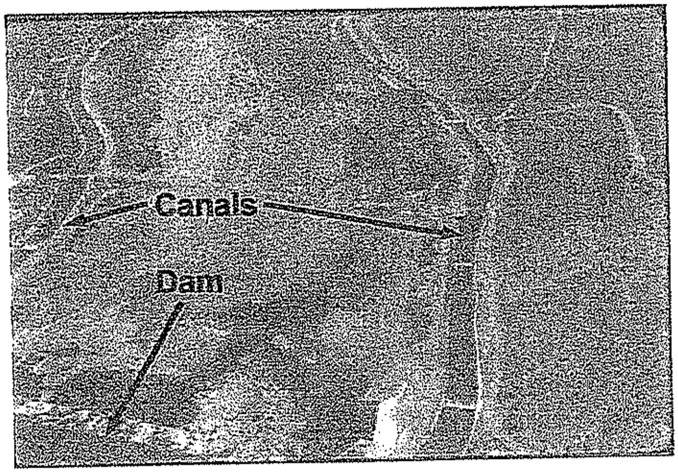
NATURAL FLOW IN GILA RIVER

The diagram to the right is of a stream channel that is hydraulically connected to ground water. This connection is like the many alluvial basins that were traversed by the Gila River and tributary streams under natural conditions. The ground water is simply the subsurface water that fully saturates pores or cracks in soils and rocks. When rain falls or snow melts, some of the water evaporates, some is transpired by plants, some flows overland and collects in streams, and some infiltrates into the pores or cracks of the soil and rocks. The water that enters the ground flows through the ground toward the stream where it eventually flows into the river channel and is carried toward the Colorado River.



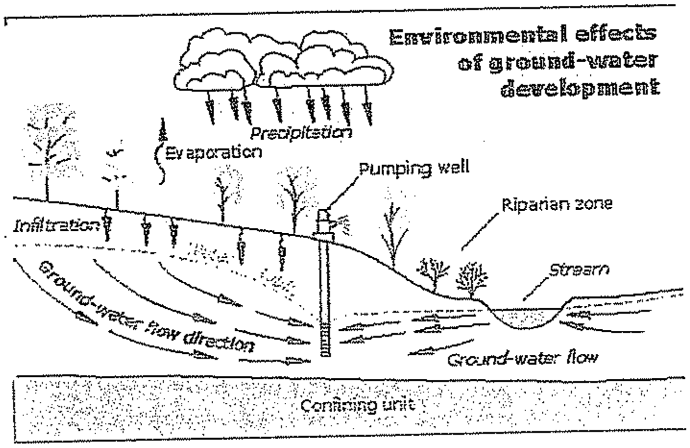
SURFACE WATER DEVELOPMENT

The photo to the right is a view looking downstream at Granite Reef diversion dam on the Salt River. Essentially all of the flow is diverted to the canals on each side of the Salt river. There is a similar major diversion on the Gila River at Asherst-Hayden dam. There are also many diversions above the several major reservoirs. Diversions by settlers started after the Treaty of Guadalupe Hidalgo in 1848 and the Gadsden Purchase of 1854 and the discovery of gold at Sutler's Mill in California in 1848. Some of the '49ers' of the goldrush drifted back and settled along Arizona rivers.



GROUND WATER DEVELOPMENT

The diagram to the right is of the stream channel above but the ground water is being withdrawn for irrigation and other uses. Ground water has been removed from storage causing the water levels to drop below the stream. Water in the stream now infiltrates into the ground as it passes through the basins. The water that once flowed to the Colorado River now is now consumed by crops and other uses before it reaches much of the Gila River.



The natural flow of the Gila River was perennial across the desert of central Arizona to the Colorado River. 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 182 days each year. During the typical year the base flow was about 290 cfs in the upper reach and 170 cfs near the mouth. Because of the large amount of stored ground water that supplied the base flow, the base flow probably did not vary greatly from one year to the next.

Hydraulic characteristics related to navigaton along the Gila River

The flow characteristics suggest that base runoff should be considered in the assessment of navigability. While base runoff is only about 10% of the mean annual runoff, base runoff is a large amount of the total runoff at least 20 percent of the time. As discussed previously, the ground-water conditions suggest that base runoff was about the same from one year to the next because of the many aquifers the fed the Gila River. Because there was a lot of stored water in these aquifers, the large reserve supplied water rather evenly during both wet and dry periods. However, in terms of using a vessel on the Gila River, the base runoff may limit navigability for at least part of a typical year. Therefore, the low and medium flow conditions of the river are examined.

We need to characterize the Gila River by defining natural parameters of the main channel that are related to navigability. Two important parameters are depth and velocity--too little depth and too much velocity limits navigability. Width is also an important parameter partly because width is commonly measured and historic observations of width are available. Channel width of main channels can be reliably estimated from flow characteristics. The depth and velocity of natural alluvial channels are related to channel width.

The problem with estimating channel size and shape corresponding to the natural flow charactersitics is there is little reliable evidence of channel width and depth before about 1860. A solution is the use of regional hydraulic geometry relations to estimate channel width using the estimate of mean annual discharge for natural watershed conditions. These equations are ideal to estimate geometry characteristics (width) because they are easy to use and they are inexpensive (Osterkamp and Headman, 1982, p. 18). Estimates of width are feasible by using qualitative evualuations of sediment characteristics and by using regional hydraulic geometry relations (Osterkamp, 1980).

An obvious source of information on channel geometry are topographic maps. However, channel hydraulics from the USGS maps and the historic accounts made after about 1860 are affected by the many diversions of the settlers upstream and within the reach. All observations and measurements of channel geometry made along the watercourse after about 1860, especially measurements of channel width and depth, may be significantly affected by the diversions. After the construction of Roosevelt Dam the morphology again was significantly altered because both the flow

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Osterkamp, W. R., and Headman, E. R., 1982, Perennial-streamflow characteristics related to channel geometry and sediment in the Missouri River basin: U.S. Geological Survey Professional Paper 1242, 37 p.

and sediment characteristics of the water entering the reach were changed. The impact of the many diversions, that were in use when the original federal land surveys were made, is not precisely known but at times much of the base runoff may have been diverted as suggested by the 1905 hydrographs for the four sites shown in the introduction of this report. The impact of the diversions, storage dams lowering of ground-water levels and removal of the riparian vegetation on the morphology of the Gila River was significant. Also, only rough estimates of channel size and shape of the main channel can be obtained from the topographic maps because of the small map scale.

Both hydraulic geometry techniques and channel geometry from topographic maps and the original land surveys are use for the analysis. There is some advantage for using the topographic maps. Much more weight, however, is given to the hydraulic geometry from natural streamflow charactersitics. The methods are:

Hydraulic geometry.-Channel size and shape were estimated using hydraulic geometry techniques. This method is based on general characteristics of natural channels and is independent of the effects of the many diversions for irrigation along the Gila River and tributary streams that started in about 1860.

Topography.-Channel size and shape were estimated using USGS topographic maps. Corresponding hydraulic geometry relations of depth versus discharge was estimated at three sites along the river. Two of the sites where selected because there were braided channels that represented a worst-case condition for navigability. It is unknown if the braided conditions were representative of natural conditions. Maps used to assess the channel hydraulics are listed in the introduction of this report. 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).

The hydraulic geometry relations are useful along a channel formed by a characteristic discharge over a range of discharge. Following very large floods the channel may have become destabilized and reaches may have developed multiple channels of braids. Braided channels divide and combine. A limiting condition of hydraulic geometry is for braided streams where increases in discharge do not result in increased channel depth, and because all flow (at normal discharge rates) remains in proximity to the wetted perimeter, velocities also remain nearly constant in the downstream direction(Osterkamp, 1980). Osterkamp (1980) suggests that downstream changes in width for braided reaches are related totally by adjustments in discharge and that mean channel depth or water velocity are independent of any channel forming discharge.

There may have been channel braiding in places along the Gila River as suggested by the oldest available USGS topographic maps. There was also at least one historic account of multiple channels. Little braiding is suggested by the maps of the channel produced from the original federal surveys and by accounts of explorers. There were many accounts of willow and cottonwoods trees along the river that clearly suggest the channel was stable in the absense of large floods.

ESTIMATE OF CHANNEL SIZE USING STREAMFLOW CHARACTERISTICS

Channel size along the Gila River at and downstream of the site of the confluence with the Salt River is estimated using streamflow characteristics. Streamflow characteristics, such as average annual flow, have proven to be indicators of channel geometry. Studies by the USGS and others of alluvial stream channels of the western United suggests that discharge characteristics are the principal control of channel size and that sediment characteristics largely determine channel shape. This technique, known by the term "hydraulic geometry", requires an estimate of the streamflow characteristic before an estimate of channel size and shape is made. Leopold and Maddock(1953) theorized that the hydraulic geometry of river channels in approximate equalibrium could be expressed as exponential or power functions.

Leopold, L. B., and Maddock, T. Jr., 1953, The hydraulic geometry of stream channels and some physiographic implications: U.S. Geological Survey Professional Paper 252, 56P.

Both (1) a bankfull-stage concept(U.S. Army Corps of Engineers, 1990), with the emphesis on relating the bankfull channel properties (dependent variables) to some formative or dominant discharge (independent variable), and (2) an average annual discharge concept have been used. The average annual discharge concept relates empirically the dimensions of recognizable active features of the channel, as the dependent variables, and average annual discharge, as the independent variable. This permits estimates of the channel dimensions to be made at ungaged sites 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 streams in the area of investigation but does not require identification of that formative discharge. The average annual discharge is used for much of this estimate of what the channel of the Gila River was like under natural conditions in about 1860.

U. S. Army Corps of Engineers, 1990, Stability of Flood Control Channels: Waterways experimental station and the committee on channel stabilization, draft

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

$$W = aQ^{b} \qquad \text{Equation 1}$$

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

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

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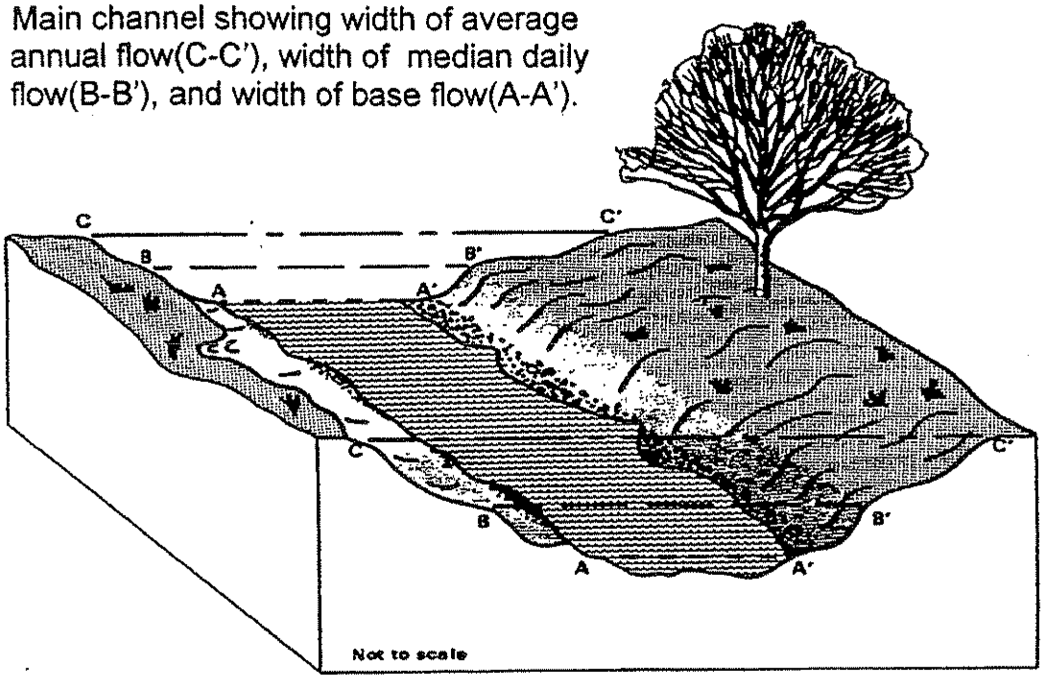
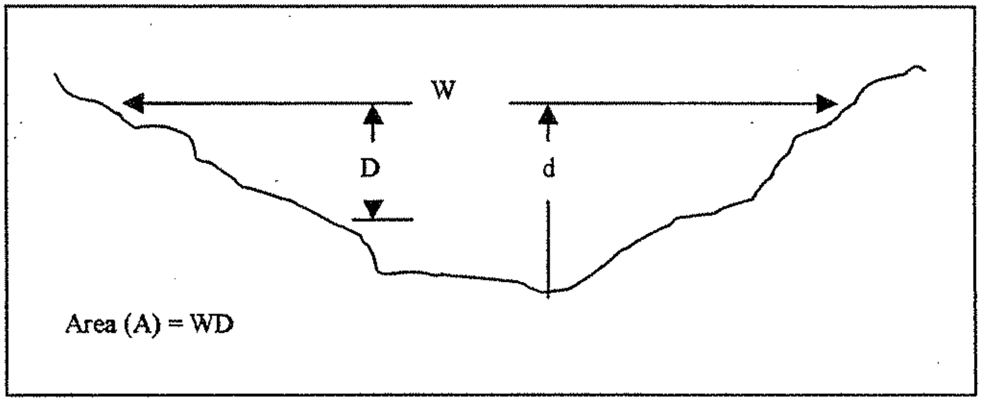
Figure 1.—Rough sketches of river channel.

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').



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



For streams of similar discharge, narrowest channels occur when the sediment load is entirely silt and clay. Channel widths increase with the tractive movement of sand, reaching a maximum in streams that transport only medium- to coarse-grained sand. When the median-particle size of channel material is coarser than sand, the bed and banks are protected and stabilized by armoring, and the resulting channels are narrow.

Other power functions along rivers, although not used in this report, are:

$$D = cQ^{f} \qquad \text{Equation 2}$$

$$V = kQ^{m} \qquad \text{Equation 3}$$

where width D = mean depth and V = mean velocity and f, m, j, c, k and p are numerical constants.

The variables of channel geometry (width and mean depth) are primarily determinants of the variables of discharge (mean discharge, variability of discharge and temporal distribution of discharge). Sediment variables mean concentration, size distribution and temporal changes in availability and size of sediment) are determine the exponent (channel shape indicator) of geometry-discharge relations (Osterkamp, 1980). The type, size and density of riparian vegetation help determine both channel size and shape but these effects are ignored in this estimate.

Osterkamp, W. R., 1980, Sediment-morphology relations of alluvial channels: Proceedings of the symposium on watershed management, American Society of Civil Engineers, Boise Idaho, p. 188-199.

Geometry-discharge relations of alluvial channels generally can be expressed adequately as width-discharge power functions. For specified conveyance and channel-sediment properties, a change in width must be accompanied by an opposite change in mean depth. Because channel width generally can be measured more accurately than mean depth, most channel-geometry studies relate width to a measure of discharge.

For a sample of discussions of the use of hydraulic geometry relations, for both stable and unstable alluvial channels, to estimate channel width, depth and velocity, see the following: Leopold and Maddock(1952), Hey(1978), Stevens and Nordin(1987), Osterkamp(1980) and Wahl.

Leopold, L. B., and Maddock, T. Jr., 1953, The hydraulic geometry of stream channels and some physiographic implications: U.S. Geological Survey Professional Paper 252, 56p.

Hey, R. D., 1978, Determinate hydraulic geometry of river channels: American Society of Civil Engineers Journal of the Hydraulics Division, vol. 104, no. HY6, p. 869-885.

Stevens, M. A. and Nordin, C. F., 1987, Critique of the regime theory for alluvial channels: American Society of Civil Engineers Journal of the Hydraulics Division, vol. 113, no. HY11, p. 1359-1380.

Osterkamp, W. R., 1980, Sediment-morphology relations of alluvial channels: Proceedings of the symposium on watershed management, American Society of Civil Engineers, Boise Idaho, p. 188-199.

Wahl, K. L., 1984, Evolution of the use of channel cross-section properties for Estimating streamflow characteristics: USGS Water-Supply Paper 2262, p. 53-66.

WIDTH-DISCHARGE-SEDIMENT RELATIONS

The geometry (simplified here to width) of an alluvial stream channel primarily is the integrated resultant of all rates of water and sediment discharge conveyed through the channel. The relative importance that the rates of water or sediment discharge might exert on channel geometry varies greatly. For example, the widths of armored alpine channels correlate well with mean discharge (Osterkamp and Hedman, 1977), but the widths of highly ephemeral stream channels, which are unable to heal effectively, are determined largely by infrequent, erosive flow events (Wolman and Gerson, 1978). 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). Summary relations of width and discharge are given below followed by more detailed relations that show the effects of fluvial sediment that is transported and that forms the bed and banks of the channels.

Osterkamp, W. R., and Hedman, E. R., 1977, Variation of width and discharge for natural high-gradient stream channels: Water Resources Research, v. 13, no. 2, p. 256-258.

Wolman, M. G. and Gerson, R., 1978, Relative scales of time and effectiveness of climate in watershed geomorphology: Earth Surface Processes, v. 3, p. 189-208.

Osterkamp, W. R., 1979a, Invariant power functions as applied to fluvial geomorphology, Rhodes, D. D., and Williams, G. P., eds., Adjustments of the fluvial system: Kendall/Hunt Publishing Co. , Dubuque, Iowa, p. 33-54.

Channel material of Gila River

The material of the channel and floodplain of the Gila River, between elevations 430-750 ft, is stratified and coarse textured alluvium(Johnson textured with areas of silty clay loam (Baremore, R. L.,1980)., 1997). Below about elevation 430 ft. the channel and floodplain is mostly coarse The material typically is stratified very fine sandy loam to silt.

In some places the soil is stratified sand. About 25% of the area is Ripley soil that is very fine sandy loam with numerous strata of very fine sand, silt and silt loam.

U.S. Soil Conservation Service Reports for the Gila River from Maricopa and Yuma Counties by Hartman, G. W.(1977), Johnson, W. W. (1997) and Baremore, R. L.(1980).

Variation of Width and Discharge

Analysis of data from three diverse groups of perennial stream channels yielded the following relation between width, W, and mean discharge, Q (Osterkamp, 1979b):

Osterkamp, W. R., 1979b, Variation of alluvial-channel width with discharge and character of sediment: U.S. Geological Survey Water-Resources Investigations 79-15, 11 p.

$$W = aQ^{0.50}$$

Values of the coefficient, a, were 7.7 for armored alpine channels, 4.9 for mostly silt and clay channels, and 9.5 for spring-effluent channels of a karst area. These values appear to be determined largely by the channel-sediment characteristics. It is important to note that the Gila River would not necessarily be expected to have hydraulic geometry charactersitics of armored alpine or spring-effluent channels of a karst channels. It also is important to note that the exponent of 0.50 is the average value for river basins studied by Leopold and Maddock (1953).

The widths of the alluvial stream channel always reflects the influence of infrequent discharges, and neither widening nor narrowing through time is pronounced. In all cases, it is inferred that erosive or channel-widening discharges winnow the channel material of fine sediment sizes and cause an increase in median-particle size. Erosive discharges also tend to straighten channels and increase the gradients. Preceding a moderate flood, the sandy-perennial stream channel of the Gila River might have been of moderate width, exhibited well developed sinuosity, and had a sand bed and stable banks of silt and fine sand. The width-mean discharge relation might have been described by the following equation:

$$W = 3.36\ Q^{0.59}$$

where Q is in cfs and W is in feet.

The above equation is for sand-bed and silt bank channels.

Osterkamp, W. R., 1980, Sediment-morphology relations of alluvial channels: Proceedings of the symposium on watershed management, American Society of Civil Engineers, Boise Idaho, p. 188-199.

Following a very large flood, the channel may more than double in width (at the expense of flood-plain area), straighten, and modify to a braided pattern. Most silt and fine sand may be washed from the bed material, and coarse-sand to gravel sizes would be added by destruction and reworking of flood-plain deposits. This braided channel condition would be unstable. Channel changes of this sort have been documented for the Cimarron River in Kansas (Schumm and Lichty, 1963) and the Gila River in Arizona (Burkham, 1972). Following extensive flood-plain destruction by a very large flood, an extended period is required for re-storage of fine sediment sizes in the channel alluvium before significant narrowing occurs. With storage of fines, a change from a braided pattern to a defined channel can proceed rapidly.

Schumm, S. A., and Lichty, R. W., 1963, Channel widening and flood-plain construction along Cimarron River in southwestern Kansas: U.S. Geological Survey Professional Paper 352-D, p. 71-88.

Burkham, D. E., 1972, Channel changes of the Gila River in Safford Valley, Arizona, 1846-1970: U.S. Geological Survey Professional Paper 655-G, 24 p.

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

$$W = 3.24\ Q^{0.62}$$

where Q is in cfs and W is in feet. This equation is for sand-bed and sand-bank channels(Osterkamp, W. R., 1980).

Channel widths from hydraulic geometry and other bed and bank material are shown in Table 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.

Estimates of channel width along the natural channel of the Gila River, corresponding to the mean annual runoff of 2,330 cfs, were from 250 to 396 feet (Table 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.

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Table 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
1	high silt-clay	3.13334	0.47	119.857	Osterkamp (1980)
2	medium silt-clay*	3.01116	0.57	250.107	same as above
3	low silt-clay*	3.11327	0.58	279.436	same as above
4	sand with silt banks*	3.36476	0.59	326.358	same as above
5	sand with sand banks*	3.23949	0.62	396.495	same as above
6	gravel*	3.69561	0.55	262.864	same as above
7	cobble	3.59036	0.54	236.325	same as above
8	boulder	4.10211	0.51	213.973	same as above
9	armored alpine	4.25097	0.50	205.194	Osterkamp (1979b)
10	mostly silt-	2.70516	0.50	130.578	same as above
11	karst area	5.24470	0.50	253.162	same as above

*Likely bed and bank material along the Gila River below the confluence with the Salt River. Based on field inspection and U.S. Soil Conservation Service Soil Survey Reports.

probably some armoring along entire river. By excluding these this analysis is very conservative

Variation of Depth and Discharge

Depths of water for the main channel along the Gila River are related to flow characteristics and channel roughness, slope and width. As mentioned previously, the average width of the Gila River for the average annual flow is about 300 ft. The channel slope is not very steep with an average drop of about 5.5 feet per mile between the Salt River and Gillespie Dam and slightly more than 2.5 feet per mile near the mouth. The corresponding depth of flow for natural conditions is estimated using channel conveyance-slope characteristics and rating curve characteristics(Rantz and others, 1982).

Rantz, S. E., 1982, Measurement and computation of streamflow: Volume 2. Computation of discharge: USGS Water-Supply Paper 2175, 631 p.

The Manning equation for a channel cross section can be used to estimate channel depths. First, the hydraulic geometry relation between depth and discharge is used:

$d = cQ^{f}$ similar to Equation 2 but this equation is for a cross section and not for along the river

where d = depth of water above channel invert, c = a coefficient that equals the depth when the discharge Q=1, *f* = exponent =slope of the discharge-depth relation. As stated previously, *f* and c are functions of physical charactersitics of the controls of the flow in the river.

The Manning equation is:

$$Q = 1.49/n \, AR^{2/3} S^{1/2} \qquad \text{Equation 4}$$

where *n* = roughness coefficient; *A* = cross-sectional area, in square feet; *R* = hydraulic radius at a cross section, in feet; equals the cross-sectional area, in square feet, divided by the wetted perimeter, in feet; *S* = energy gradient.

Manning's discharge equation was developed for uniform flow in which the water surface profile and energy gradient are parallel to the streambed, and the area, hydraulic radius, and depth remain constant throughout the reach. The equation is considered valid for nonuniform conditions, such as that for most natural channels, if the energy gradient or friction slope is modified to reflect only losses due to boundary friction (Barnes, 1967, p. 5). Manning's discharge equation is widely used by the USGS for conditions of channel control to compute flow ratings(Rantz and others, 1982).

Barnes, H. H., 1967, Roughness characteristics of natural streams: U. S. Gological Survey Water-Supply Paper 1849, 213 p.

Several assumptions and simplifications must be made before Manning's equation can be used to estimate *C* and *f* of Equation 2. For the mean annual flood discharge it is assumed that R can be adequately represented by the mean cross-sectional depth, D, and *S* can be represented by the channel slope, S_o, or by the water-surface slope, S_w. The area. *A,* in equation 5 is represented by the mean depth, D, multiplied by the top width, *W,* that was estimated in the previous section of this analysis.

For a wide range of flood depths, the relation between d and W is:

$$W = a_1\, d^{x} \qquad \text{Equation 5}$$

Where the parameter x is a function of shape; it is 0 for a rectangular shape, 1/2 for a parabolic shape, and 1 for a triangular shape.

Considering the previous assumptions and simplifications, Manning's discharge equation can be represented by:

$$Q = a_1(1.49/n)\,(D)^{5/3}\,(d)^{x}\,S_o^{\,1/2} \qquad \text{Equation 6}$$

A further simplification is made; D is represented by the formula "D = $a_2 d$" where *d* = depth above the channel invert as defined previously. The parameter a_2 is also a function of channel shape; it is 1 for a rectangular shape, ½ *for* a triangular shape, and 2/3 for a parabolic shape. The depth, *d,* now can be represented by

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$$d = \left(\frac{n}{a_1(a_2)^{5/3}(1.49)(S_o)^{1/2}}\right)^{3/(5+3x)} (Q)^{3/(5+3x)} \qquad \text{Equation 7}$$

The above equation 7 is directly comperable to equation 2, therefore,

$$C = \left(\frac{n}{a_1(a_2)^{5/3}(1.49)(S_o)^{1/2}}\right)^{f} \qquad \text{Equation 8}$$

$$f = \left(\frac{3}{(5+3x)}\right) \qquad \text{Equation 9}$$

Equations 7, 8, and 9 are approximately correct for stage-discharge relations for discharges in uniform channels. The value x would range from 0 to 1 and, therefore, f would range from 0.60 to 0.38 for stable channel controls. The typical natural channel, like the natural channel of the Gila River, is approximately parabolic in shape(based mostly on the author's experience with ratings), for which f would be 0.46.

For a parabolic channel, using equation 9, $x = ½$, $a_2 = 2/3$, $D = a_2d$ and using the W versus D relation of Equation 5

$$Q = (1.49/n)\ (a_2d)^{5/3}\ W\ So^{½} \qquad \text{Equation 6(repeat)}$$

Substituting the average estimated channel width (W = 300 ft), S = 0.001 for upper reach of the river and using n = .035,

$$2330 = 42\ (.67d)^{1.67}\ (300)\ (.001)^{.5}$$

Rearranging and solving for the depth in the upper reach of the Gila River,

$$d_{upper} = 4.31 \text{ ft}$$

For the lower reach of the Gila River, at a slope of about 0.0005, the estimated depth for the mean annual discharge is

$$d_{lower} = 5.36 \text{ ft.}$$

Additional estimates of water depth for various channel width shown in Table 1 are shown in Table 2. Because of the lesser channel gradient near the mouth, the depth of flow is greater for the mean annual discharge of 2,330 cfs(Figure 2).

Discussion of widths and depths

Obviously, a large number of historic measurements of channel characteristics, especially channel width and depth for dry-weather flows, would be important information for assessment of navigability. However, in the absence of historic measurements of channel geometry at several locations along the river, the hydraulic geometry is considered a reliable general estimate of channel width and depth. Streamflow characteristics have proven to be a valid indicator of channel dimensions using hydraulic geometry relations. The hydraulic geometry relations, that are rather symetric relations between channel depths, widths and velocities(Langbein, 1962), are applied to past conditions of natural flow for the Gila River.

Langbein, W. B., 1962, Hydraulics of River Channels as Related to Navigability: U. S. Geological Survey Water-Supply Paper 1539-W, 30 p.

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The vegetation composition of the riparian zone is not considered in this estimate. This variable would have an unknown influence on the channel morphology. However, this influence may be to stabilize the banks and thereby narrow the main channel. A narrowing of the width may tend to increase water depths and enhance navigability.

Table 2.—Estimated depth of water for average annual discharge of 2,330 cfs.

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

Row	W(feet)*	slope	d(feet)	Remarks
1	250.107	0.0010	4.80686	
2	279.436	0.0010	4.49746	
3	326.358	0.0010	4.09751	
4	396.495	0.0010	3.64581	
5	262.864	0.0010	4.66550	
6	300.000	0.0010	4.30987	Average est. of bed material
7	250.107	0.0010	4.80686	
8	279.436	0.0010	4.49746	
9	326.358	0.0010	4.09751	
10	396.495	0.0010	3.64581	
11	262.864	0.0010	4.66550	
12	300.000	0.0010	4.30987	Average est. of bed material
13	250.107	0.0005	5.91793	
14	279.436	0.0005	5.53702	
15	326.358	0.0005	5.04463	
16	396.495	0.0005	4.48852	
17	262.864	0.0005	5.74390	
18	300.000	0.0005	5.30607	Average est. of bed material
19	250.107	0.0005	5.91793	
20	279.436	0.0005	5.53702	
21	326.358	0.0005	5.04463	
22	396.495	0.0005	4.48852	
23	262.864	0.0005	5.74390	
24	300.000	0.0005	5.30607	Average est. of bed material

*See Table 1.

Channel depth-velocity curves shown in Figure 3, and the data shown in Table 3, are related to navigability along the watercourse(Langbein, 1962). The width-, velocity-, and depth-duration relations for the main channel are shown in Figures 4-6, respectively. The similar depth-duration curves for the upper and lower reaches(Figure 6) suggest rather similar navigability along the river.

Table 3. Flow depths and velocities for upper and lower reaches of the Gila River

Depth(ft)	Velocity(ft/s)	
	Upper	Lower
0	0	0
0.5	0.65	0.50
1.0	1.01	0.80
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

It is interesting that the width-duration curve(Figure 4) shows that channel widths typically were from about 200-350 ft and more and that several of the historic observations of width are in this ballpark(US Corps of Engineers, Appendix 11).

US Corps of Engineers, 1995, Gila River, Gillespie Dam to Yuma, AZ: Reconnaissance report(FCD 0000028).

Some of the quantitative accounts of the width in the Corps report are:

YEAR	WIDTH	REMARKS
1846-47	60-80 yards	At Gila bend. Depth of 3 ft.
1846-48	150 yards	3-4 ft. deep.
1849	<100 yards	Narrow at this point.
1856	150 ft.	Near mouth. Depth variable.

Figure 2.—Depth-Q curves for main channel of the Gila River in natural state.

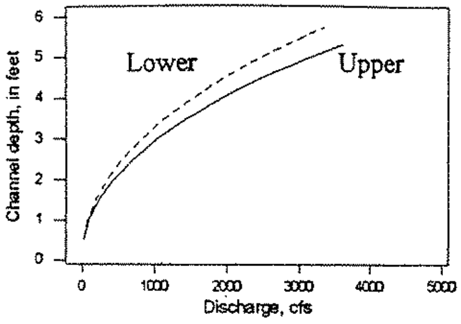


Figure 3.—Depth-velocity curves for main channel of the Gila River in natural state.

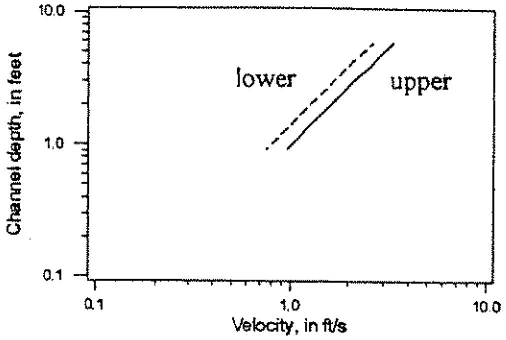


Figure 4.—Width-duration curves for upper and lower reaches of the Gila River in natural state.

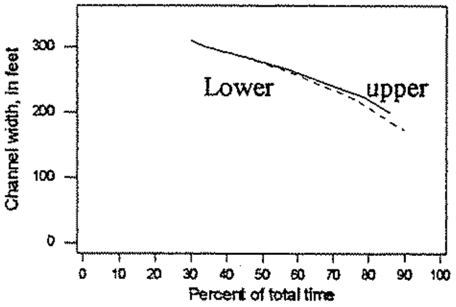


Figure 5.—Velocity-duration curves for upper and lower reaches of the Gila River in natural state.

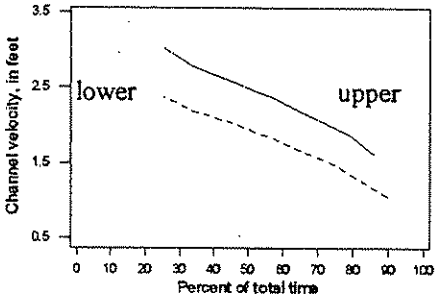


Figure 6.—Depth-duration curves for upper and lower reaches of the Gila River in natural state.

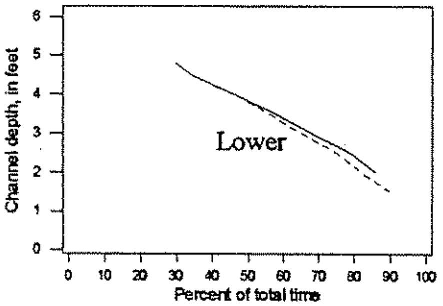
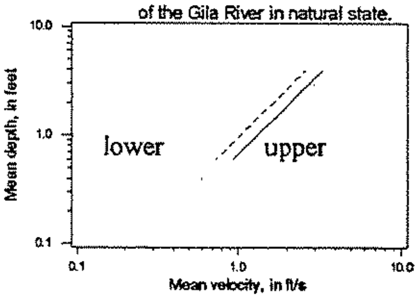


Figure 7.—Mean depth of flow in main channel versus mean velocity for upper and lower reaches of the Gila River in natural state.



In the lower reaches of the Gila River, the reaches below the Salt, the baseflow from the ground-water basins was a small part of ground-water discharge. Other components of ground-water discharge, evapotranspiration and ground-water underflow, undoubtedly were much larger in comparison. In fact, because of high losses to evapotranspiration in the hot-dry dessert, there was a net loss of base flow during typical years especially during long-dry periods. The Gila River was perennial throughout the entire reach but much of the flow was derived from the upper basins where baseflows and spring runoff were a much larger component.

The similar depth-duration relations(Figure 6) along the Gila River below the Salt reflect the net loss of base flow in the lower reaches. The loss of depth associated with the loss of base flow is offset by the increase of depth associated with the decrease in channel slope(Figure 6). In regard to flow depth, an important parameter for navagability, there were no diversions or ground-water withdrawals by anglos to diminish depths in the lower reaches. Also, as previously discussed, the variability of outflow from the many basin-fill aquifers would be much less than the variability of spring runoff and storm runoff. The flow depths typically were between 1.5 to 5 ft and depths exceeded 4 ft about 50% of the time.

TOPOGRAPHY—ESTIMATES OF CHANNEL WIDTH AND DEPTH

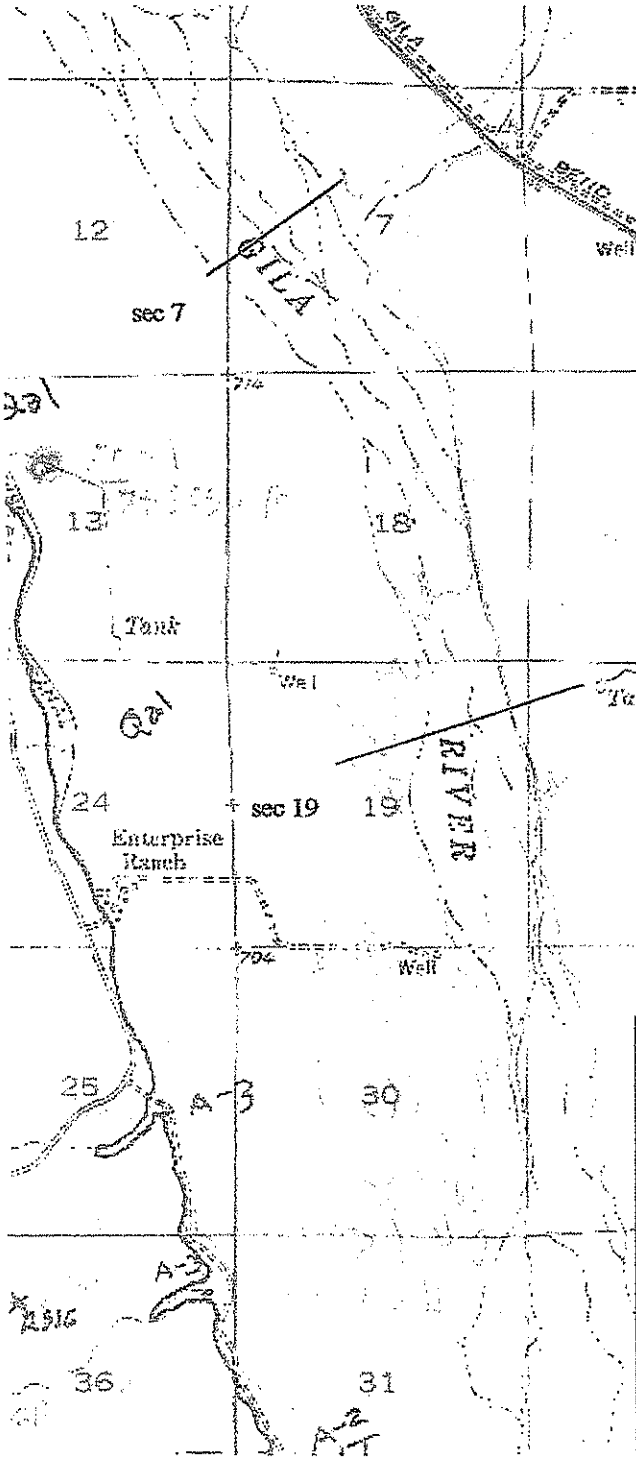
Historic USGS topographic maps were used in conjunction with historic accounts of the channel hydraulics(width, depth, velocity and vegetation) to estimate the predevelopment conditions. Definition of the low water channel(s) was the objective because low-flows limit navigation of shallow-draft vessels. The historic maps used were 15 minute series (Scale 1/62,500) topo. quads. Channel geometry was scaled from the contour intervals and scaling was performed at several locations to produce a rough estimate of a repre-sentative cross section. Focus was on the channel conditions shown on the older maps (Survey dates 1902 to 1927). Hydraulic conditions along the channel of the Gila River were also obtained from *Historic Descriptions of the River* by the U. S. Bureau of Land Management since 1867(Arizona State Land Department, Gila River Navigability Study-Draft Final Report, September, 1996). Other useful information was in *Historical Overview/River Chronology* of the same report. Historic descriptions of the channel from several other sources were also used. Historic descriptions indicate channel movement at a few locations but the descriptions are not inconsistent with the channel on the topographic maps. Based on these accounts and channel conditions gleaned from the maps, three cross sections were selected to represent worst case channel geometry of the Gila River.

Navigation during low flows was limited where the low-water channels may have been braided. Flow appeared to divide into two or more channels in these areas and there may not have been much depth for rafts and small boats during long-dry periods when base runoff was low. Where low water was in a single channel all of the low water was confined to the channel and flow depths, the major limiting parameter for navigation on the Gila River, were greatest where low water was in three channels the low water was distributed and more total flow was needed to produce the needed depths.

The low water channel of the Gila River is formed in alluvium and the shape, size and location of this channel changes with time and with distance along the river. Burkham (1972) documented channel changes of the Gila River upstream in the Safford Valley. While the destabilization of the Gila River channel in Safford Valley occured after settlers diverted flow for irrigation, similar but probably lesser changes may have occured in the lower Gila before 1860. U. S. Soil Conservation Service maps of the soils along the Gila River channel show a wide area of recent alluvium that suggests laterial channel movement on the order of hundreds to a few thousand feet. Similar amounts of movement as a result of large floods, following the human effects, was documented upstream by Burkham(1972). Of significance to navigation, Burkham found that large floods temporarily widened the channel. Thus, the width of the low water may be greater and the corresponding depth may be less following large floods that temporarily reshaped the channel. The multi-channel cross section used for this hydraulic analysis is judged to represent this worst-case condition for navigation. How well it represents natural conditions before 1860 is unknown.

CROSS SECTIONS FROM COTTON CENTER QUAD-AERIAL PHOTOS OF 1947

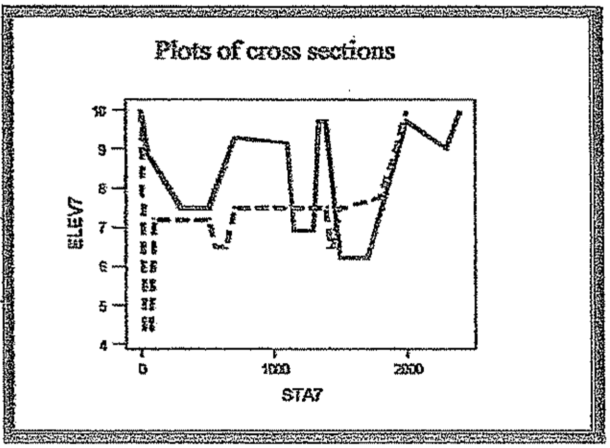
Elevations from linear interpolation between contours. Sec 7 is about 3-4 mile below Gillespie Dam and sec 19 is about 5 mile below the dam. These estimates are made in a braided channel area where predevelopment flow would have divided into multiple channels.



STA7	ELEV7(+710)
0	10.00
50	8.88
300	7.48
500	7.48
700	9.30
1100	9.16
1150	6.92
1300	6.92
1350	9.72
1400	9.72
1480	8.80
1500	6.22
1700	6.22
1730	8.22
2000	9.72
2300	9.02
2400	10.00

STA19	ELEV19(+690)
0	10.00
25	4.40
75	4.40
100	7.20
500	7.20
550	6.50
625	6.50
700	7.48
1400	7.48
1425	6.50
1450	6.50
1500	7.48
1800	7.76
2000	10.00

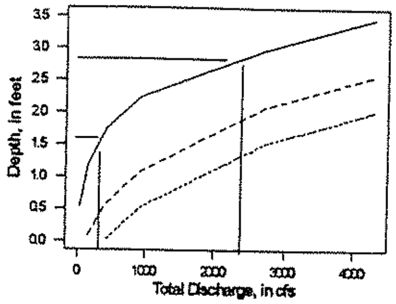
Worst Case - may n't be for natural condition probably not



Plots of cross sections

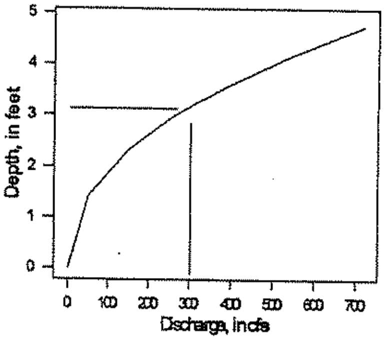
The depth-discharge relations for the three braids at cross section 7 are shown to the right. The relations are from channel conveyance-slope estimates with adjustment for trapazoidal channel shape. The depth corresponding to the mean annual runoff of 2,330 cfs is about 2.8 feet(See figure below) versus a depth of 4.31 feet for a single channel(See Fig. 2). At a base runoff of about 300 cfs the estimated depth in the main braid is 1.6 feet.

Depth versus total discharge for the three braided channels at cross section 7.



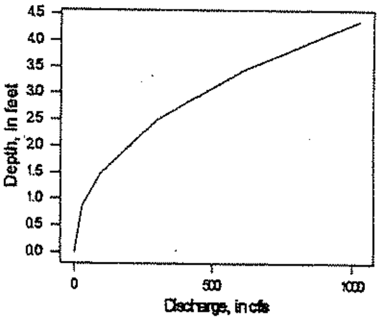
The depth-discharge relation for the main braid at cross section 19 are shown to the right. The relation is from channel conveyance-slope estimates with adjustment for trapazoidal channel shape. At a base runoff of about 300 cfs the estimated depth is about 3 feet. This estimated depth is about 1 ft more than the depth shown in Figure 2 for the same base discharge. The channel is narrower at section 19 than for the width determoned from hydraulic geometry techniques

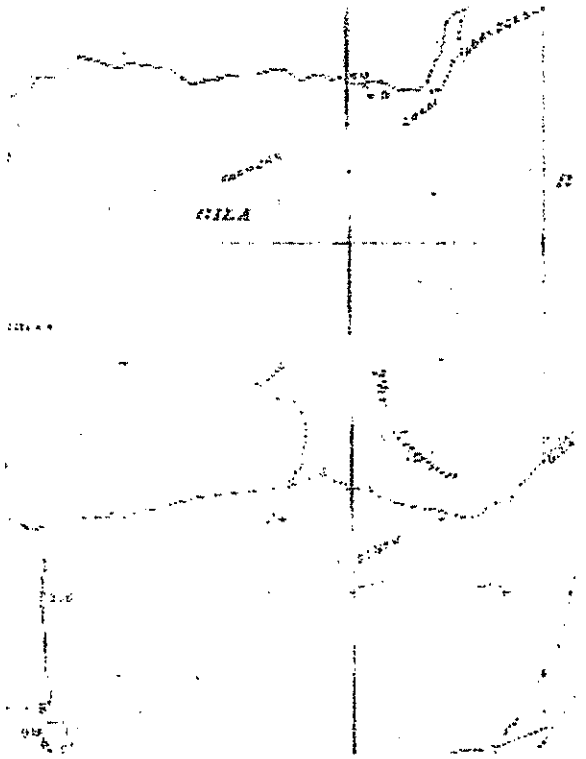
Depth-discharge in the main braid at cross section 19. (Flow spreads into other braids at greater depths.)



The depth-discharge relation for the cross section of the single channel near Yuma. The relation is estimated using channel conveyance-slope with adjustment for the trapazoidal channel shape. This relation shows more depth than the relation in Figure 2 for the lower reach.

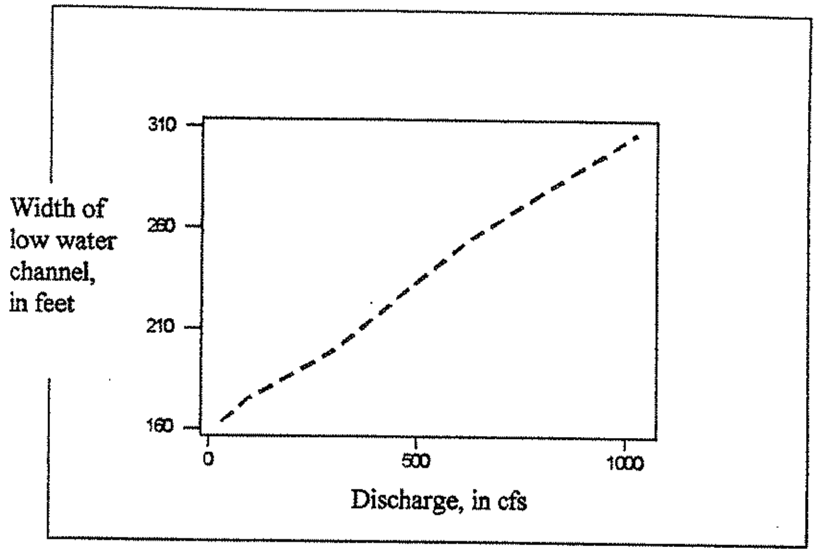
Depth-discharge in the main braid at cross section nr Yuma (Represents section in Yuma area estimated from topography)





Gila River in 1926-27 downstream of Gillespie Dam at Maricopa County-Yuma County line. Note the Farmer's Canal(top of scene) and the South Gila Ditch(bottom of scene) that are "abandoned". Also note the oxbow "The Lagoon" that was cut off by channel movement. The low-flow channel appears about 200-300 ft wide. At bankfull stage the depth is about 6 to 8 ft. AZTEC. ARIZ. USGS 15 MIN. QUAD EDITION OF 1929. CONTOUR INTERVAL = 25 ft.

The width of the low water channels typically is between 80 to 400 feet. The width-discharge relation for the Yuma cross section is shown below.



SUMMARY OF CHANNEL HYDRAULICS

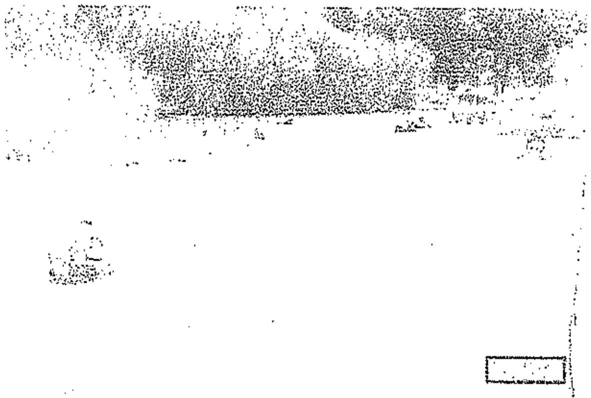
In the interest of simplicity the hydraulics of the watercourse are characterized using general hydraulic geometry of natural rivers. These general relations provide a basis for assessment of the navigability of the Gila River.

Channel geometry from topographic maps is not optimal for several reasons including (1) the channel geometry shown by the maps reflects many years of human effects such as the diversions for irrigation by the settlers and (2) the scale of the maps is to small for definition of the main channel.

The estimated depth of flow along the Gila River is at least 2 ft approximately 90% of a typical year. The estimated worst-case flow depth that may have occured where channels were temporarily braided was about 1.5 ft at base runoff. For approximately 70% of a typical year the flow depth was more than 3 ft, the flow velocity was more than 1.5 ft/sec and the channel width was more than about 250 ft.

Marc

Where and when the Gila River was navigable in the approximately xxx mile reach between the Salt River and Yuma?



Recreating on about 50 cfs in the Gila River watershed.
Verde River in Verde Valley-April, 2000

Navigability along the Gila River is evaluated using the natural hydrology and channel hydraulics. Three methods of assessing instream flows are used.

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

The second method is based on hydraulics of a single channel cross section that is representive of the 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. The standard method, that uses the channel velocity and depth from the hydraulic geometry relations of the previous section, is based on the minumum tractive force required for upstream navigation. The tractive force of the Gila River is compared with a limiting tractive force required for commercial navigation on several rivers.

METHOD 1: A rule of thumb method for white water boating summarized on next three pages. This is from the Bureau of Outdoor Recreation Report D6429.

In terms of stream flow criteria, canoes and kayaks may be grouped together. Both are small, maneuverable, and capable of upstream and cross-stream maneuvers. The drift boats and rafts are larger, less maneuverable and almost impossible to move upstream in heavy water. They are, however, very stable in heavy water and can carry unskilled passengers; they are used almost exclusively by commercial river guides.

In either class of craft, a certain minimum condition must be met in a stream to provide even a limited white water experience. The exact conditions of gradient and flow that yield white water vary from stream to stream, but a good rule of thumb is that white water streams have a gradient in excess of 10 feet per mile and a flow in excess of 500 cubic feet per second. These conditions will provide Class I white water on the International River Classification scale. This scale recognizes six grades of white water. These may be subjectively described as:

> 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. A spraydeck on open boats is useful.
>
> Class IV - Difficult. Long rapids with powerful waves and many obstacles are present. Passages are difficult to see and powerful, precise maneuvering is required. A spraydeck is essential on open boats.
>
> 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.

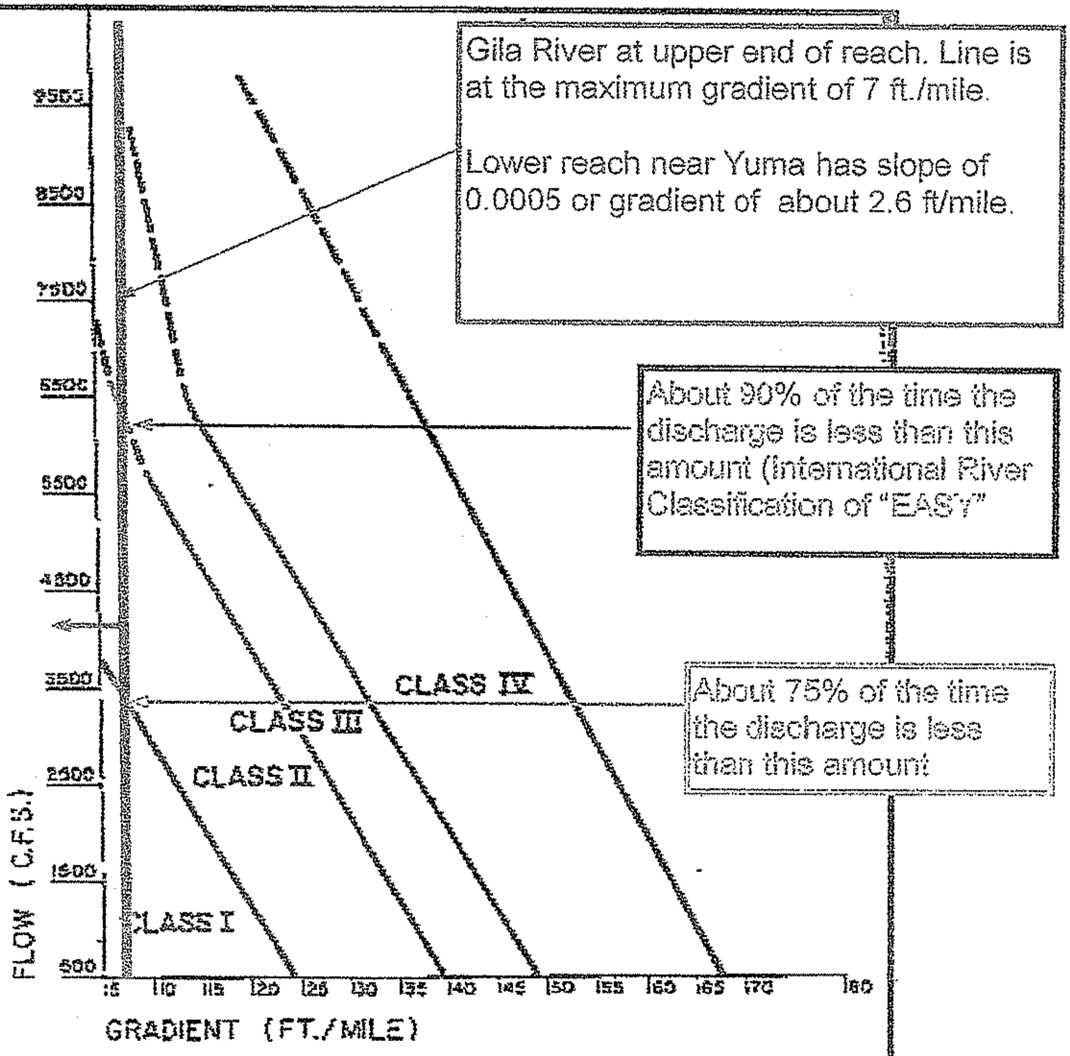
For recreational white water boating, only Classes I through IV are of interest. Class I marks the minimum level for a white water experience, Class III is the usual upper bound for open boats, and Class IV is the upper limit for most recreational kayakers. Rafts, drift boats, kayaks, and covered canoes can negotiate Class V waters if they are expertly handled. Class VI waters are stunt waters for expert boaters with maximum safety precautions.

TABLE 2

Summary of Instream Flow Requirements for Recreation

	ACTIVITY	MINIMUM CONDITION	MAXIMUM CONDITION	OPTIMUM CONDITION	COMMENTS
FISHING	Wading	W = -- D = -- V = --	W = -- D = 4 ft V = 2.5 ft/sec	W = -- D = <4 ft V = <2.5 ft/sec	All conditions should be checked against fish. survival flow.
	Boating--Canoeing	W = 25 ft D = 6 in V = --	W = -- D = -- V = 10 ft/sec	W = >25 ft D = 2-5 ft V = <5 ft/sec	
	Boating--Low Power	W = 25 ft D = 1 ft V = --	W = -- D = -- V = 10 ft/sec	W = >25 ft D = 2-5 ft V = <5 ft/sec	
	Bank	W = -- D = -- V = --	W = D = Flood V =	W = based D = on fish V = catchability	
WATER BOATING	Rafts & Drift Boats	W = 50 ft D = 1 ft V = 5 ft/sec (Class I)	W = -- D = -- V = 15 ft/sec (Class V & VI)	W = >100 ft D = 2-5 ft V = 10 ft/sec (Class II,III,IV,V)	In all cases, check against International Classification.
	Canoes & Kayaks	W = 25 ft D = 3-6 in V = 5 ft/sec (Class I)	W = -- D = -- V = 15 ft/sec (Class IV & V)	W = >75 ft D = 2-3 ft V = 10 ft/sec (Class II,III,IV)	
TRANQUIL WATER BOATING	Canoeing	W = 25 ft D = 6 in V = --	W = -- D = -- V = 5 ft/sec	W = >75 ft D = 2-5 ft V = <1.5 ft/sec	
	Rowing	W = 25 ft D = 1 ft V = --	W = -- D = -- V = 5 ft/sec	W = >75 ft D = 2-5 ft V = <1.5 ft/sec	
	Sailing	W = 100 ft D = 2 ft V = --	W = -- D = -- V = 1.5 ft/sec	W = >200 ft D = ~ 5 ft V = ~ 0 ft/sec	
	Low Power	W = 25 ft D = 2 ft V = --	W = -- D = -- V = 10 ft/sec	W = >100 ft D = ~ 5 ft V = <5 ft/sec	
	High Power	W = 100 ft D = 5 ft V = --	W = -- D = -- V = 15 ft/sec	W = >300 ft D = 10 ft V = <5 ft/sec	
WATER CONTACT	Swimming	W = 25 ft D = 3 ft V = --	W = -- D = -- V = 3 ft/sec	W = >100 ft D = 5 ft V = <1.0 ft/sec	Water temp - max 50-100°F Visibility - Opt=Depth Bacteria max 1000mpn
	Wading	W = -- D = -- V = --	W = -- D = 4 ft V = 2.5 ft/sec	W = -- D = 1-4 ft V = 2-5 ft/sec	Max D x V = 10 Opt D x V = 2-5 + above
	Tubing	W = 25 ft D = 1 ft V = 1 ft/sec	W = -- D = -- V = 10 ft/sec	W = >75 ft D = 2-5 ft V = 5 ft/sec	Same as Swimming
	Water--Skiing	W = 200 ft D = 5 ft V = --	W = -- D = -- V = 3.5 ft/sec	W = >500 ft D = 10 ft V = <2.5 ft/sec	Same as Swimming

Gila River meets these.



Gila River at upper end of reach. Line is at the maximum gradient of 7 ft./mile.

Lower reach near Yuma has slope of 0.0005 or gradient of about 2.6 ft/mile.

About 90% of the time the discharge is less than this amount (International River Classification of "EASY"

About 75% of the time the discharge is less than this amount

ESTIMATING RIVER DIFFICULTY
(Assumes Fairly Even Gradient)

AFTER ARIGHI, AND ARIGHI, 1974

RULE OF THUMB RATING SHOWN ABOVE.

Class I is very easy, II is easy, III is medium difficulty, IV is difficult, V is very difficult.

The above rating of river difficulty was prepated by Jason M. Cortell and Associates Inc. of Waltham Mass. for the Bureau of Outdoor Recreation of the U. S. Dept. of the Interior in July 1977.

METHOD 2: The U.S. Fish and Wildlife Service(FWS/OBS-78/34) developed a method of assessing streamflow suitability for recreation. The single cross section technique, that is very simple, is used. This method uses a single section taken across the Gila River. The product of this approach is determination of the lowest flow acceptable for a particular form of recreation. The following table shows the minimum requirements:

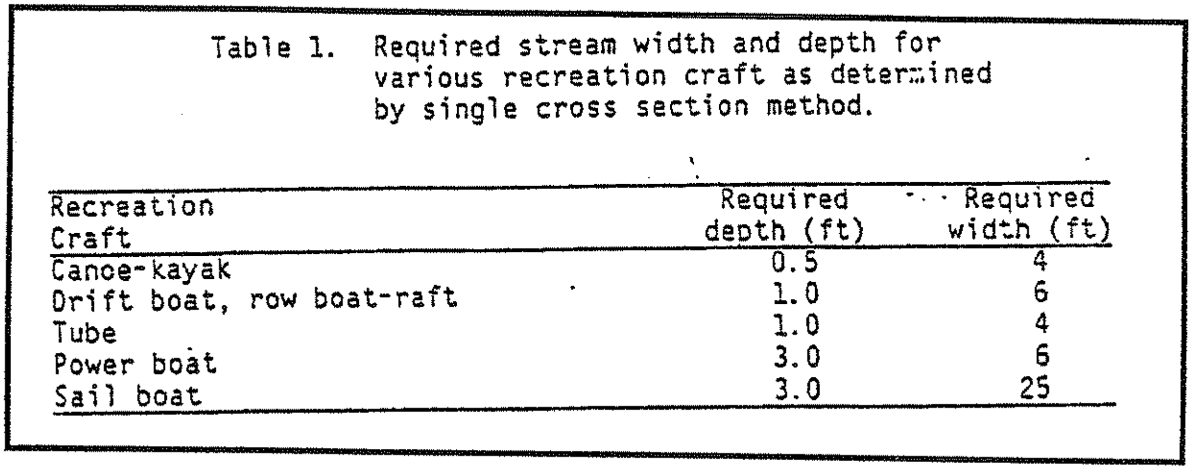


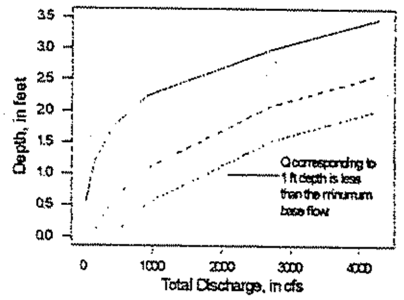
Table 1. Required stream width and depth for various recreation craft as determined by single cross section method.

Recreation Craft	Required depth (ft)	Required width (ft)
Canoe-kayak	0.5	4
Drift boat, row boat-raft	1.0	6
Tube	1.0	4
Power boat	3.0	6
Sail boat	3.0	25

Clearly, the above minimum width and depth requirements nearly all of the time along the Gila River(See the depth-duration and width-duration curves shown in figures 4 and 6 of the previous section).

The required stream depth for drift boats is less than the depth for cross section 7 that represents the worst-case flow condition for the Gila River (See graph on the right)

Depth versus total discharge for the three braided channels at cross section 7.



quality of a particular recreation activity which takes place in the stream.

SINGLE CROSS SECTION METHOD

This method requires that only a single cross sectional measurement be taken across a stream. The product of such an approach is a determination of the lowest flow acceptable for recreation. The approach is based on the assumption that a single cross section, properly located, can define a minimum flow requirement. Such a cross section is located at an area displaying the least depth across the entire stream. When this area provides minimum depths for boat passage, the flow at this level may be defined as a minimum acceptable flow. It is assumed that when sufficient water to support boating is available in these critical areas, other areas will have sufficient water to support most of the other instream recreation activities. This approach is best applied to those streams in which flows are expected to be higher than the minimum most of the time.

Criteria for this approach are set forth in Table 1. Criteria have been developed for boating activities only, but for various types of boating craft. Only minimum criteria are presented because this approach provides information on "minimum flows." Criteria are measured in terms of stream depth and width. Velocity is not considered because a minimum velocity is not considered necessary for this approach.

Table 1. Required stream width and depth for various recreation craft as determined by single cross section method.

Recreation Craft	Required depth (ft)	Required width (ft)
Canoe-kayak	0.5	4
Drift boat, row boat-raft	1.0	6
Tube	1.0	4
Power boat	3.0	6
Sail boat	3.0	25

The criteria of Table 1 are minimal and would not provide a satisfactory experience if the entire river was at this level. However, the cross section measured for this method is the shallowest in the stream reach. Therefore, these minimum conditions will only be encountered for

METHOD 3: This tractive force method combines the characteristics of vessels and rivers to produce a minimum tractive force for river navigability. The method was developed by the U. S. Geological Survey(Langbein, 1962). Langbein states:

> *About 20,000 miles of river channel is used for commercial navigation in the United States. The use of rivers for the transportation of goods and people not only played a most historic role in the development of the continent, but even today the rivers carry a significant amount of commercial freight. Yet there have been few studies to test the navigability of rivers in relation to the hydraulics of vessels—if by navigability one means transport by commercial vessels: barge or river boat, as distinct from pleasure boating, or exploration. This paper is based therefore on the primary premise that navigability means two-way navigability in fact/ recognizing that even navigable rivers differ in their hydraulics and, to a corresponding degree, in their navigability.*

This particular assessment of the navigability of the Gila River, that is based on 1962 standards for commercial navigability, is summarized from Langbein as follows:

A. The hydraulic geometry of the river is characterized by its width, depth and velocity. This was accomplished in the previous section on the hydraulics of the natural channel of the Gila River.

B. The hydraulic character of vessels is determined using resistance formulas, specific tractive force, shallow-water drag, slope drag, loss of bed clearance with speed and rounding river bends. An important characteristic of a vessel its specific tractive force(Ts), a dimensionless factor defined as the ratio of the thrust to the weight. In these terms Ts is equivalent to the slope of a river, which measures the downstream component of the force of gravity per unit weight of water. The specific tractive force of a vessel may be calculated from data on its horsepower, design speed, and displacement as follows:

$$Ts = \frac{\text{Horsepower x 550}}{\text{Speed, in ft./s x displacement, in tons x2240}}$$

A vessel moving upstream at velocity (V) must overcome frictional resistance (R). For a vessel moving at uniform speed (V = constant), the resistance equals the thrust, so that Ts=R/W where W = displace weight. Using this relation, the above equation for Ts and the resistance of the vessel that is a function of velocity and is based on the Manning equation, is:

$$V = 25\, d^{2/3}\, (P/WV)^{1.5}$$

where d = the draft of the vessel

A vessel moving upstream must not only overcome the frictional and other retardational forces due to its motion, but additional energy must be expended to raise the vessel. The force involved is known as the slope drag.

The existence of the slope drag force may be illustrated by the diagram below.

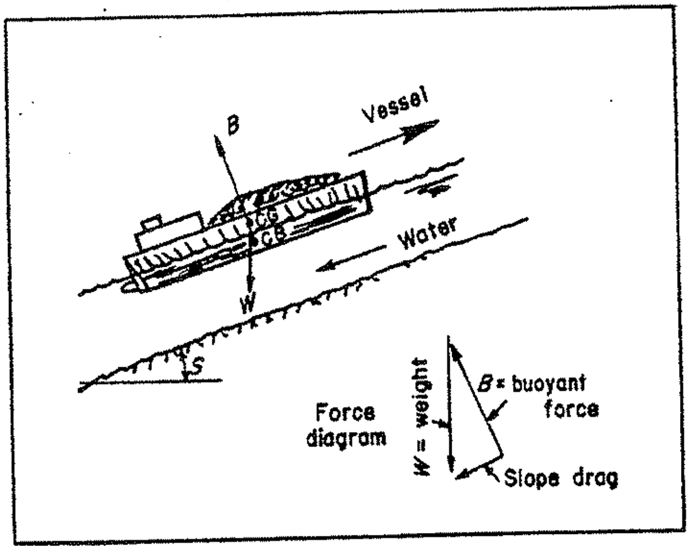


FIGURE 9.—Schematic illustration of slope drag on a vessel moving upstream.

In a floating vessel, the center of buoyancy, CB in the diagram is below the center of gravity, CG. The buoyant force acts along the line through CG and CB. For a vessel in level water, this line is vertical, but as depicted, the buoyant force is deflected by the slope angle, *s*. The weight acting at the center of gravity remains vertical. Thus, there is a component of force equal to the product of the sine of the angle, *s*, and the weight of the vessel. Since for small angles, the sine equals the slope, one may write with sufficient accuracy that the slope force acting on the vessel equals s times its weight as follows:

$$\text{Slope drag} = sW.$$

The above force is called the slope drag for vessels moving upstream and the slope thrust for vessels moving downstream. The slope drag is usually small in relation to the hydrodynamic drag, but it may become significant for large vessels moving up steep rivers-an unlikely condition for the Gila River.

C. The commercial navigability of the Gila River is evaluated using minimum specific tractive force. The Gila river is then briefly compared to other rivers.

If we consider that the limit of navigability is achieved when the vessel speed is just sufficient to make headway upstream against the river current, then V must equal the water velocity. For this condition Langbein(1962) developed the following relation of the minimum specific tractive force that must be developed by a vessel to maintain upstream headway:

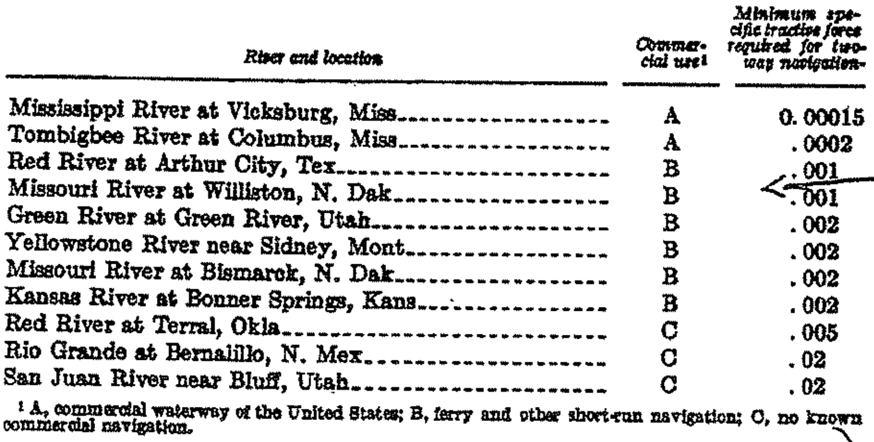
$$T_s=\frac{V^2}{2500}\left(\frac{f}{d^{4/3}}+\frac{1}{D^{4/3}}\right).$$

where D = channel depth
f = resistance ratio for shallow water

There is an optimum draft of about 0.7 for a given channel.

The specific tractive force as defined by the above equation equals that minimum which must be expended to maintain two-way navigation in a channel of depth D and river velocity V. The diagram on the following page shows the computed specific tractive force of various channels in terms of the channel depth and river velocity as computed by the above equation using optimum draft. This diagram defines the physical conditions that must be met to sustain upstream river navigation. Also shown are the depth-velocity curves for several rivers in the United States representing the minimum tractive force for flow over a riffle or shallow cross section. Also shown is the depth-velocity relation for the Gila River.

The minimum specific tractive force for several rivers in the United States is shown below(Langbein(1962), p. W-23.



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
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 Bismarck, 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, commercial waterway of the United States; B, ferry and other short-run navigation; C, no known commercial navigation.

Gila River, Arizona — .001

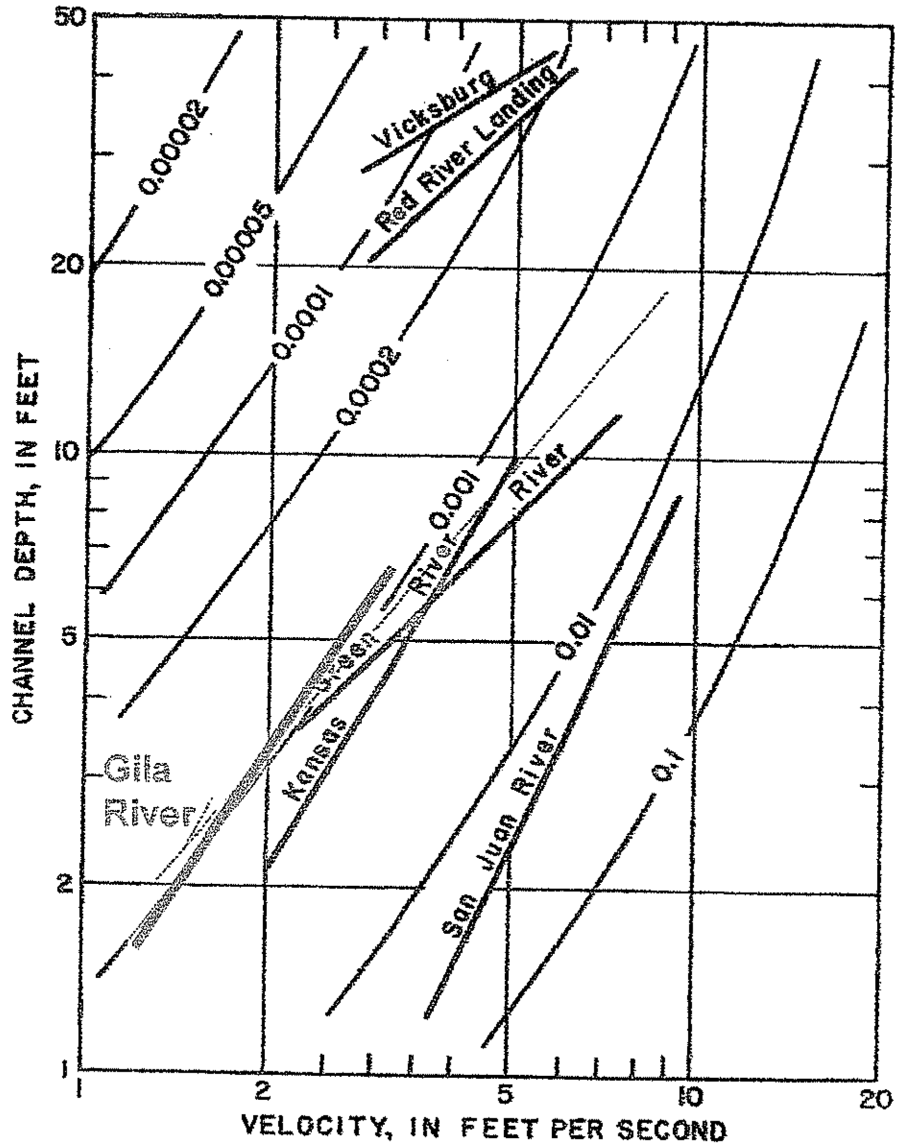


FIGURE 13.—Depth-velocity curves for several rivers in relation to minimum specific tractive force required for upstream navigation.

Average depth-velocity curve for Gila River plotted on Figure 13 of USGS Water-Supply Paper 1539-W. A minimum tractive force of 0.001 is indicated for the natural channel of the Gila River.

Results

According to Langbein (1962), in regard to data for the several rivers in the previous table and figure, "...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.

Navigability of the Gila River below Gillespie Damsite was limited by areas with multiple (braided) channels because flow was divided among two or more channels. Computations showed the flow depths of the split flow was less than 1 ft in all of the split channels about one month in a typical year. Low flow navigation would be unlikely in these areas of split flow about one month or perhaps 5 or 6 weeks of a typical year.

Navigability during high flows, as with all natural rivers, was also limited. The analysis, using the rule of thumb technique, suggests navigability would be difficult during about 2 weeks of high flow. However, this period may be a few days longer because of tributary inflow from areas below the confluence of the Gila and Salt Rivers.

Alluvial channels like that of the Gila River between Gillespie Damsite and Yuma are susceptable to scour, fill, laterial movement and changes in shape. Changes of the low-water channel would most likely affect navigability following large floods down the Gila River and at the confluence of tributaries that carry floodwater debris into the channel of the Gila River. Deposited sediment from tributary inflow would have created riffles in the Gila River. Large floods would have caused temporary channel widening with corresponding lesser depths. Thus, there were times and places where changes in channel geometry would have adversely affected navigabilty.

The variation of annual amounts of base runoff(Q_{10}) is unknown. A rough estimate of the variation is about 25% of the typical base flow for wet and dry years.

This assessment of the navigability of the Gila River, that is based on standards for commercial navigability, clearly shows the river is navigable. The estimated tractive force of the Gila River is about 0.001 and this value is well above the limit for feasible navigation and near the lower limit for feasible commercial navigation. As with most rivers, navigability would have been restricted during both high and very low flow periods.

The Gila River passed the three Federal tests of nanigability, including the rigorous Federal test by Langbein (1962).

GLOSSARY OF HYDROLOGY TERMS

ACRE-FEET (AF)—A unit commonly used for measuring the volume of water. See Acre-Foot.

ACRE-FOOT (AF)— A unit commonly used for measuring the volume of water; equal to the quantity of water required to cover one acre (43,560 square feet or 4,047 square meters) to a depth of 1 foot (0.30 meter) and equal to 43,560 cubic feet (1,234 cubic meters), or 325,851 gallons.

723.97 ACRE-FOOT PER YEAR IS EQUAL TO 1 CUBIC FOOT PER SECOND

ALLUVIAL—An adjective referring to soil or earth material which has been deposited by running water, as in a Riverbed or flood plain.

ALLUVIUM—A general term for deposits of clay, silt, sand, gravel, or other particulate material that has been deposited by a stream or other body of running water in a streambed, on a flood plain, on a delta, or at the base of a mountain.

AQUIFER—A geologic formation, a group of formations, or a part of a formation that is water bearing. A geological formation or structure that stores or transmits water, or both, such as to wells and springs. Use of the term is usually restricted to those water-bearing structures capable of yielding water in sufficient quantity to constitute a usable supply.

BANK, and BANKS—The slope of land adjoining a body of water, especially adjoining a river, lake, or a channel. With respect to flowing waters, banks are either right or left as viewed facing in the direction of the flow.

BASE FLOW—The fair-weather or sustained flow of streams; that part of stream discharge not attributable to direct runoff from precipitation, snowmelt, or a spring. Discharge entering streams channels as effluent from the groundwater reservoir. Also referred to as Groundwater Flow.

BASE RUNOFF—Sustained or fair weather runoff. In most streams, base runoff is composed largely of groundwater effluent. 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 more appropriate term.

BASIN—(1) A geographic area drained by a single major stream; consists of a drainage system comprised of streams and often natural or man-made lakes. Also referred to as Drainage Basin, Watershed, or Hydrographic Region.

BRAIDED STREAM—A complex tangle of converging and diverging stream channels separated by sand bars or islands.

BRAIDING (of River Channels)—Successive division and rejoining of riverflow with accompanying islands.

CANAL—A constructed open channel for transporting water.

CHANNEL (WATERCOURSE)—A natural stream that conveys water; a ditch or channel excavated for the flow of water. River, creek, run, branch, anabranch, and tributary are some of the terms used to describe natural channels, which may be single or braided. Canal, aqueduct, and floodway are some of the terms used to describe artificial (man-made) channels.

CHANNEL BANK—The sloping land bordering a channel. The bank has steeper slope than the bottom of the channel and is usually steeper than the land surrounding the channel.

CLIMATE—The sum total of the meteorological elements that characterize the average and extreme conditions of the atmosphere over a long period of time at any one place or region of the earth's surface. The collective state of the atmosphere at a given place or over a given area within a specified period of time. Compare to Weather. Basic types of climates include:

> [1] Continental—The climate characteristic of land areas separated from the moderating influences of oceans
> by distance, direction, or mountain barriers and marked by relatively large daily and seasonal fluctuations in temperature;
>
> [2] Oceanic—The climate characteristic of land lares near oceans which contribute to the humidity and at the same time have a moderating influence on temperature and the range of temperature variation.

CUBIC FEET PER SECOND (CFS)—A unit expressing rate of discharge, typically used in measuring streamflow. One cubic foot per second is equal to the discharge of a stream having a cross section of 1 square foot and flowing at an average velocity of 1 foot per second. It also equals a rate of approximately 7.48 gallons per second, 448.83 gallons per minute. 1.9835 acre-feet per day, or 723.97 acre-feet per year.

DAM—A structure of earth, rock, or concrete designed to form a basin and hold water back to make a pond, lake, or reservoir. A barrier built, usually across a watercourse, for impounding or diverting the flow of water. Typical type during early development was dam was the Embankment Dam—A dam structure constructed of fill material, usually earth or rock, placed with sloping sides and usually with a length greater than its height.

DIRECT RUNOFF—The runoff entering stream channels most immediately after rainfall or snowmelt. It consists of surface runoff plus interflow and forms the bulk of the Hydrograph of a flood. Direct runoff plus Base Runoff compose the entire flood hydrograph.

DRAINAGE BASIN—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. The term is used synonymously with Watershed, River Basin, or Catchment.

EPHEMERAL STREAM—A stream that flows only in direct response to precipitation, and thus discontinues its flow during dry seasons. Such flow is usually of short duration. Most of the dry washes of more arid regions may be classified as ephemeral streams. Also see Stream.

EROSION, BANK—Destruction of land areas bordering rivers or water bodies by the cutting or wearing action of waves or flowing water.

FLOOD PLAIN, also Floodplain—(1) A strip of relatively smooth land bordering a stream, built of sediment Carried by the stream and dropped in the slack water beyond the influence of the swiftest current
(2) The lowland that borders a stream or river, usually dry but subject to flooding.

FLOW DURATION CURVE—A cumulative frequency curve that shows the percentage of time that specified discharges are equaled or exceeded.

FLOW, NATURAL—The rate of water movement past a specified point on a natural stream from a drainage Area which has not been affected by stream diversion, storage, import, export, return flow or change in consumptive use resulting from man's modification of land use. Natural flow rarely occurs in a developed country.

GAGING STATION—A particular site on a stream, canal, lake, or reservoir where systematic observations of Gage Height or discharge are obtained.

GAGING STATION NUMBER—A U.S. Geological Survey (USGS) numbering system consisting of an eight-digit number assigned to a Gaging Station which identifies the station in downstream order relative to other gaging stationsand sites where streamflow data are collected. The first two digits designate the major drainage basin, the others the station.

GRADED STREAM—A stream in which, over a period of years, the slope is delicately adjusted to provide, with available discharge and with prevailing channel characteristics, just the velocity required for transportation of the sediment load supplied from the drainage basin. Also, a stream in which most irregularities, such as waterfalls and cascades, are absent. Streams tend to cut their channels lower at a very slow rate after they become graded.

HYDRAULICS—(1) The study of liquids, particularly water, under all conditions of rest and motion. (2) The branch of physics having to do with the mechanical properties of water and other liquids in motion and with the application of these properties in engineering.

HYDROLOGIC BUDGET—An accounting of the inflow, outflow, and storage in a hydrologic unit, such as a drainage basin, aquifer, soil zone, lake, reservoir, or irrigation project.

HYDROLOGIC CYCLE—The circuit of water movement from the atmosphere to the earth and return to the atmosphere through various stages or processes such as precipitation, interception, runoff, infiltration, percolation, storage, evaporation, and transportation. Also referred to as the Water Cycle and Hydrogeologic Cycle.

HYDROLOGY—The science of waters of the earth, their occurrence, distribution, and circulation; their physical and chemical properties; and their reaction with the environment, including living beings.

INFILTRATE, also Infiltration—(1) The flow of a fluid into a substance through pores or small openings; to cause a liquid to permeate a substance by passing through its interstices or pores. It connotes flow into a substance in contradistinction to the word Percolation, which connotes flow through a porous substance. Also the process whereby water passes through an interface, such as from air to soil or between two soil horizons.

MEAN ANNUAL RUNOFF—The average value of all annual runoff amounts usually estimated from the period of record or during a specified base period from a specified area.

MEDIAN—(Statistics) In a set of observations, the middle-most value with an equal number of observations lying above and below the median value.

MEDIAN STREAM FLOW (MEDIAN HYDRO)—The rate of discharge of a stream for which there are equal numbers of greater and lesser flow occurrences during a specified period.

NATURAL FLOW—The rate of water movement past a specified point on a natural stream from a drainage area for which there have been no effects caused by stream diversion, storage, import, export, return flow, or change in Consumptive Use caused by man-controlled modification to land use. Natural flow rarely occurs in a developed county.

RIFFLE—Shallow rapids in an open stream, where the water surface is broken into waves by obstructions such as shoals or sandbars wholly or partly submerged beneath the water surface. Also, a stretch of choppy water caused by such a shoal or sandbar; a rapid.

RIPARIAN—Pertaining to the banks of a river, stream, waterway, or other, typically, flowing body of water as well as to plant and animal communities along such bodies of water.

RIVER—A natural stream of water of considerable volume, larger than a brook or creek. A river has its stages of development, youth, maturity, and old age. In its earliest stages a river system drains its basin imperfectly; as valleys are deepened, the drainage becomes more perfect, so that in maturity the total drainage area is large and the rate of erosion high. The final stage is reached when wide flats have developed and the bordering lands have been brought low.

RIVER BANKS—The portion of the channel cross section that restricts lateral movement of water at normal discharges. Banks often have a gradient steeper than 45 degrees and exhibit a distinct break in slope from the stream bed.

SEDIMENT—(1) In the singular the word is usually applied to material in suspension in water or recently deposited from suspension. In the plural the word is applied to all kinds of deposits from the waters of streams, lakes, or seas, and in a more general sense to deposits of wind and ice.

SOIL—The meaning of this term varies depending on the field of consideration: (1) Pedology—the earth materials which have been so modified and acted upon by physical, chemical, and biological agents that it will support rooted plants; (2) Engineering Geology—the layer of incoherent rock material that nearly everywhere forms the surface of the land and rests on Bedrock, also called Regolith; (3) Ecology—A dynamic natural body on the surface of the earth in which plants grow, composed of mineral and organic materials and living forms.

STAGE-DISCHARGE CURVE (RATING CURVE)—A graph showing the relation between the gage height, usually plotted as the ordinate, and the amount of water flowing in a channel, expressed as volume per unit of time and plotted as the abscissa.

STREAM—A general term for a body of flowing water; natural water course containing water at least part of the year. 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. Some classifications of streams include, in relation to time:

[1] Ephemeral Streams—Streams which flow only in direct response to precipitation and whose channel is at all times above the water table.

[2] Intermittent or Seasonal Streams—Streams which flow only at certain times of the year when it receives water from springs, rainfall, or from surface sources such as melting snow.

[3] Perennial Streams—Streams which flow continuously.

And, in relation to ground water:

[4] Gaining Streams—Streams or a reach of a stream that receive water from the zone of saturation. Also referred to as an Effluent Stream.

[5] Insulated Streams—Streams or a reach of a stream that neither contribute water to the zone of saturation nor receive water from it. Such streams are separated from the zones of saturation by an impermeable bed.

[6] Losing Streams—Streams or a reach of a stream that contribute water to the zone of saturation. Also referred to as an Influent Stream.

[7] Perched Streams—Perched streams are either losing streams or insulated streams that are separated from the underlying ground water by a zone of aeration.

STREAMBANKS—The usual boundaries, not the flood boundaries, of a stream channel. Right and left banks are named facing downstream (in the direction of flow).

STREAMBED—The channel through which a natural stream of water runs or used to run, as a dry streambed.

STREAMBED EROSION—The movement of material, causing a lowering or widening of a stream at a given point or along a given reach.

STREAM CHANNEL—The bed where a natural stream of water runs or may run; the long narrow depression shaped by the concentrated flow of a stream and covered continuously or periodically by water.

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. Streamflow is a more general term than runoff, as streamflow may be applied to discharge whether or not its is affected by diversion or regulation.

TRANSPIRATION—(1) The quantity of water absorbed, transpired, and used directly in the building of plant tissue during a specified time period. It does not include soil evaporation. (2) The process by which water vapor escapes from a living plant, principally through the leaves, and enters the atmosphere. As considered practically, transpiration also includes Guttation. Transpiration, combined with Evaporation from the soil, is referred to as Evapotranspiration.

WATER BALANCE—A measure of the amount of water entering and the amount of water leaving a system. Also referred to as Hydrologic Budget.

WATER BUDGET—(Hydrology) An accounting of the inflows to, the outflows from, and the storage changes of water in a hydrologic unit or system. Also see Water Balance.

WATERSHED—(1) All lands enclosed by a continuous hydrologic drainage divide and lying upslope from a specified point on a stream. Also referred to as Water Basin or Drainage Basin. (2) A ridge of relatively high land dividing two areas that are drained by different river systems. Also referred to as Water Parting.

WATERSHED AREA (DRAINAGE AREA)—The watershed area at a point in the stream refers to the area of the earth from which the water concentrates toward that point, through the drainage system.

WATER TABLE—The level of groundwater; the upper surface of the Zone of Saturation for underground water. It is an irregular surface with a slope or shape determined by the quantity of ground water and the permeability of the earth material. In general, it is highest beneath hills and mountains and lowest beneath valleys. Also referred to as Ground Water Table.

precipitation, interception, runoff, infiltration, percolation, storage, evaporation, and transportation