NAVIGABILITY ALONG THE NATURAL CHANNEL OF THE SAN PEDRO RIVER

(From the border with Mexico
to the mouth at the Gila River
near Winkleman, Arizona)

EXECUTIVE SUMMARY OF ANALYSIS BY
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Hydrologic, hydraulic and morphologic
assessment

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Introduction

At the request of the Arizona Center of Law in the Public Interest, I assessed the navigability of the natural channel of the San Pedro River using hydraulic geometry methods where current and historic hydrologic information is used to predict the natural condition of a river. This assessment is for the reach of the San Pedro River that extends from the U.S./Mexico border to the mouth at the Gila River. The purpose of the assessment was to determine if this 123-mile reach (distance along valley) of the San Pedro River was susceptible to navigation at the time of Arizona statehood (February 14, 1912) in its ordinary and natural condition. This assessment was prepared for proceedings before the Arizona Navigable Stream Adjudication Commission (ANSAC)[1]. The following is a summary of my testimony before ANSAC.

The assessment used a systematic three-step procedure that uses known, quantifiable data regarding the San Pedro River and extrapolates from that data to determine the flow of the river in its natural condition. First, as described more fully below, the natural hydrology was identified and expressed in typical flow-duration curves using various sources of discharge data obtained at sites along the study reach. Channel geometry was then applied to the flow characteristics identified in step 1 using known sediment characteristics of the San Pedro River. This process calculated the width, depth and flow of the natural river. Finally, navigability was evaluated using two independent methods used by federal agencies to determine whether a watercourse is capable of being navigated by various water craft. Published information and standard engineering hydraulic, hydraulic geometry and hydrologic methods were used to accomplish the three steps.

This particular three-step procedure was necessary because at the time of statehood, and well before, both the natural hydrology and morphology of the river had been significantly altered by human activity. Large cattle herds and numerous stock tanks, as well as diversions for mining, irrigation, and domestic use have, in varying degrees, impacted the stream flow and morphology of the San Pedro River for at least 300 years. Groundwater and surface water removals have resulted in lower flow rates in the San Pedro River than there would be if the River had remained in its ordinary and natural condition. The method used in this assessment eliminates the effect of those impacts by using annual runoff data, which quantifies the amount of water that would be present in the river if there were no diversions.

[1] The research and analysis were presented to ANSAC using multiple Power Points consisting of 279 slides that were divided into three segments: (1) the analysis, signed May 22, 2013, with concluding opinion on slide 169 (“Bisbee I”), (2) the appendix, signed May 22, 2013, from slides 170-231 (“Bisbee II”), and (3) further information presented at the Phoenix hearing, signed July 27, 2013, from slides 232-279 (“Phoenix”). References are provided to the corresponding slides.

Analysis

History of the San Pedro River[2]

Research of many scientific and historic documents shows that diversions from both the river and springs for irrigation and livestock, mostly cattle, in the San Pedro Valley has been practiced continuously since ancient times. Indians were irrigating along the river through at least 1919 and at least 144 diversions by the Spanish, Mexicans and Caucasians have been made over the past few hundred years. The impact of human activities such as irrigation diversions, livestock watering at springs, and grazing and herding of cattle became apparent in the 1850s as evidenced by turbid streamflow, channel incision and a couple of accounts of no flow in a short reach of the river.

River morphology has changed largely because the river is formed in its own sediment. Massive cattle grazing and logging in the watershed and along the San Pedro River have changed the runoff and sediment yield resulting in widening, down cutting and straightening of the natural meandering river channel. Apparently the change of channel morphology was delayed several years following Spanish introduction of large cattle herds. In short, the San Pedro River has been affected to some degree by humans for about 300 years and it has been significantly affected by humans since about 1850.

Thus, any observations of the amount and distribution of base flow, channel geometry, channel stability and channel material made after 1850 likely does not represent natural conditions. Context is important when assessing navigability in the natural and ordinary condition; the natural condition can best be assessed when viewed through the eyes of geomorphology and hydrology. Accordingly, my assessment is based on hydrologic and morphologic principles developed for alluvial rivers like the San Pedro.

Step One: The Hydrology

A. Description of river basin hydrology[3]:

Important hydrologic characteristics of the San Pedro River are:

- The San Pedro River drained about 696 square miles at the upper end of the study reach and about 4,460 square miles at the lower end.

[2] See Bisbee I, slides 17 through 37; Bisbee II, slides 2 through 22; 25 through 30; Phoenix, slides 12 through 32.
[3] See Bisbee I, slides 2, 10,16, 55, 59, 60, 69, Bisbee II, slides 56 through 62.

- The watershed was hydrologically diverse because of the diversity of climate, geology and topography.

- The mountainous areas along the east and west sides of the watershed typically received more than 20 inches of precipitation per year. The warm-dry valley area typically received less than 16 inches of precipitation per year.

- Precipitation fell during two distinct periods--summer and winter. There was light snow accumulation in the higher mountains with occasional melting to produce spring runoff along the river. Much of the direct runoff for navigation was from the summer rainfall in the mountainous areas.

- When rain fell onto the land in the San Pedro River watershed it started moving according to basic principles of hydrology. A portion of the precipitation seeped into the ground to replenish ground water. Some of the water flowed downhill on the land surface as direct runoff and appeared in surface streams that were unaffected by artificial diversions, storage, or other works of man in or on the stream channels.

- In the San Pedro River watershed, much of the runoff from storms reached the river channel directly on the land surface via overland flow, flow in rills, creeks and streams. Direct runoff was seasonal because the storms were seasonal and provided runoff for navigation for part of each year.

- The portion of the water that replenished the ground water was very important for the susceptibility of the San Pedro River to navigation. Under natural conditions the water that replenished the ground water mostly along the mountain fronts all along the river valley was temporarily stored, and later discharged to the river at springs and seeps. This base runoff was slowly and steadily released from storage during dry periods. Because precipitation, and therefore direct runoff, was seasonal and there are a few months each year with little precipitation, the base runoff provided perennial flow for navigation to the San Pedro River.

- Thus, this base runoff was derived from rather constant (steady) groundwater discharge all along the river from the regional and also an alluvial aquifer. The regional aquifer is defined as having recharge zones away from the river, primarily at mountain fronts and along ephemeral channels. The alluvial aquifer along the river was recharged from the regional aquifer and from storm flow (direct runoff). Based on recent environmental isotope data, we know that the composition of base flow was mostly from regional groundwater and also from summer storm runoff that may have been stored as alluvial groundwater—at times for several years.

- In the absence of evapotranspiration (ET) along the riparian area the base runoff would have steadily increased along the river throughout an ordinary year. However, the base runoff varied considerably because ET varied seasonally.

Large amounts of the rather steady inflowing groundwater to the riparian area were consumed (converted to water vapor) during the summer months. Summer base runoff (roughly represented by Q_{90}, the amount of base runoff equaled or exceeded 90% of the time during a typical year) decreased along the river. Base runoff also varied considerably throughout the year.

B. Identifying the Flow Duration Curve for the San Pedro[4]:

In order to determine the hydrology of the San Pedro River in its natural condition, I decided to use a methodology, flow duration curves, that is regularly employed by hydrologists for a number of purposes. To construct a flow duration curve (FDC), stream flow discharges are ranked in decreasing order and plotted on a graph. The FDC shows the full range of stream flow in a given river, and also shows the percentage of time that the river's stream flow is at any particular level.

To determine the shape of the FDC that I would use for my assessment of the San Pedro River, I used post-development gage data to prepare a FDC. Although post-development discharge data are not an accurate measure of the natural stream flow, in my opinion it does sufficiently reflect the range and patterns of the San Pedro's stream flow to form the basis of a representative FDC. To create the FDC, I computed the average annual hydrograph using daily discharge data that had been collected at the Tombstone gage for the period of record. I ranked those averaged daily discharge readings in decreasing order and plotted them on a graph. That gave me the representative shape of the FDC for the flow of the San Pedro River.

C. Quantifying Pre-development Flow:

The next step in the process was an attempt to quantify pre-development flow so that I could then apply the FDC to that data. In this regard, I used two independent data sources: predevelopment base runoff and annual average runoff. Each one will be explained separately:

1. Base Runoff[5]

Base runoff is that portion of stream flow that comes from under the ground. As discussed above, base runoff in the upper San Pedro River was derived from groundwater discharge to the river from the regional and alluvial aquifer. In 1986, G. W. Freethey and T. W. Anderson of the U.S. Geological Survey prepared USGS Hydrologic

[4] Bisbee I, slides 56 through 65; Bisbee II, slides 39 through 48.
[5] Bisbee I, slides 66 through 72; Bisbee II, slides 49 through 55.

Investigations Atlas HA-664, “Pre-development hydrologic conditions in the alluvial basins of Arizona and adjacent parts of California and New Mexico,” which calculated predevelopment base runoff for San Pedro River, as well as other southwestern rivers. I used the base runoff calculations from USGS HA-664 for pre-development base flow for the Charleston gage, the upper basin (at the narrows) and lower basin (at the mouth). As I indicated in Slide 72 of my Bisbee Presentation, the USGS HA-664 estimate of predevelopment base runoff at the Charleston gage was one of five independent estimates of predevelopment base runoff at the Charleston gage published in the scientific literature between 1982 and 2006. Those five estimates ranged from 7000 ac. ft. (10 cfs) to 9600 ac. ft. (13 cfs). The Freethey estimate that I used (10 cfs) was the lowest of the five.

Because I also wanted to prepare a FDC for the U.S./Mexico border, I obtained the data for predevelopment base runoff for the Mexican border using USGS SIR 2006-5228, prepared by D.R. Pool and J.E. Dickenson in 2007.

2. Average annual runoff[6]

To understand why I used average annual runoff for my analysis, it is important to first understand what runoff is. Runoff is that part of the precipitation that naturally appears in surface streams. Therefore, it is the same thing as “stream flow” unaffected by artificial diversions, storage, or other works of man in or on the stream channels. In other words, runoff is the same as predevelopment stream flow. Runoff includes both direct flow and base flow.

For the average annual runoff data, I started by using USGS Open File Report 87-535, which computed the average annual runoff for each of the 2,148 hydrologic cataloging units in the United States and Puerto Rico. (Preparation of Average Annual Runoff Map of the United States, 1951-80, by William R. Krug, Warren A. Gebert, and David I. Graczyk.) The two hydrologic cataloging units for the San Pedro River are 15050202 (upper basin) and 15050203(lower basin). An objective of USGS Open File Report 87-535 was to determine the “average runoff near its source, rather than the cumulative runoff after several sources have contributed runoff to large rivers.” *Id.* at p. 1.

Because the Report by Krug and others did not include the upper 696 sq. miles of the watershed in Mexico, I had to independently the average annual runoff for the border site that I used in my assessment was determined as follows. First, I computed the average annual direct runoff for USGS gage 09470500 at Palominas, which is

[6] Bisbee I, slides 80 through 97, Phoenix slide 9-11.

located about 4 miles from the border and represents a drainage area of 737 sq. miles (which includes the 696 sq. miles located in Mexico). Then I adjusted that amount by using the ratio 696/737 to determine the direct runoff for the Mexico portion only. To get annual average runoff (which includes both direct and base runoff), I added the base runoff, which as discussed in the previous section was estimated to be 4 cfs at the border. This resulted in an average annual runoff at the U.S./Mexico border of 33 cfs.

To calculate the average annual runoff for the join, the runoff for the upper basin was adjusted by assuming the 696 square mile area in Mexico had the same unit runoff (cfs/sq mi) as the 1760 square mile area for the upper basin (15050202). To calculate the adjusted runoff for the upper basin, the runoff given in USGS Open File Report 87-535 was simply multiplied by the ratio of 1760/2456. The resulting average annual runoff of 92 cfs was used at the narrow or join (which is the end point of hydrologic unit 15050202).

To determine the average annual runoff at the mouth (which is the end point of hydrologic unit 15050203) it was necessary to add in the runoff from the upper watershed (15050202), because, as noted above, the Report by Krug and others did not measure cumulative runoff. This meant that in order to determine the average annual runoff at the mouth, it was necessary to combine the average annual runoff for both hydrologic units. However, because the runoff from hydrologic unit 15050202 would experience losses to evapotranspiration (ET) before reaching the mouth, I adjusted for that loss. Thus, using the data from USGS Open File Report 87-535 and adjusting for ET, I determined that the average annual runoff at the mouth was 113 cfs.

USGS Open File Report 87-535 did not calculate average annual runoff at the Charleston gage, so I calculated that amount by using the annual average stream flow for water years 1904 to 2012, which was 52.1 cfs. Because the latest USGS statistics for the Charleston gage show a significantly reduced base flow and even periods of no flow, that indicates to me that the summer base runoff of 10 cfs (Q90) has been diverted by humans. Consequently, to determine the average annual runoff (which as noted above includes both direct runoff and base runoff) I added 10 cfs base runoff to the 52.1 annual average stream flow to estimate an annual average runoff of 62 cfs at the Charleston gage. That estimate correlated with the annual average runoff estimates that USGS Open File Report 87-535 reported for the mouth and join. It is also significantly lower than the average annual runoff estimate of 80 cfs that the U.S. Bureau of Reclamation calculated for the Charleston gage in 1952. (U.S. Bureau of Reclamation(1952) *Report on water supply of the lower Colorado River basin; Project planning report.* U.S. Department of the Interior, (p. 152), 444 p.

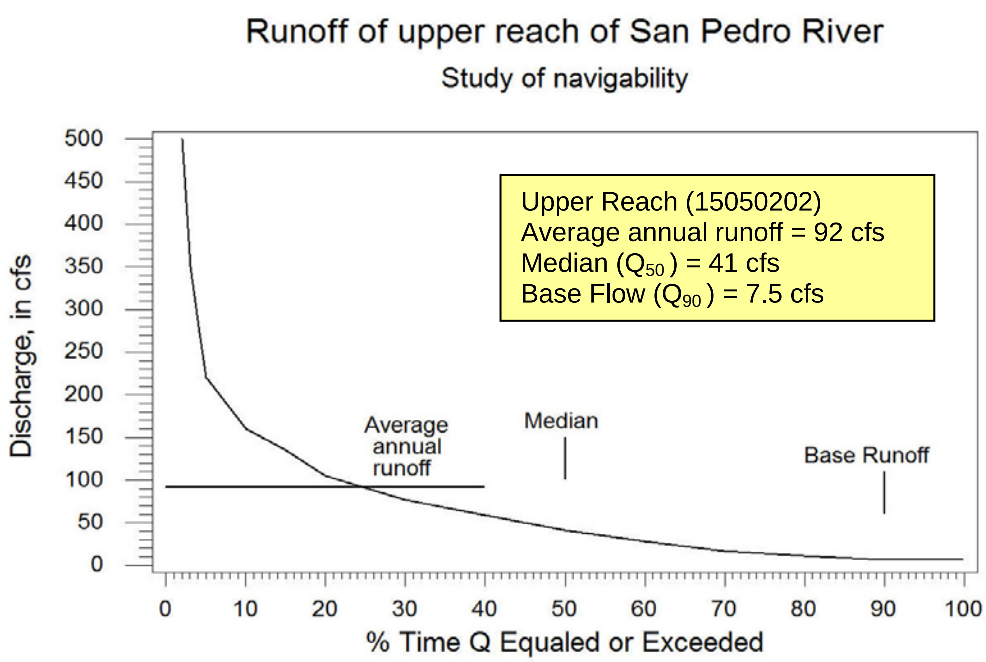
D. Combining the Data and the FDC[7]

Once I had determined the base runoff and average annual runoff for each of the four points on the river, the final step in the hydrological analysis was applying the FDC to the predevelopment flow levels. To do this, I knew that the lower end of the curve should correspond to the base runoff. The second reference point was the average annual runoff. The curve needed to be positioned so that the amount of stream flow above that second data point was equal to the amount below it. Once I positioned the FDC on the graph, I was able to determine the median flow for each of the four points as well.

Site	Area (sq. mile)	Mean Annual (cfs)	Median Annual (cfs)	Base Flow (cfs)
US/Mexico Border	696	33	18	4
Charleston	1234	62	25	10
Join (upper reach)	2456	92	41	7.5
Mouth	4456	113	50	4

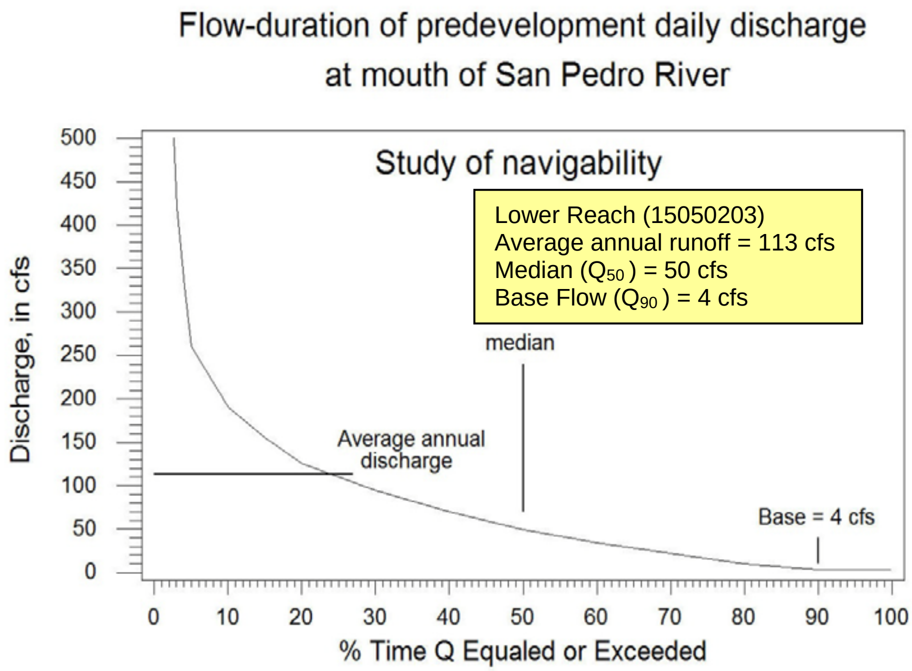
The FDC for three of the four sites shown on graphs:

Join (upper reach):

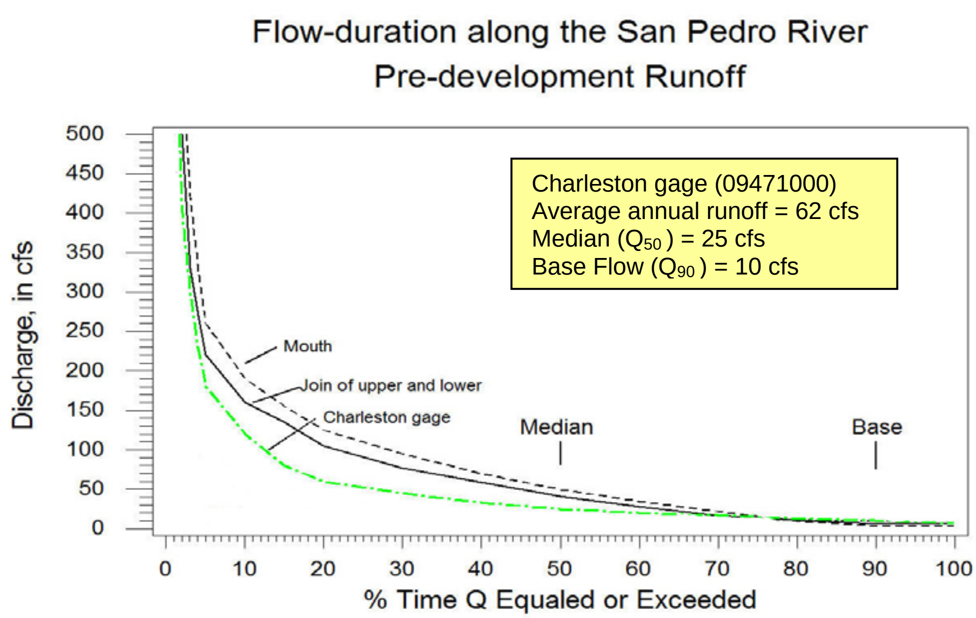


[7] Bisbee I, slides 94 through 96, 98 through 99.

Mouth:



Charleston:



Step 2: Hydraulics and Morphology[8]

The second step in the process is to apply the information about the River's hydrology to its morphology. First, it is important to identify the hydraulic/morphologic characteristics of the River under natural conditions at the time of statehood. We know the following:

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

- San Pedro River had a single meandering channel based largely on a standard channel morphology relation between bank full discharge and channel slope.

- The natural channel and floodplain were composed of fine sand, silt and clay with interspersed pebble to gravel beds.

The amount of flow, as defined by the flow-duration curves (previously discussed), is the principal control of channel size and the sediment characteristics largely determine channel shape. In the case of the San Pedro River, I computed the channel width by using established sediment-morphology relations of alluvial channels. Using this methodology, I defined width-duration relations at the four sites along the River. Widths were computed for average annual runoff, median flow, and base runoff. According to my calculations, the channel widths ranged from about 12 feet (base runoff) to 47 feet.(average annual runoff).

After I computed the channel widths, I compared my results with measurements of channel widths that were taken by Federal land surveyors between 1877 and 1879 as set forth in the Fuller Report prepared for the ASLD. Although the San Pedro River was not in its natural condition at that point in time, the measurements do provide somewhat of a cross-check. The computed widths agreed reasonably well with the width measured by the Federal surveyors.[9]

Next, I computed channel depth-duration and velocity-duration relations for the four sites using a technique based on the standard Manning hydraulics equation for open channel flow. I used Techniques of Burkham (1977) to account for the parabolic shape of the channel. For the hydraulics equation, I used the average annual flow of 33 cfs to 113 cfs on the upper and lower ends of the study reach, respectively. I used a width of 12 to 47 feet, and an energy gradient of about .0028 for the upper channel and about .0021 for the lower channel. I used a sinuosity of 1.5, and a roughness coefficient of 0.035. Using these inputs, I estimated the representative cross section characteristics of width, depth and velocity. According to these calculations, the

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[8] Bisbee I, slides 102 through 136; Phoenix, slides 2 through 8.
[9] Bisbee I, slides 119 through 121.

maximum channel depths at the mouth ranged from about 1 foot to over 2.5 feet, with a median depth of 1.5 feet. 80% of the time, the maximum channel depth at the mouth was greater than 1 foot. At the join, the maximum channel depth ranged from slightly less than one foot to over 2.5 feet, with a median depth of 1.4 feet. 80% of the time, the maximum channel depth at the join was greater than 1 foot. Finally, at the Charleston gage, the depths ranged from slightly less than one foot to over 2.5 feet, with a median depth of 1.25 feet. 80% of the time, the maximum channel depth at the Charleston gage was greater than 1 foot.

Step 3: Navigability[10]

The final step in my assessment was evaluating whether, if it had been in its ordinary and natural condition at the time of statehood, the San Pedro River was susceptible of navigation. In evaluating the River for navigability, I used two methods developed by the federal government. First, I applied the "Bureau of Outdoor Recreation Method" developed in 1977 for the Bureau of Outdoor Recreation of the U.S. Department of Interior. The second method that I used was the Fish and Wildlife Service Method. This method is a single cross section technique that is very simple to use and is based on a minimum flow recommended for a particular watercraft activity. The USFW method establishes minimum depth and width requirements for canoes, kayaks, drift and row boats. All of these minimum requirements are met along nearly all of the San Pedro River.

My specific findings regarding the navigability characteristics of the San Pedro are as follows:

- The width and current (velocity) of the San Pedro River flow easily met the standards for navigability. Nearly all of the time flow width was sufficiently great. Except during large floods, the flow velocity was sufficiently small for navigability along the San Pedro River.

- The depth of flow along the San Pedro River limited navigability in the upper reach between the Mexican border and one mile below Lewis Springs (which I assumed, for the purposes of my assessment, had the same characteristics as Charleston site). This reach was marginally but not fully acceptable for navigation using the Federal standard. Thus, I do not consider this reach susceptible to navigation.

- According to my assessment, about 20% of the time during a typical year, the depth of the natural flow along the San Pedro River also limited navigability in the remaining reach of the River (between one mile below Lewis Springs, located 19 miles north of the border, and the mouth at the Gila River). In the absence of direct runoff, the summer ET simply consumed a lot of water in the riparian zone reducing the depth to below 1 foot.

[10] Bisbee I, slides 137 through 145.

- However, for the remaining 80% of the time, the natural flow for the reach from below the Lewis Springs area to the mouth had sufficient width and depth, and an acceptable velocity for canoeing and kayaking based on the navigability methods of the two Federal agencies.

- The median runoff also supports a finding of navigability for the same reach (from a mile below Lewis Springs to the mouth). During a typical year, 50% of the time, the discharge equaled or exceeded 25 cfs a mile below Lewis Springs, 41 cfs at the Join and 50 cfs at the mouth near Winkleman. The corresponding median depths of flow were 1.2 ft, 1.3 ft and 1.4 ft.

- Navigability was independent of undesirable conditions such as temporary braiding of the river channel following floods, low flow from severe droughts, beaver dams and flow variability. These characteristics are related to how the River might have been used for navigation rather than its susceptibility to navigation in its ordinary and natural condition.

Final Observations[11]

As discussed in my testimony, my assessment was a conservative one. Some of the ways in which it is conservative are as follows:

- I ignored the discharge to springs as part of the base runoff;

- I ignored some of the impact that water consumed at the City of Cananea and the Cananea mine had on the base runoff at the Mexican border;[12]

- In calculating the loss of base runoff due to ET, I opted not to factor in the recent study that indicates that predevelopment ET was 40% of post 1970 losses to ET;

- While the analysis used the average annual runoff as defined by methods of the USGS, the portion of the total runoff associated with inflowing groundwater to the river (base runoff) was conservatively low;

- I used the minimum sinuosity of 1.5 for my analysis, instead of a possible 2.0. Using the lower sinuosity produced conservatively low estimates of natural depths of flow, which accounts for small riffles that are typical of meandering stream like the natural San Pedro, the few hard rock constrictions along the river where the natural channel slope may have been slightly more than the typical channel slope, and local areas of channel braiding.

[11] Phoenix, slides 43 through 48.
[12] Bisbee I, slides 76 through 78; Phoenix slide 19.

I used the conservative approach because the San Pedro River alternates between gaining and losing reaches. The non-uniform base runoff is a result of varying rates of mountain front and stream channel recharge along the River, the sediment deposits at mouths of tributary streams and variable hydraulic characteristics of the stream alluvium. This approach also accounts for possible multiple channels for short reaches, as well as variable hydrologic/morphologic conditions, such as small riffles, that are typical along natural rivers like the San Pedro.

Conclusion[13]

Based on all the hydrologic and hydraulic information, data and analysis contained in this report, and applying the Federal standards, it is the author's opinion that the natural channel of the San Pedro River, from about one mile below the Lewis Springs area to the mouth at the Gila River, was susceptible to navigation at the time of Arizona statehood in its ordinary and natural condition. For about 80% of the time during a typical year, the width, depth and velocity were acceptable for use of small water craft such as canoes, kayaks, drift boats, row boats and rafts.

[13] Bisbee I, slides 146 through 152; 167 through 169.