Further information to clear up possible confusion from Bisbee meeting.

Presented Aug. 1, 2013

July 27, 2013

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1 0f 7

Hydraulic Geometry for Beginners

First, for this study it was considered necessary to define the natural geometry of the San Pedro River because both the natural hydrology and the morphology of the river have been changed by human activity.

At a particular location on a river the discharge (Q) can be expressed mathematically as the product of width (*w*) x mean depth (*d*) x mean velocity (*v*).

Or,Q = *wdv*

LEOPOLD, L., *and* MADDOCK, T. JR, 1953, .The Hydraulic Geometry of Stream Channels and Some Physiographic Implications: USGS Professional Paper 252, 57p.

Streams with natural alluvial channels, like the San Pedro once was, form their own geometry. Engineers and geologists have developed a method (the hydraulic geometry method) of defining this channel geometry as follows:

$$w = aQ^b$$

$$d = cQ^f$$

$$v = kQ^m$$

"These relationships at a given channel cross section … are greatly similar even for river systems very different in physiographic setting. The relationships are described by the term 'hydraulic geometry.'" (Leopold and Maddock, p.1).

$$Q = \text{area} \times \text{velocity, or, } Q = wdv$$

substituting from the above

$$Q = aQ^b \times cQ^f \times kQ^m$$

or

$$Q = ackQ^{b+f+m}$$

It follows therefore that

$$b + f + m = 1.0$$ exponents

and

$$a \times c \times k = 1.0$$ coefficients

(Leopold and Maddock, p.8).

4 0f 7

Since the 1970s the USGS has conducted a series of studies (with many reports) to develop empirical relations among discharge characteristics and geometry variables of alluvial stream channels. This effort refined and improved on the classic work of scientists like Leopold and Maddock. The method by Osterkamp (1980) used for this study of the San Pedro River is an example of such refinement. Osterkamp found that for alluvial channels in the western US, discharge was the principal control of channel size and sediment characteristics largely determine channel shape. After discussing the method with Waite Osterkamp, the author thought his method was the best available for this analysis.

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

5 0f 7

Alluvial channel hydraulic geometry is used for many purposes. For example, it is used for stream channel restoration and channel design.

United States Department of Agriculture, 2007, National Engineering Handbook--Part 654 Stream Restoration Design: Natural Resources Conservation Service, 48 p.

Unfortunately the hydraulic geometry method, partly because of its complexity, has been misused.

"Using discharge and channel geometry measurements from U.S. Geological Survey streamflow-gaging stations and data from a geographic information system, regression relations were derived to predict river depth, top width, and bottom width as a function of mean annual discharge for rivers in the State of Washington." (Magirl and Olsen, p1)

Magirl, C. S. and Olsen, T. D., 2009, Navigability Potential of Washington Rivers and Streams Determined with Hydraulic Geometry and a Geographic Information System, USGS Scientific Investigations Report 2009–5122, 23p.

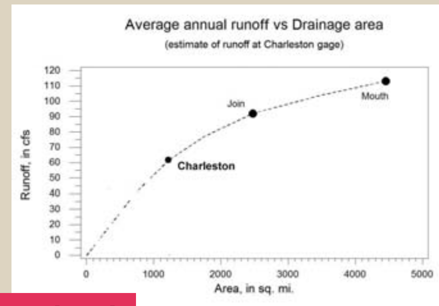
The State of Washington study was fatally flawed and the estimates of channel width and depth were useless. The authors readily admitted the following issues:

- **Many sites along channels were affected by man-made structures,**
- **Both base-level and mountainous tributary stream were part of the data set,**
- **Finally, anthropogenic impacts on rivers and streams that alter channel geometry were not explicitly analyzed for this study. Instead, all rivers, whether free flowing or highly modified, were analyzed together as one population.**

1 of 2

It's interesting to examine the average annual runoff (predevelopment) at the USGS Charleston gage (09471000)

The average annual runoff corresponding to the drainage area of 1,234 mi^2 is about 62 cfs using the relation to the right.



See next 2 slides for more detail

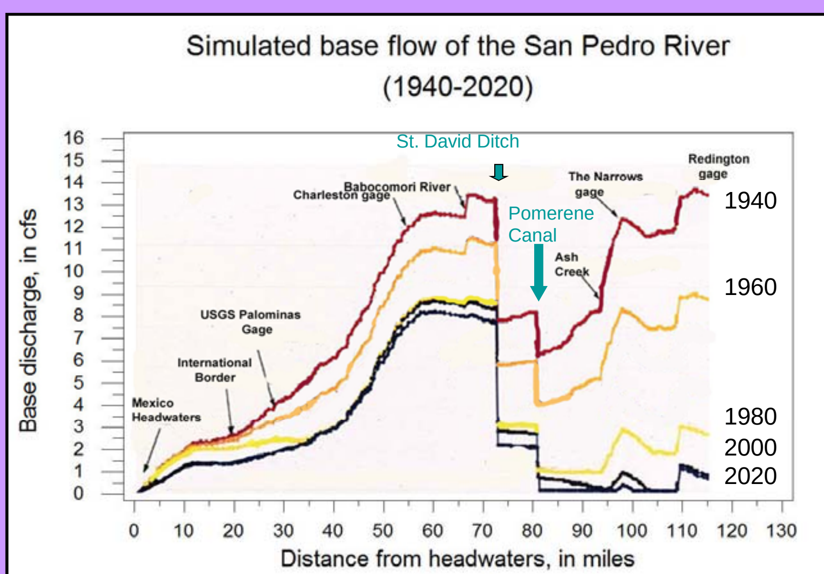
The runoff is 10 cfs greater than the annual mean streamflow of 52.1 cfs for water years 1904-2012

Mean of 39899 days

July 27, 2013

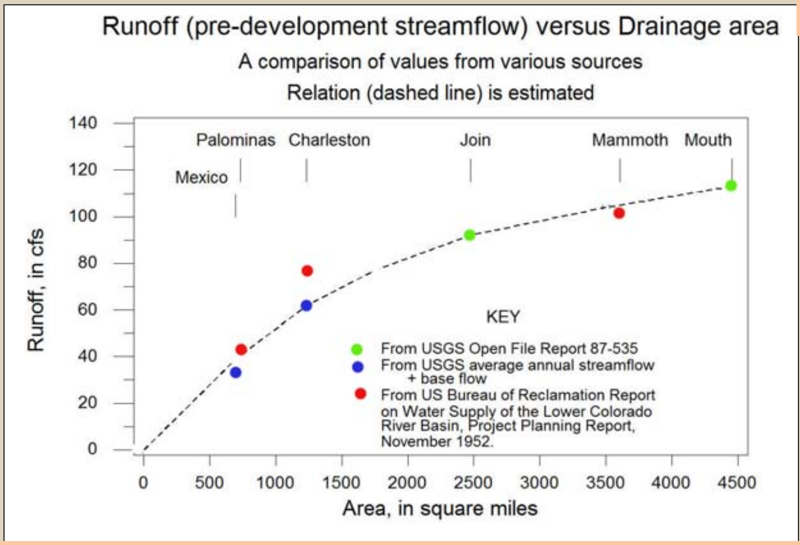
Slide 97 of Bisbee ppt

Modified from Goode and Maddock, 2001



Slide 207 of Bisbee ppt

10



USBR, 1952, Report on Water Supply of the Lower Colorado River Basin: US Department of Interior, Bureau of Reclamation Project Planning Report, (p. 152), 444 p.

Early Mining

Evidence of copper production suggests the base runoff of the San Pedro River at the Mexican border and above Lewis Springs was greater than the base runoff of several models of groundwater that used 1940 as starting point of development.

Consider the next 8 slides

Water Requirements of the Copper Industry

According to the USGS a little more than 25 gallons of water is used for the production of one pound of copper from domestic ore (abstract of USGS WSP 1330-E). This amount compares well with the use of 28 gallons per pound given in slide 74 of the ANSAC report by Hjalmarson, PE, May 24, 2013.

Mussey, O., 1961, Water Requirements of the Copper Industry, *Present and future water requirements for the mining and metallurgy of copper:* GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1330-E, 44p.

The Cananea mining enterprise controls water use at the headwaters of the San Pedro River. "The large copper mining operation in Cananea, Sonora, began in the 1880s. Water came from nearby springs and both surface water and groundwater in both the San Pedro amd Rio Sonora watersheds." (Stromberg and Tellman, 2009) This very large mine supports a significant part of the population of Cananea, the largest city on the Mexican side of the basin.

Stromberg, J. C. and Tellman, B., 2009, ECOLOGY AND CONSERVATION OF THE SAN PEDRO RIVER: The University of Arizona Press Tucson, p. 222.

"Pumping in the Cananea region, located in the far southern portion of the watershed, is too far removed to directly impact groundwater in the Sierra Vista sub-basin. However, pumping in this area undoubtedly impacts the baseflow of the river near Cananea."

CEC, 1999, Ribbon of Life-An Agenda for Preserving Transboundary Migratory Bird Habitat on the Upper San Pedro River: Commission for Environmental Cooperation, Montreal Canada, 32p.

"After a second ore body was discovered in 1884, Phelps Dodge acquired the mines. By the mid-1880's, the Copper Queen's smelters were turning out more than 20,000 tons of ore annually. By 1900, Phelps Dodge recognized the need for new smelters." USDA, 2000.

USDA, 2000, Soil Survey of Cochise County, Arizona--Douglas-Tombstone Part: United States Department of Agriculture, Natural Resources Conservation Service, 733 p.

In the Cananea mine area Mowry discusses historic mining activity and perennial springs such as "…water comes from copious springs …" (page 105) and "…. a permanent stream at the foot of the mountains, about a mile or a mile and a half from the mines." (page 104)

Mowry, S., 1864, ARIZONA AND SONORA: THE GEOGRAPHY, HISTORY, AND RESOURCES OF THE SILVER REGION OF NORTH AMERICA., 251p.
(SYLVESTER MOWRY, OF ARIZONA, GRADUATE OP THE U. S. MILITARY ACADEMY AT WEST POINT, LATE: LIEUTENANT THIRD ARTILLERY, U. S. A., CORRESPONDING MEMBER OF THE AMERICAN INSTITUTE, LATE U. S. BOUNDARY COMMISSIONER, ETC., ETC., ETC. , #rd edition: NEW YORK: HARPER & BROTHERS, PUBLISHERS, FRANKLIN SQUARE.)

1913

SONORA

(Special Correspondence.)—Mineral exports through the customs house at Agua Prieta during the month of October was valued at ₱3,755,800, being an increase of ₱450,700 over the preceding month. Considering the condition of the country, the increase in exports of mineral is nothing short of remarkable, and the amount of last month is the largest ever shipped through that port in any one month heretofore. The October gross smelter production of the Cananea smelter will be a little over 7,000,000 lb. Of that amount the output from the Cananea company's own ores will be in the neighborhood of 2,800,000 lb. Over 40 ft.

Smelting ore from other mines such as Miami in AZ

November 22, 1913 MINING AND SCIENTIFIC PRESS, p. 833

1916

Cananea (1916) was a community of 16,000 inhabitants, located 40 miles south of the international boundary line, on a branch railway of the Southern Pacific lines of Mexico. (Weed, p. 1683)

Weed, W., H., 1918, INTERNATIONAL EDITION, THE MINES HANDBOOK, AN ENLARGEMENT OF
" **THE COPPER HANDBOOK"**
A MANUAL OF
THE MINING INDUSTRY OF THE WORLD
Nature of Ore Deposits, etc.
VOL. XIII
Supplementing Volumes I to XII
PUBLISHED BY W. H. WEED
29 Broadway, New York City
1918P

1922

1916 *THE MINES HANDBOOK, 1922*

plant, reverberatory furnaces for smelting fine ore and Great Falls type Bessemer converters 12' in diameter.

The company owns and operates 36 miles of standard and narrow gauge railroad, including branches, spurs and sidings connecting with the Nogales and Naco branches of the Southern Pacific lines of Mexico and by this line with the El Paso and Southwestern Railroad at Naco, Ariz.

The following table summarizes operations:

Year	Ore Concentrated tons	Cost of Milling	Products Smelter, tons	Cost of Smelting
1920	288,176	.....	782,989	.....
1919	220,821	$1,87	715,621	$3.51
1918	289,098	1.25	902,520	3.38
1917	171,202	...	481,632	2.61

Production: output and earnings since beginning of operations—

Year	Tons Mined	Mng. Cost per Ton	% Cu.	Copper, Lb.	Silver Oz.	Gold, Oz.	Cost per Lb. Cu. Cents	Earnings
1920	1,053,806	.....	.....	43,672.939	1,778.617	10,089	16.304	$560,078
1919	929.193	$3.643	.....	41.404,810	1,739,789	9,167	14.750	1,104,037
1918	1,169,998	$3.240	2.430	52,694,731	1,666,993	9,846	15.082	$3.434,620
1917	574.582	2.900	2.273	24,711.204	655,656	3,804	17.951	2,497,888
1916	1,143,508	2.612	2.258	48,663,381	1.464,808	8,710	11.395	6,908,513
1915	285,701	2.493	2.700	16,335,081	635.997	3,773	11.086	1,410,543
1914	413.766	3.146	2.201	21,858,920	907,310	6,055	10.724	638,955
1913	765.063	2.854	2.363	44,480,513	1,497,938	8,021	9.631	2,344.592
1912	1,121,346	2.902	2.146	48,157,847	1,559,996	7,232	10.310	2,580,749
1911	945,160	2.355	2.414	44.897,466	1,339.839	5,892	9,483	1,318,473
1910	....	.....	.....	45.771,925	1,187,820	5,483	11.437	459,202
1909	....	.....	.....	44,547,689	933,549	5,887	11.612	544.107
1908	....	.....	.....	18,619,609	447.663	2,879	......	214.141
(b)	....	.....	.....	58,180,856	766,422	6.100	......	3,220,247
(a)	....	.....	.....	247,144,706	2,006.679	13,795	......	9,870,762

Employs 3,247 men, 211 of wh[illegible] are not Mexicans. Improvements in 1922 will cost $1,000,000.

The disappearing-reappearing San Pedro River of 1855 and 1857

"Arroyo cutting is a process also associated with streamflow changes. **Early in the 1850s there was a major impact on the channel**, and later, large floods on the unprotected river during the 1890s and 1900s produced severe erosion." (Arias 2000).

Arias, H. M., 2000, International Groundwaters: The Upper San Pedro River Basin Case: Natural Resources Journal, UNM School of Law, Spring 2000, Vol. 40, No.2, p 199-221.

The disappearing-reappearing San Pedro River of 1855 and 1857

Four accounts of a "dry" river are interesting. The account by Parke on his second exploration for a Pacific railroad was during July 1855 and may be valid.

The other 3 accounts are were made in September 1857. One of these was by Tevis who was prone to exaggeration. The other two appear to be by Hutton, an engineer for the Pacific wagon road. His supervisor was Leach who received Hutton's report and placed his name on the same report.

Consider the following 9 slides:

Turbidity of base flow

Turbidity makes the water cloudy or opaque.

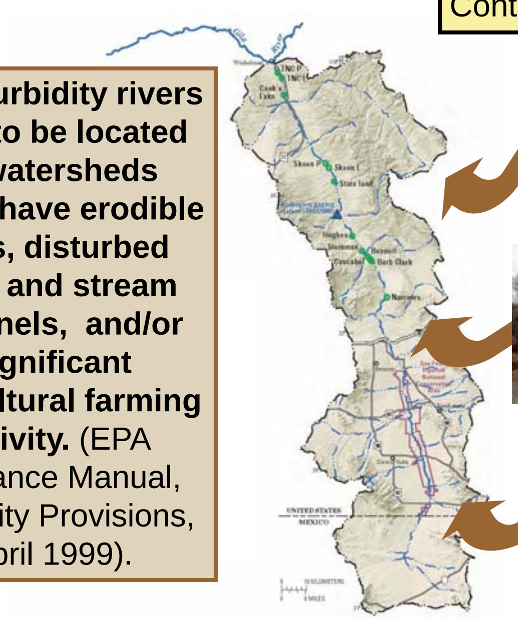
Both Parke (July 1855) and Hutton (Sept. 1857) observed "turbid" water in the San Pedro River that disappeared but reappeared as "clear and limpid." *First*, its odd that both men would use nearly identical words. *Second*, what is the significance of turbid base flow in the river?

A possible reason both accounts used “turbid” flow followed by disappearing flow that reappeared as clear and “limpid” is because Mr. Hutton was an engineer on both the Pacific railroad and the Pacific wagon road explorations.

Nature-based runoff of desert streams typically is clear. Thus, why was the flow turbid in July 1855 and September 1857?

Context is important

High turbidity rivers tend to be located in watersheds which have erodible soils, disturbed soils and stream channels, and/or significant agricultural farming activity. (EPA Guidance Manual, Turbidity Provisions, April 1999).



There were diversions along the San Pedro in the 1850s

In fact, there were continuous diversions by Indians through 1919

"Irrigation in the San Pedro Valley has been practiced since ancient times. When the first Spanish explorers came into this region during the sixteenth century, they found Indians irrigating along the river." (US Congress, p. 185)

US Congress, June 30, 1919, Indians of the United States, Hearings before the Committee on Indian Affairs, House of Representatives, 66th Congress, on the condition of various Indian tribes, Vol. 2.

"In more recent years Mexicans have integrated into this valley and have irrigated small patches of land. Some of these parcels have been **continuously irrigated to the present time**, this being especially true of the lands along the upper part of the river, on the old Spanish grants, and in the lower Benson valley." (US Congress, 1919, p. 185)

"When the general territory, south of the Gila, was obtained from Mexico through the Gadsden Purchase in 1854, two old Spanish land grants on the upper portion of the San Pedro were recognized by this Government. These land grants cover much of the area's early irrigation along the San Pedro, and some of these tracts have been **continuously irrigated** to the present time." (US Congress, 1919, p. 66)

"Until about 1860 the Indians maintained their rancherias along the San Pedro. Since that time, however, they have either been forced out or have vacated their land, and at the present time only two Indian ditches, irrigating 20 acres, are diverting water from the San Pedro. On the Aravaipa, a tributary to the San Pedro, one Indian ditch serving 80 acres is being operated at the present time." (US Congress, 1919, p. 66)

"From the annual report of the Indian agent of the San Carlos Indian Reservation it has been learned that prior to 1868, about 75 Indians irrigated small tracts along the river and Aravaipa Creek, a tributary. Many of the Indians either have abandoned their lands or have been forced out by the whites, and those few who remain at the present time are cultivating only a few acres." (US Congress, pp. 185-86)

Additional support for a perennial pre-development San Pedro River.

The San Pedro River was first surveyed by Federal Land Surveyors (Harris) in 1877-79.

"The San Pedro River appears to have had **water throughout its length** at the time of Harris's survey (November and December 1879): he measured the river as 23 to 36 ft wide at most locations, and as wide as 56 ft at a few places." (Sayre, p. 105)

Sayre, Nathan F., 2011, *A History of Land Use and Natural Resources in the Middle San Pedro River Valley, Arizona:* JOURNAL OF THE SOUTHWEST, *Volume 53, Number 1, Spring 2011, p 87-137.*

Also, there was streamflow at all of the 159 crossings of the San Pedro River when first surveyed by Federal Land Surveyors in 1877-79.

Huckleberry, G., 1996, Historical Channel Changes on the San Pedro River, Southeastern Arizona: Arizona Geological Survey Open-File Report 96-15, 37p.

Floodwater farming in the valley is implied due to evidence of the San Pedro River as a **perennial stream**, abundant habitations along its course, and by large cleared areas along the floodplains of small tributary drainages. Some evidence of prehistoric irrigation has been found along the lower San Pedro in the Sonoran desert region of the river.

Arizona State Land Department, 2007, Arizona Stream Navigability Study for the San Pedro River: revised by JE Fuller Hydrology & Geomorphology, Inc.

Mowry 1864

ARIZONA AND SONORA:

THE

GEOGRAPHY, HISTORY, AND RESOURCES

OF THE

SILVER REGION OF NORTH AMERICA.

BY

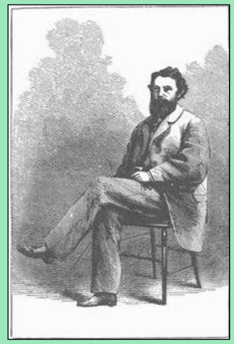
SYLVESTER MOWRY,

OF ARIZONA,

GRADUATE OF THE U. S. MILITARY ACADEMY AT WEST POINT, LATE
LIEUTENANT THIRD ARTILLERY, U. S. A., CORRESPONDING
MEMBER OF THE AMERICAN INSTITUTE, LATE
U. S. BOUNDARY COMMISSIONER,
ETC., ETC., ETC.

Third Edition. Revised and Enlarged.

NEW YORK:
HARPER & BROTHERS, PUBLISHERS,
FRANKLIN SQUARE.
1864.



Mowry 1864

"The San Pedro valley is next reached, and lying some ten or twelve feet below the bottom land, unmarked by trees, the river is not observed until at its very margin. **It was here about thirty feet wide and two and a half deep.** Its depth varies with the rainy and dry seasons." (Page 184)

Mowry 1864

" On the San Pedro route water is abundant and convenient in the **entire valley of the Rio San Pedro**." Besides this permanent supply, "water is found, after the rains, on the playas and in depressions in the drains."

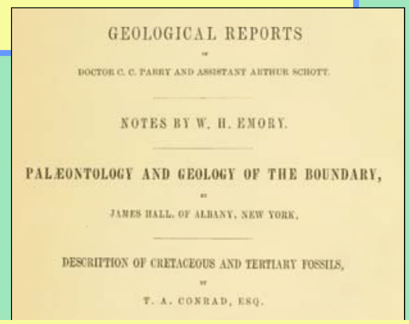
(page 219—quoting Lieutenant Parke of the The Southern Railroad Route to the Pacific.)

"Throughout the **whole course of the San Pedro** there are beautiful valleys susceptible of irrigation and capable of producing large crops of wheat, corn, cotton, and grapes and there are on this river the remains of large settlements which have been destroyed by the hostile Indians, the most conspicuous of which are the mining town of San Pedro and the town of San Cruz Viejo. There are also to be found here, in the remains of spacious corrals, and in the numerous wild cattle and horses which still are seen in this country, the evidences of its immense capacity as a grazing country." (page 94, Vol. 1)

Report on the u.s. and Mexican Boundary Survey, Vols I-I/., 1857, U. S. 34th Congress, 1st Sess., Sen. Exec. Doc. 108, H.R. Exec. Doc. 135, Washington. D.C., Emory.

"It is this latter character which sufficiently accounts for the fact that the San Pedro is the only branch of the Gila River, coming from the south which furnishes an **uninterrupted stream of running water** along its whole course." (page 18, Vol. 2)

Report on the U.S. and Mexican Boundary Survey, Vols I-I/., 1857, U. S. 34th Congress, 1st Sess., Sen. Exec. Doc. 108, H.R. Exec. Doc. 135, Washington. D.C.


GEOLOGICAL REPORTS

DOCTOR C. C. PARRY AND ASSISTANT ARTHUR SCHOTT.

NOTES BY W. H. EMORY.

PALÆONTOLOGY AND GEOLOGY OF THE BOUNDARY,

JAMES HALL, OF ALBANY, NEW YORK.

DESCRIPTION OF CRETACEOUS AND TERTIARY FOSSILS,

T. A. CONRAD, ESQ.

CHAPTER 1, GENERAL GEOLOGICAL FEATURES OF THE COUNTRY. WASHINGTON, D. C., *April* 1, 1852.

A description of an 1858 fire along the San Pedro River is particularly graphic: members of the Leach Wagon Road party set fire to a sacaton grass swale, and "the entire length of the Valley of the San Pedro was traversed by the flames consuming every vestige of this once luxurient growth" (National Archives and Records Center, 1858, p. 31-32).

Turner, R. M., 1974 , QUANTITATIVE AND HISTORICAL EVIDENCE OF VEGETATION CHANGES ALONG THE UPPER GILA RIVER, ARIZONA: GEOLOGICAL SURVEY PROFESSIONAL PAPER 655-H, 20 p.

Direct runoff and sediment yield can increase significantly after a major fire.

Conservative approach to this analysis of navigability along San Pedro River.

Predevelopment hydrology (base runoff) probably under estimated for following reasons:

- Models of ground water typically were based on assumption that 1940 conditions represented predevelopment. Natural base runoff probably was greater than that for 1940. (slides 17-22)
- Based on more recent analysis by Anderson and Freethey, 1994, in USGS PP1406-D, the base runoff (Q_{90}) used for the analysis probably is low (USGS HA-664 by Freethey and Anderson, 1986). (slides near end of appendix).

3 of 6

- Discharge to springs in the lower reach was not considered part of the base runoff. (near end of appendix).
- The base runoff at the Mexican border does not account for the water consumed at City of Cananea or the Cananea mine. Several GW models ignored base runoff at Mexican border. (slides 73-78).
- The loss of base runoff to ET does not consider the possibility that predevelopment ET was 40% of post 1970 losses to ET. (Appendix slides 23-24).
- Our limited understanding of base runoff associated with the stream alluvium (slide 55).
- General uncertainty of predevelopment conditions. (slides 7-9, 16-35).

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4 of 6

Predevelopment depths probably under estimated as follows:

A minimum predevelopment sinuosity of 1.5 was used for the analysis, instead of a possible 2.0. This minimum sinuosity agrees with Leopold and Wolman who had “suggested that a sinuosity 1.5 marks the lower boundary for true meandering, although most later authors agree on a somewhat lower threshold sinuosity of 1.3.”

Lagasse, P. F., and others, 2004, Methodology for Predicting Channel Migration: Transportation Research Board of the National Academy of Sciences, 213 p.

A minimum likely predevelopment sinuosity of 1.5 produced a maximum channel slope with corresponding greater flow velocities, shallower depths and smaller widths. Conservatively low estimated depths mostly accounted for the following:

• 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 more than the typical channel slope. (Recent channel slope below these restrictions probably is greater than the natural slope was as channel material has been removed (by head cutting) downstream from these hard rock areas.

Reasons for the conservative approach

•Alternating gaining and losing reaches along the river. Non-uniform base flow is result of varying rates of mountain front and stream channel recharge along the river, sediment deposits at mouths of tributary streams and variable hydraulic characteristics of stream alluvium.

•Possible multiple channels for short reaches.

•General accounting for recognized variable hydrologic/morphologic conditions, such as small riffles, that are typical along natural rivers like the San Pedro.