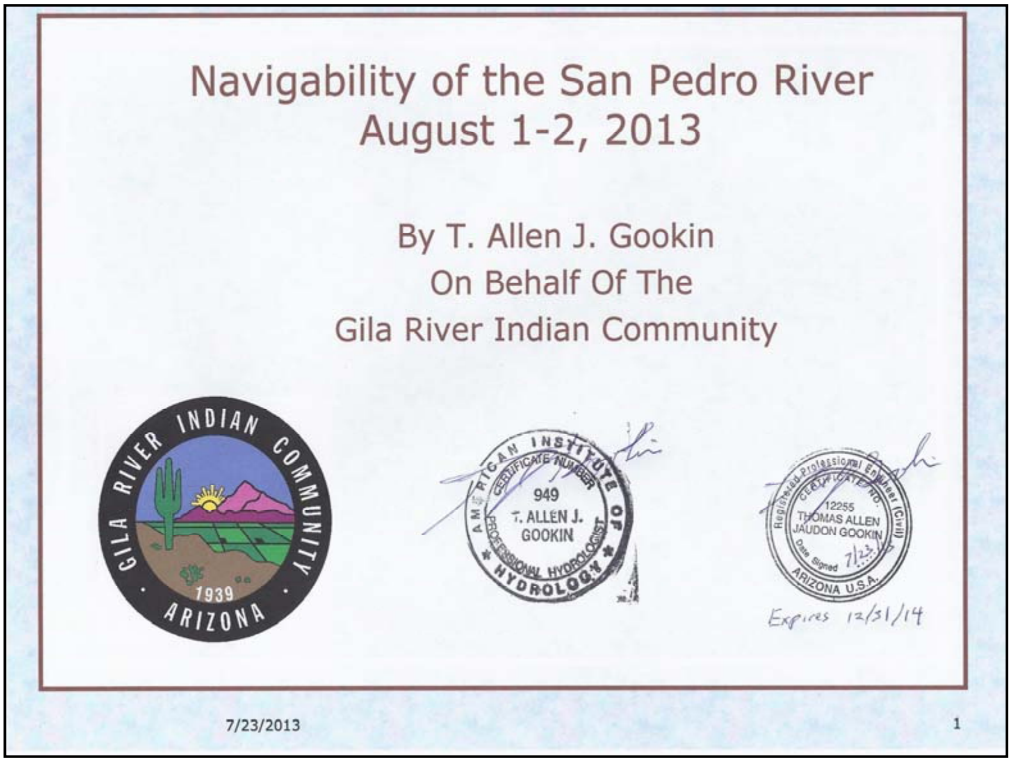


Navigability of the San Pedro River
August 1-2, 2013

By T. Allen J. Gookin
On Behalf Of The
Gila River Indian Community

AMERICAN INSTITUTE OF HYDROLOGY
CERTIFICATE NUMBER
949
T. ALLEN J.
GOOKIN
PROFESSIONAL HYDROLOGIST

Registered Professional Engineer (Civil)
CERTIFICATE NO.
12255
THOMAS ALLEN
JAUDON GOOKIN
Date Signed 7/23
ARIZONA U.S.A.

Expires 12/31/14

7/23/2013

Registered Professional Engineer
Registered Land Surveyor
Certified Professional Hydrologist
State Water Right Surveyor (Nevada)

Legal Standards

Navigable in Fact or
Susceptible of Navigability

Ordinary and Natural as of the
date of Statehood

Navigable in Fact

- Only 1 instance of using a boat is recorded
  - Pattie Beaver Trapping Party made a canoe
  - Probably on the San Pedro River
    - It was made because “one of our number had already been drowned, man and horse, in attempting to swim the river”
  - This means that the river was at or near flood stage

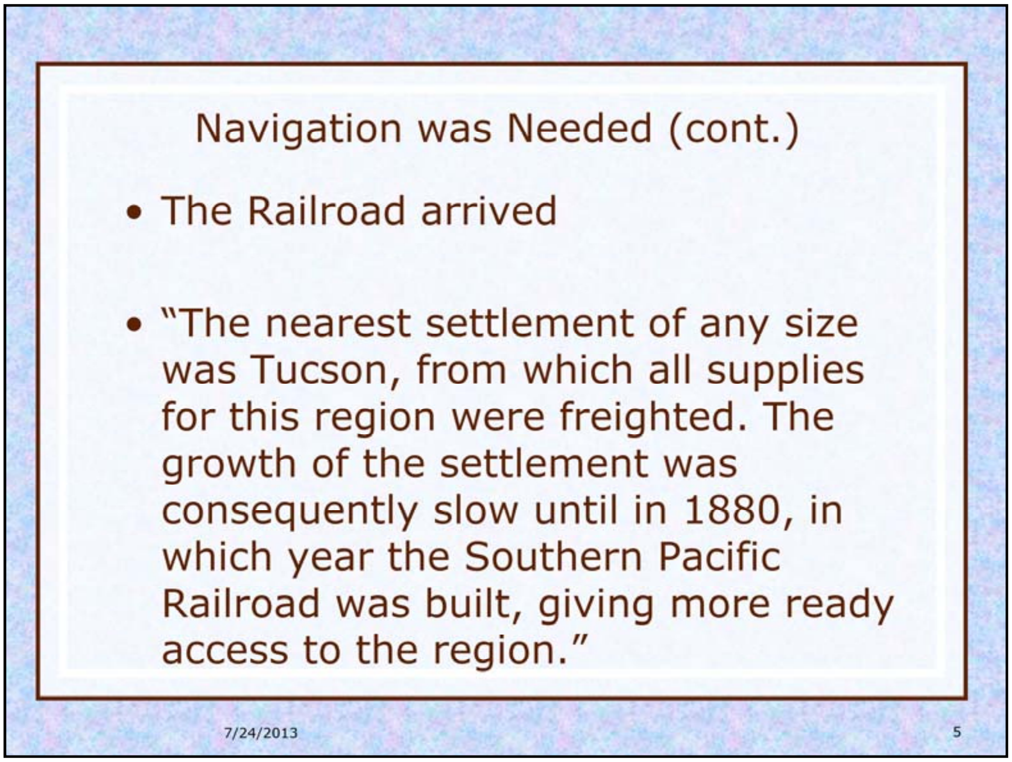
Source: Pattie, pg 136

Navigation was Needed

- Mines began in 1877
  - Needed equipment
  - Needed way to get the product out
- "Large shipments of mining and smelting equipment transported in twenty-mule team freight wagons to the early developed mining regions of southern Arizona, crossed over this bridge"

7/24/2013

Source: Fuller pg 3-19

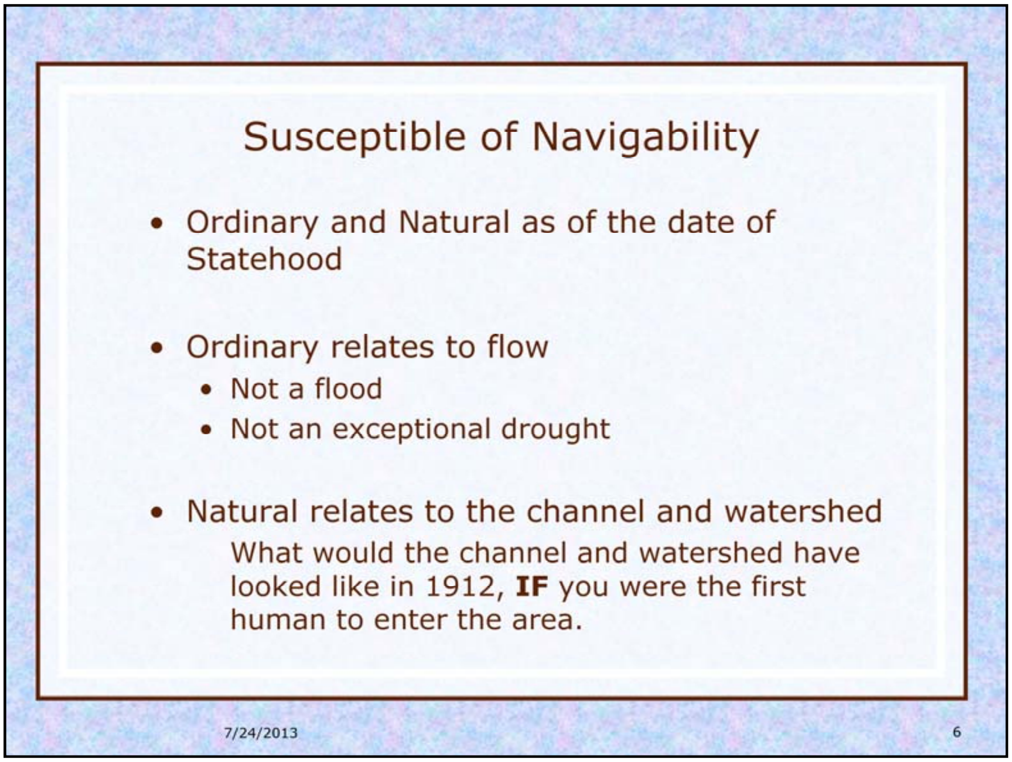


Navigation was Needed (cont.)

- The Railroad arrived
- “The nearest settlement of any size was Tucson, from which all supplies for this region were freighted. The growth of the settlement was consequently slow until in 1880, in which year the Southern Pacific Railroad was built, giving more ready access to the region.”

Source: Carpenter and Bransford pg 249

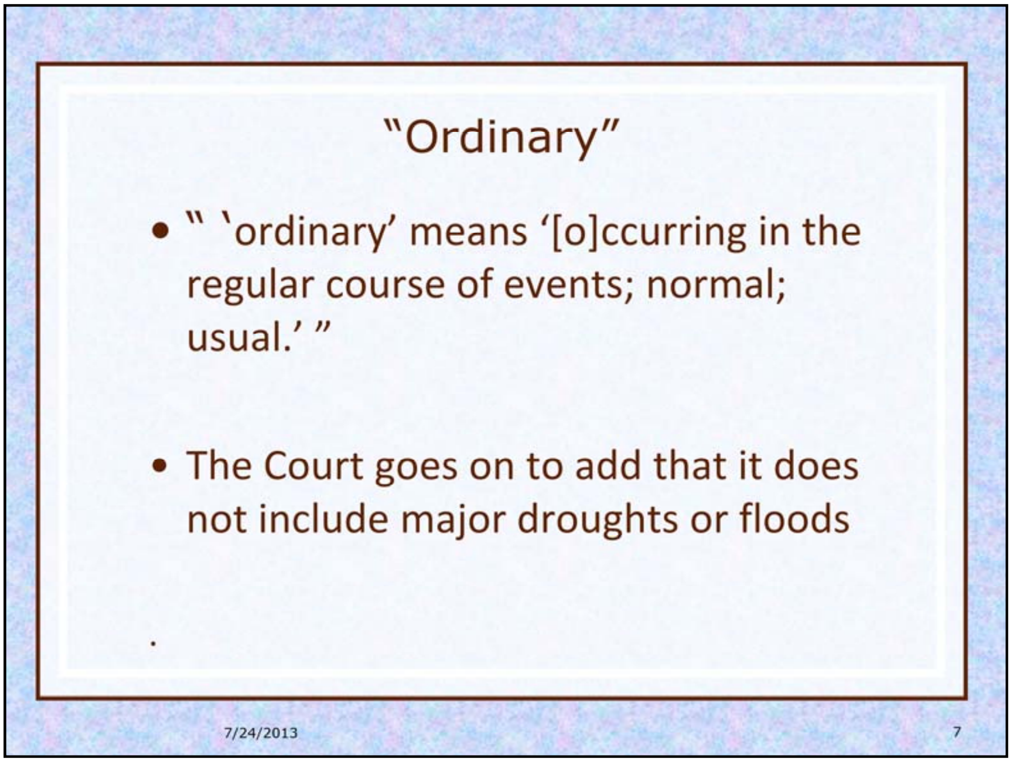
See Appendix A - The Need for Transportation



Susceptible of Navigability

- Ordinary and Natural as of the date of Statehood
- Ordinary relates to flow
  - Not a flood
  - Not an exceptional drought
- Natural relates to the channel and watershed

  What would the channel and watershed have looked like in 1912, **IF** you were the first human to enter the area.

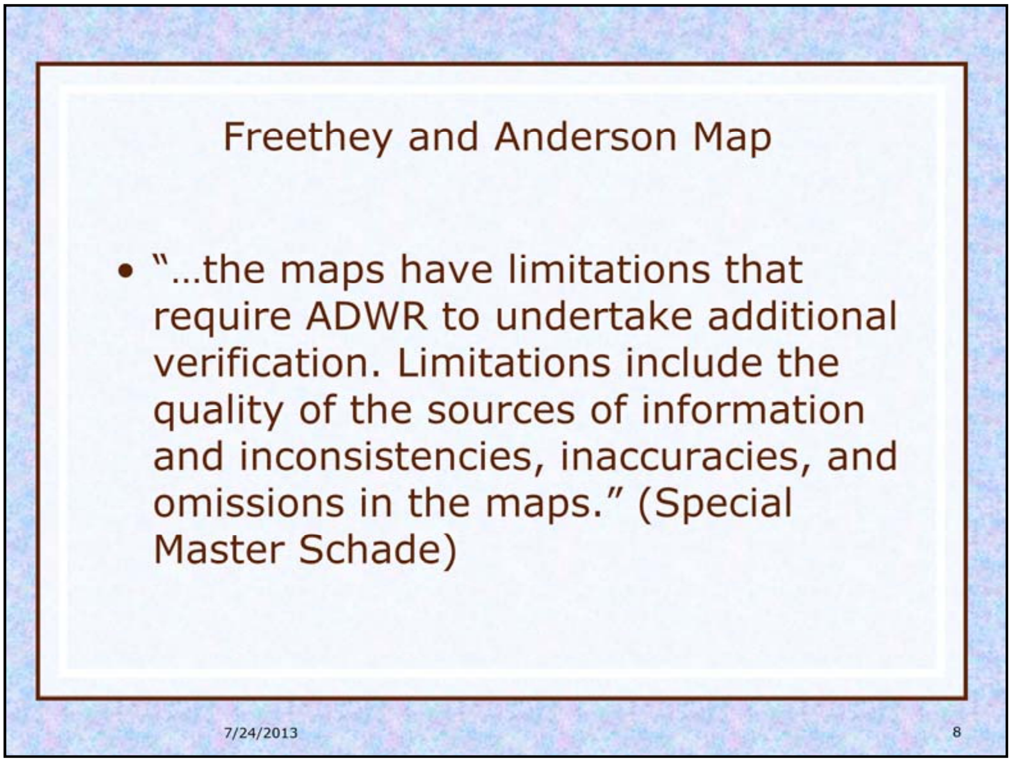


“Ordinary”

- “ ‘ordinary’ means ‘[o]ccurring in the regular course of events; normal; usual.’ ”
- The Court goes on to add that it does not include major droughts or floods

.

Source: Hyatt pg 24



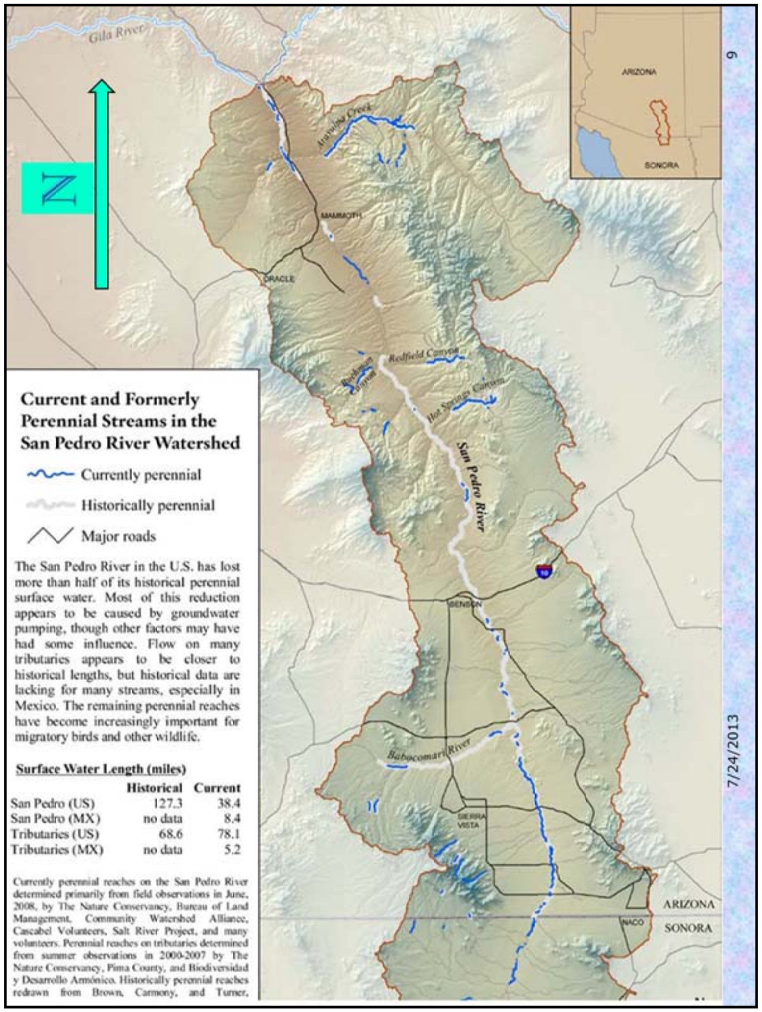
Freethey and Anderson Map

- "…the maps have limitations that require ADWR to undertake additional verification. Limitations include the quality of the sources of information and inconsistencies, inaccuracies, and omissions in the maps." (Special Master Schade)

7/24/2013

Source: Freethey and Anderson

Source: ADWR Appendix A-3 pg 26-27



Current and Formerly Perennial Streams in the San Pedro River Watershed

- Currently perennial
- Historically perennial
- Major roads

The San Pedro River in the U.S. has lost more than half of its historical perennial surface water. Most of this reduction appears to be caused by groundwater pumping, though other factors may have had some influence. Flow on many tributaries appears to be closer to historical lengths, but historical data are lacking for many streams, especially in Mexico. The remaining perennial reaches have become increasingly important for migratory birds and other wildlife.

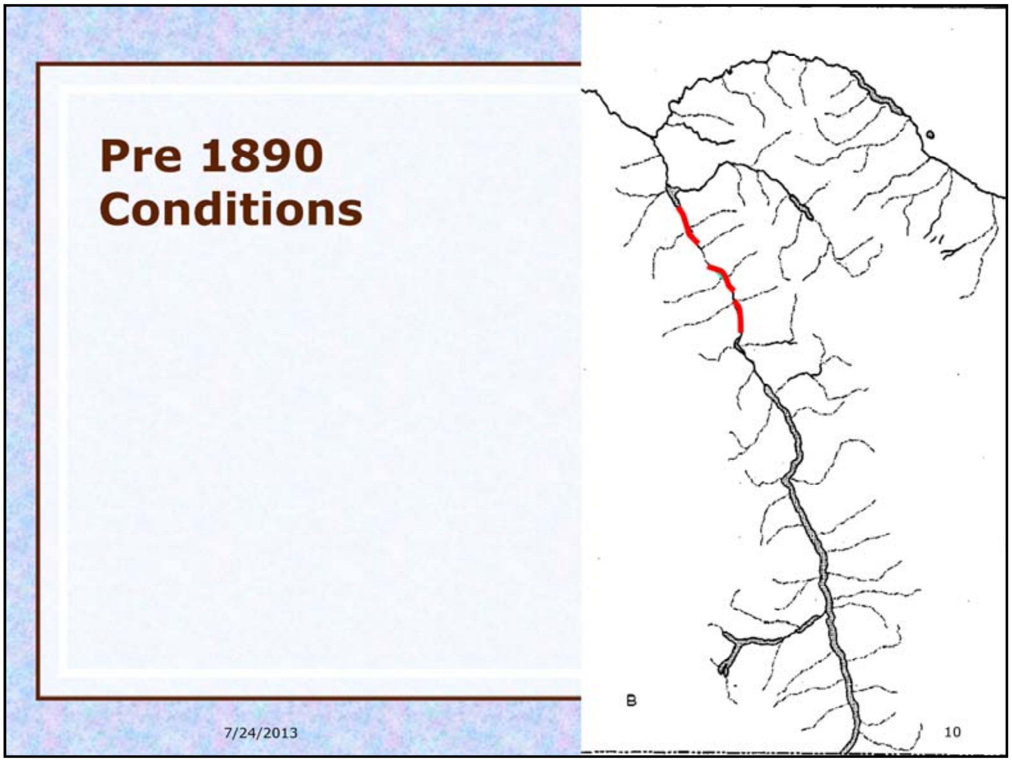
Surface Water Length (miles)

	Historical	Current
San Pedro (US)	127.3	38.4
San Pedro (MX)	no data	8.4
Tributaries (US)	68.6	78.1
Tributaries (MX)	no data	5.2

Currently perennial reaches on the San Pedro River determined primarily from field observations in June, 2008, by The Nature Conservancy, Bureau of Land Management, Community Watershed Alliance, Cascabel Volunteers, Salt River Project, and many volunteers. Perennial reaches on tributaries determined from summer observations in 2000-2007 by The Nature Conservancy, Pima County, and Biodiversidad y Desarrollo Armónico. Historically perennial reaches redrawn from Brown, Carmony, and Turner,

7/24/2013

Source: Turner



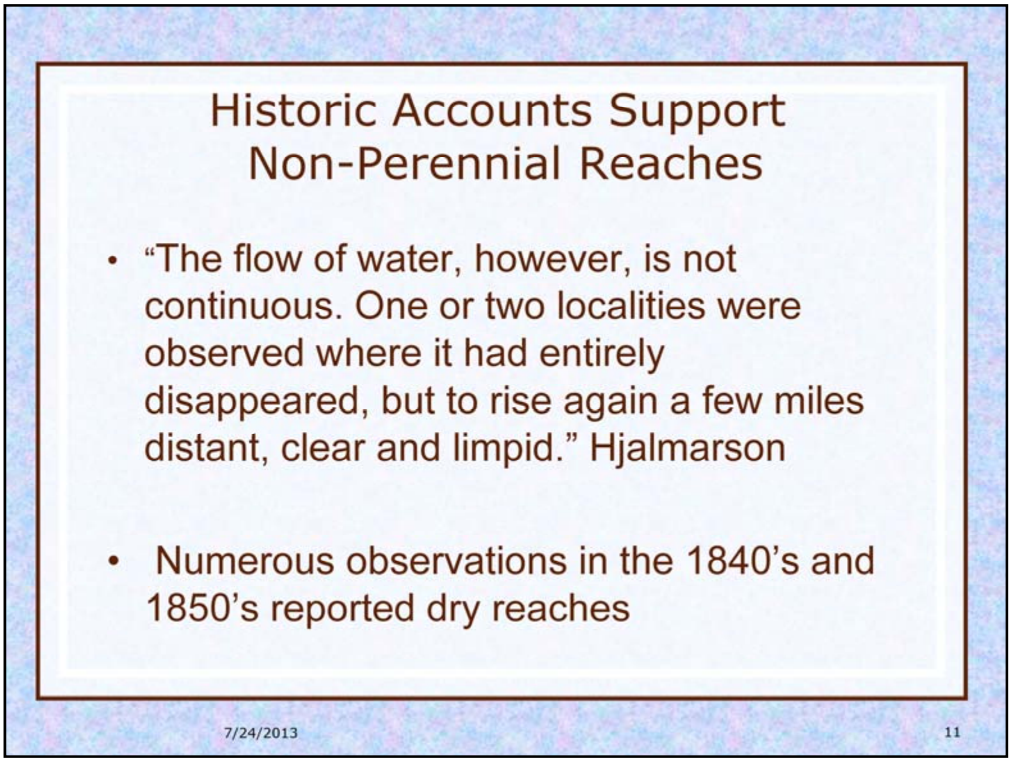
Pre 1890 Conditions

7/24/2013

Source: Hendrickson and Minckley Figure 9b

Dashed Lines are ephemeral flow.
These reaches are highlighted in red.
Note the map has no category for intermittent flow.

Wide areas on river are cienega/marsh



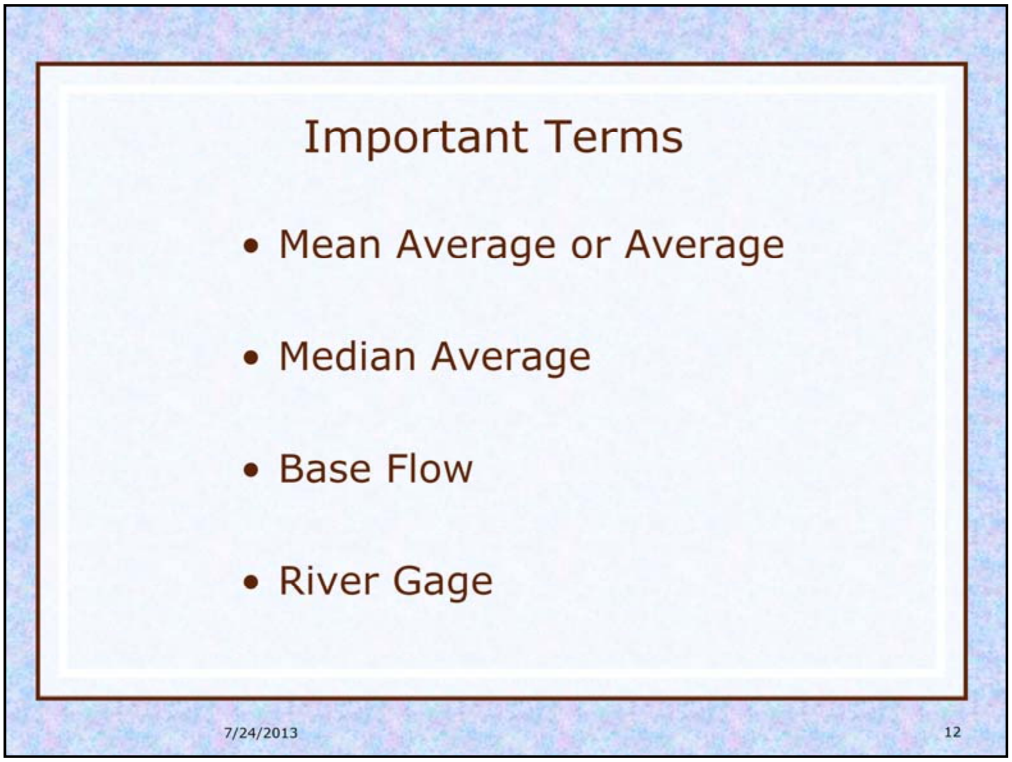
Historic Accounts Support Non-Perennial Reaches

- “The flow of water, however, is not continuous. One or two localities were observed where it had entirely disappeared, but to rise again a few miles distant, clear and limpid.” Hjalmarson
- Numerous observations in the 1840’s and 1850’s reported dry reaches

7/24/2013 11

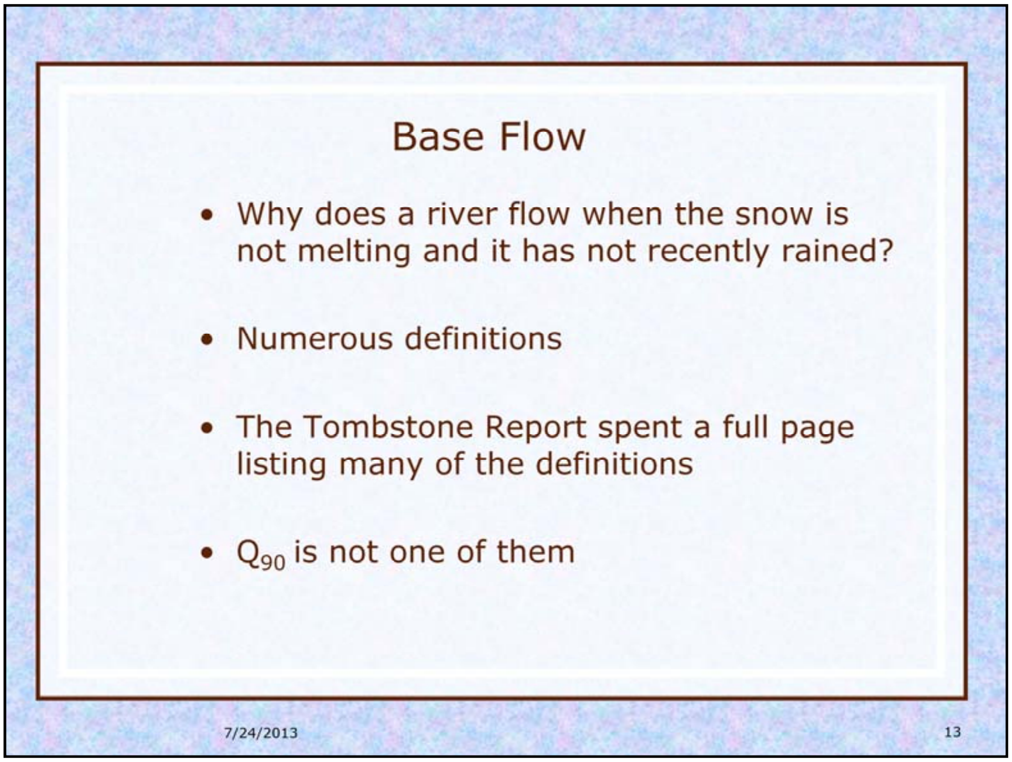
Source: Hjalmarson 1988 (attachment to article)

See Appendix A - Intermittent Flows



Important Terms

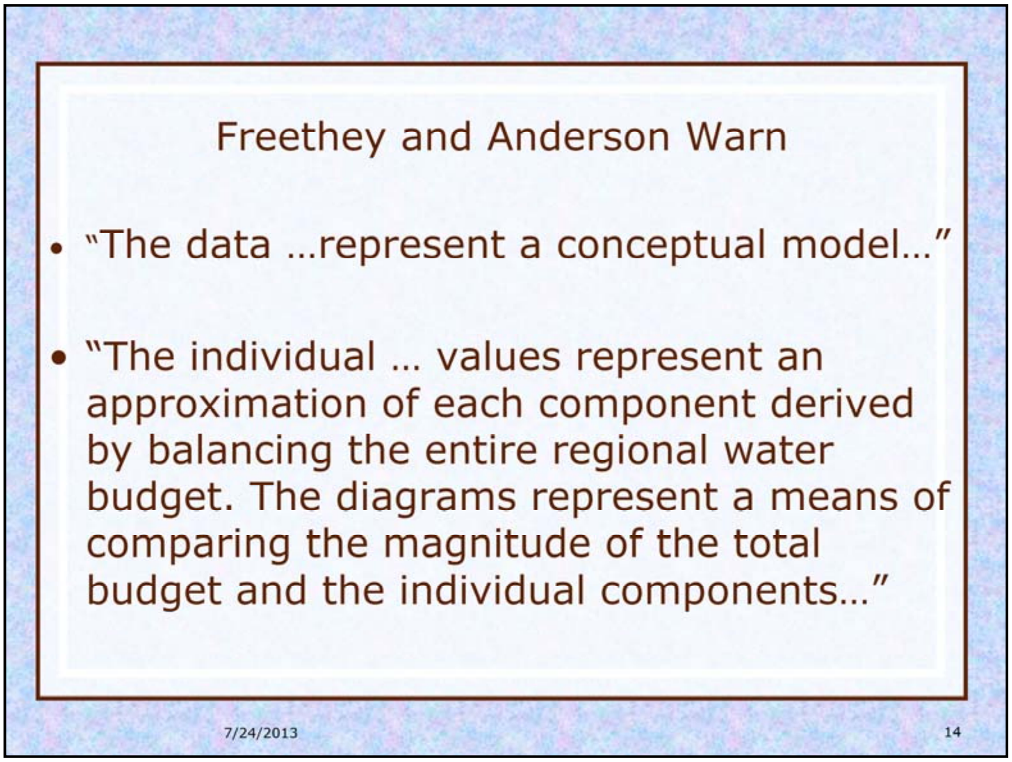
- Mean Average or Average
- Median Average
- Base Flow
- River Gage



Base Flow

- Why does a river flow when the snow is not melting and it has not recently rained?
- Numerous definitions
- The Tombstone Report spent a full page listing many of the definitions
- Q_{90} is not one of them

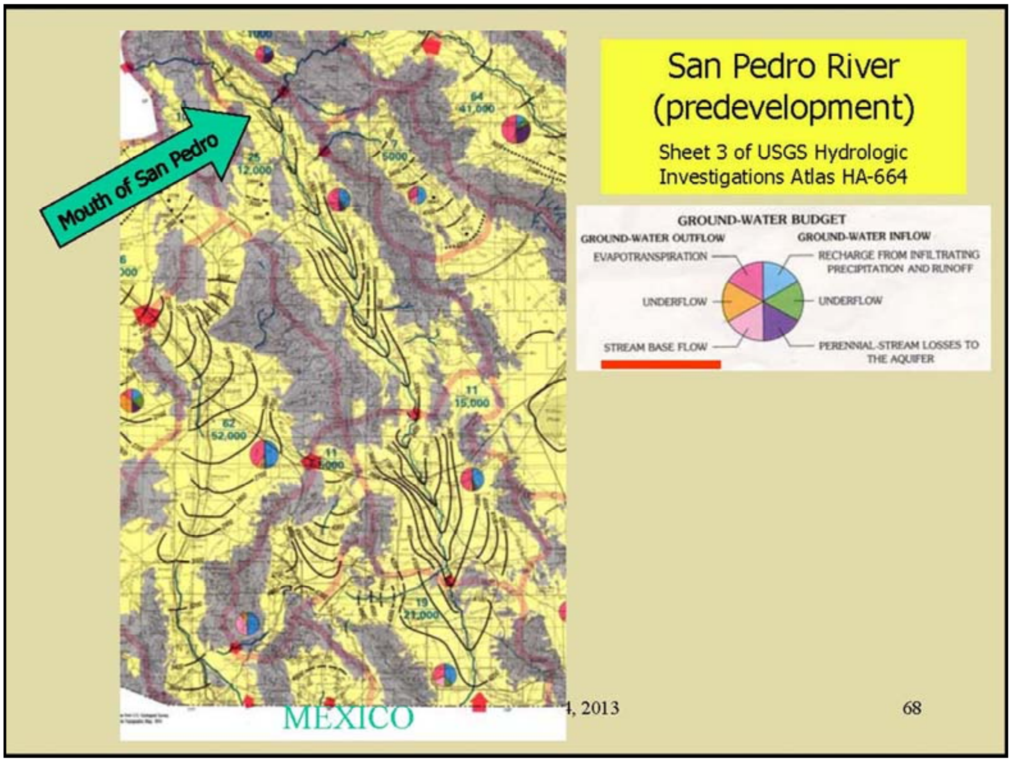
Source: Kennedy and Gungle



Freethey and Anderson Warn

- "The data …represent a conceptual model…"
- "The individual … values represent an approximation of each component derived by balancing the entire regional water budget. The diagrams represent a means of comparing the magnitude of the total budget and the individual components…"

Source: Freethey and Anderson Plate 1



San Pedro River (predevelopment)

Sheet 3 of USGS Hydrologic Investigations Atlas HA-664

GROUND-WATER BUDGET

GROUND-WATER OUTFLOW	GROUND-WATER INFLOW
EVAPOTRANSPIRATION	RECHARGE FROM INFILTRATING PRECIPITATION AND RUNOFF
UNDERFLOW	UNDERFLOW
STREAM BASE FLOW	PERENNIAL-STREAM LOSSES TO THE AQUIFER

4, 2013

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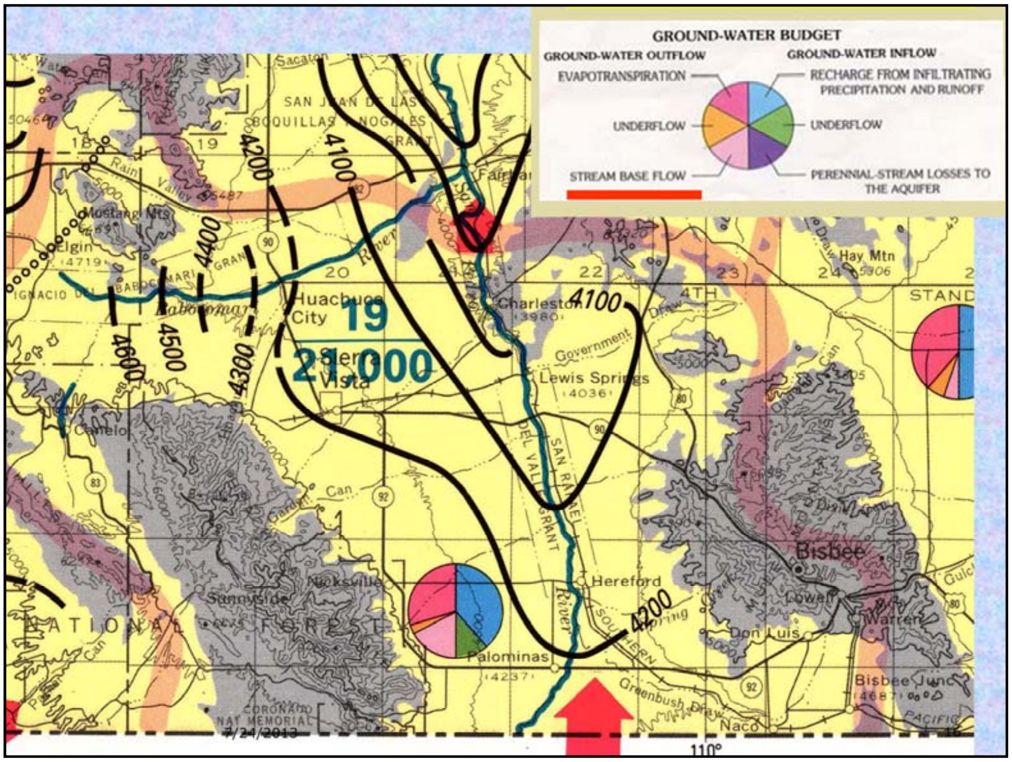
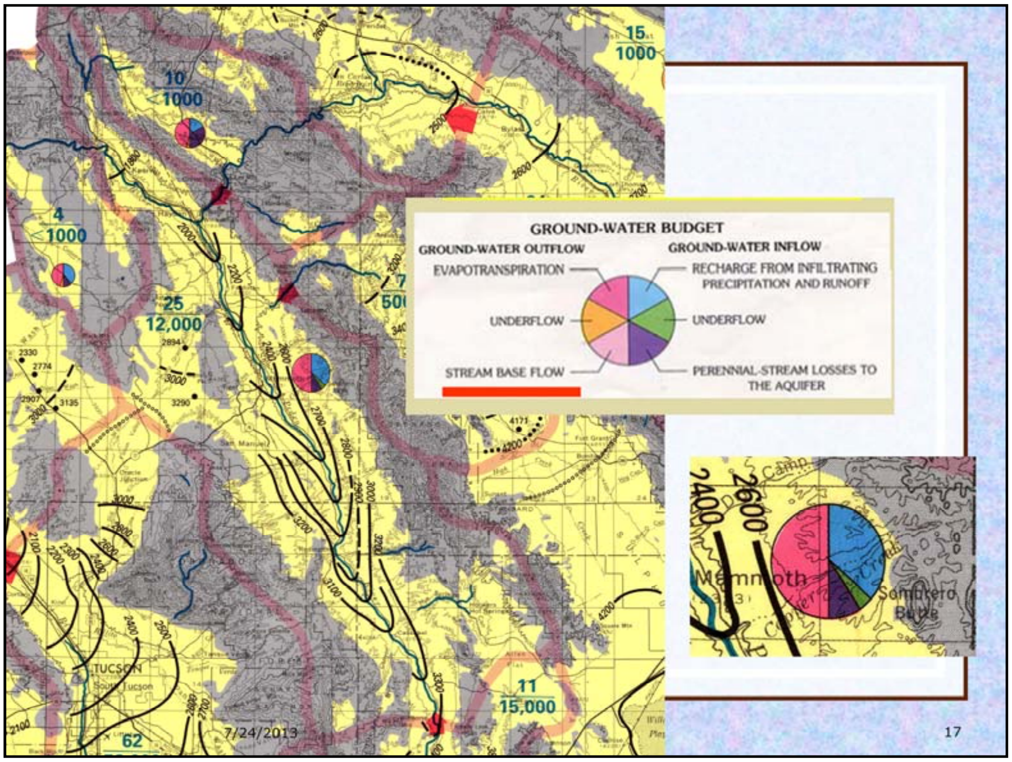
Source: Hjalmarson 2013 Slide 68



Source: Freethey and Anderson Plate 3



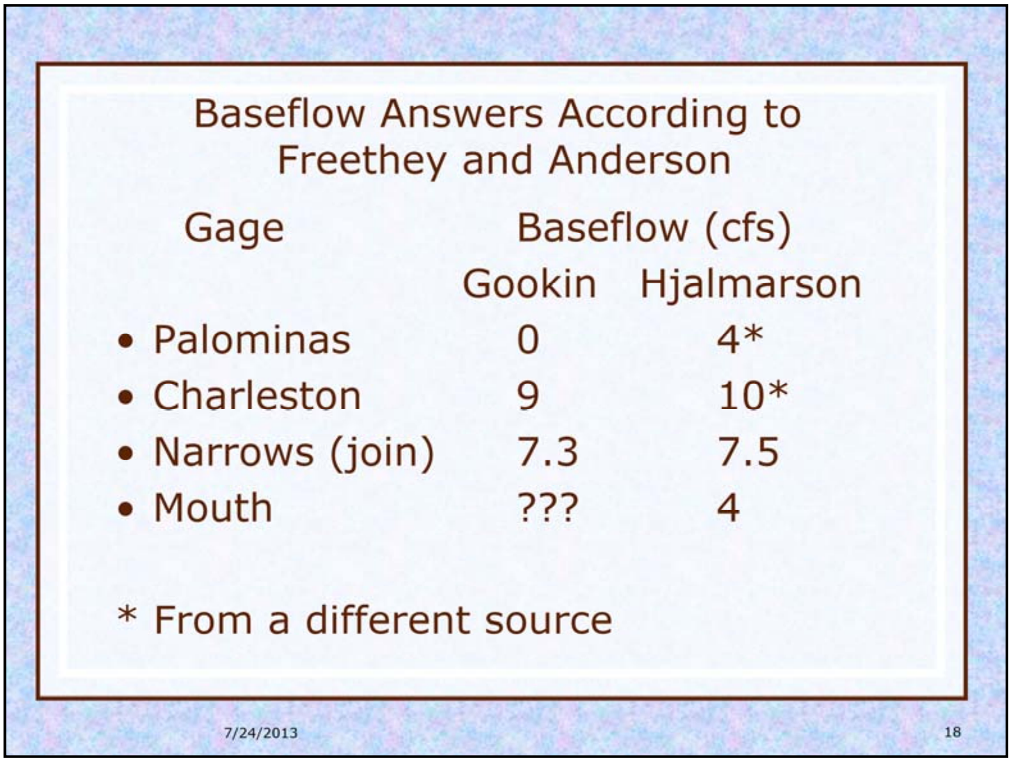
GROUND-WATER BUDGET

GROUND-WATER OUTFLOW
- EVAPOTRANSPIRATION
- UNDERFLOW
- STREAM BASE FLOW

GROUND-WATER INFLOW
- RECHARGE FROM INFILTRATING PRECIPITATION AND RUNOFF
- UNDERFLOW
- PERENNIAL-STREAM LOSSES TO THE AQUIFER

7/24/2013

Source: Freethey and Anderson Plate 3



Baseflow Answers According to Freethey and Anderson

Gage	Baseflow (cfs)	
	Gookin	Hjalmarson
• Palominas	0	4*
• Charleston	9	10*
• Narrows (join)	7.3	7.5
• Mouth	???	4

* From a different source

Source: Hjalmarson 2013, data from Slide 71

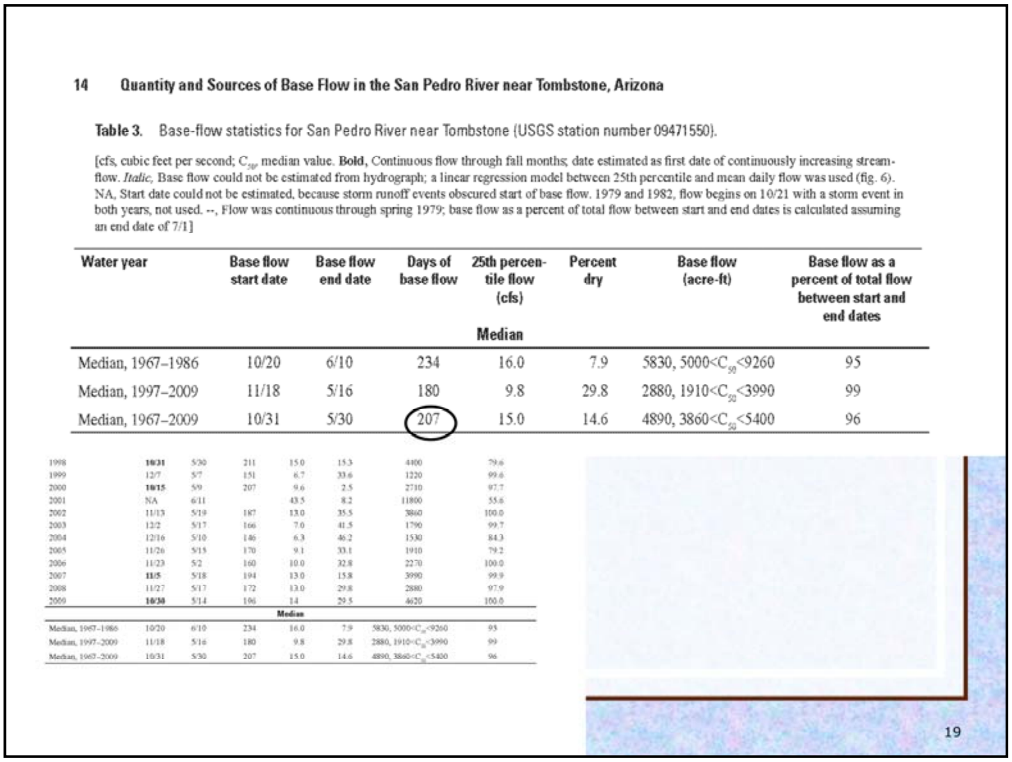


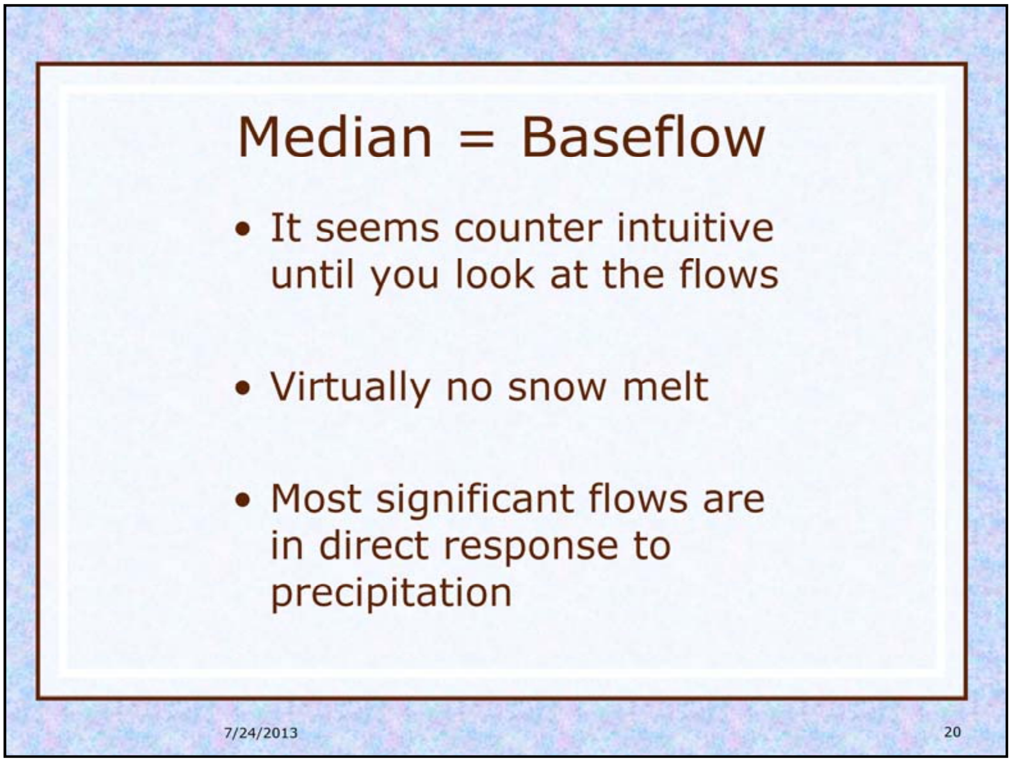
Table 3. Base-flow statistics for San Pedro River near Tombstone (USGS station number 09471550).

[cfs, cubic feet per second; C_{50}, median value. **Bold**, Continuous flow through fall months; date estimated as first date of continuously increasing streamflow. *Italic*, Base flow could not be estimated from hydrograph; a linear regression model between 25th percentile and mean daily flow was used (fig. 6). NA, Start date could not be estimated, because storm runoff events obscured start of base flow. 1979 and 1982, flow begins on 10/21 with a storm event in both years, not used. --, Flow was continuous through spring 1979; base flow as a percent of total flow between start and end dates is calculated assuming an end date of 7/1]

Water year	Base flow start date	Base flow end date	Days of base flow	25th percentile flow (cfs)	Percent dry	Base flow (acre-ft)	Base flow as a percent of total flow between start and end dates
				Median			
Median, 1967–1986	10/20	6/10	234	16.0	7.9	5830, 5000<C_{50}<9260	95
Median, 1997–2009	11/18	5/16	180	9.8	29.8	2880, 1910<C_{50}<3990	99
Median, 1967–2009	10/31	5/30	207	15.0	14.6	4890, 3860<C_{50}<5400	96

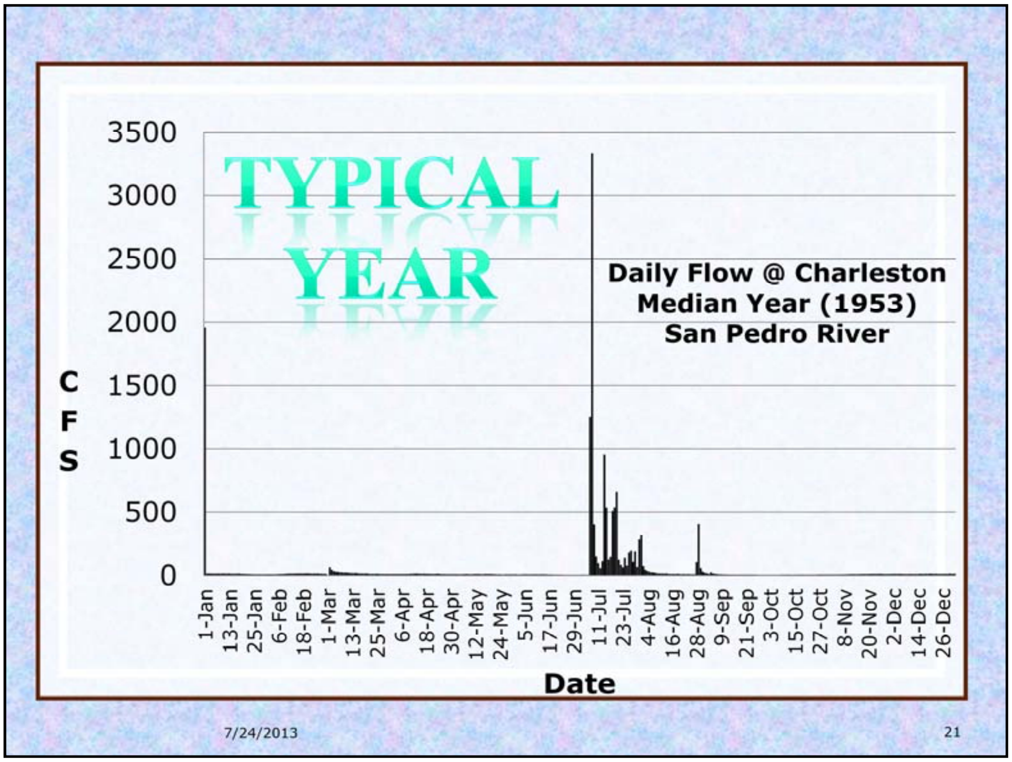
1998	**10/31**	5/30	211	15.0	15.3	4400	79.6
1999	12/7	5/7	151	6.7	33.6	1220	99.6
2000	**10/15**	5/9	207	9.6	2.5	2710	97.7
2001	NA	6/11		43.5	8.2	11800	55.6
2002	11/13	5/19	187	13.0	35.5	3860	100.0
2003	12/2	5/17	166	7.0	41.5	1790	99.7
2004	12/16	5/10	146	6.3	46.2	1530	84.3
2005	11/26	5/15	170	9.1	33.1	1910	79.2
2006	11/23	5/2	160	10.0	32.8	2270	100.0
2007	**11/5**	5/18	194	13.0	15.8	3990	99.9
2008	11/27	5/17	172	13.0	29.8	2880	97.9
2009	**10/30**	5/14	196	14	29.5	4620	100.0
				Median			
Median, 1967–1986	10/20	6/10	234	16.0	7.9	5830, 5000<C_{50}<9260	95
Median, 1997–2009	11/18	5/16	180	9.8	29.8	2880, 1910<C_{50}<3990	99
Median, 1967–2009	10/31	5/30	207	15.0	14.6	4890, 3860<C_{50}<5400	96

Source: Kennedy and Gungle pg 14

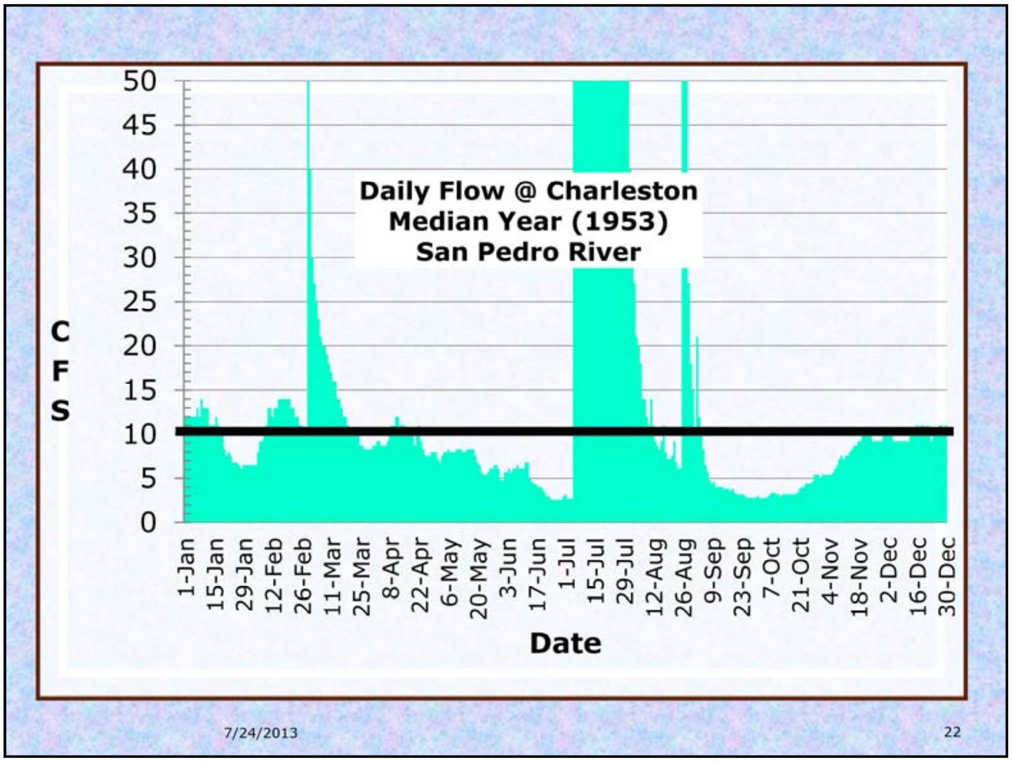


Median = Baseflow

- It seems counter intuitive until you look at the flows
- Virtually no snow melt
- Most significant flows are in direct response to precipitation



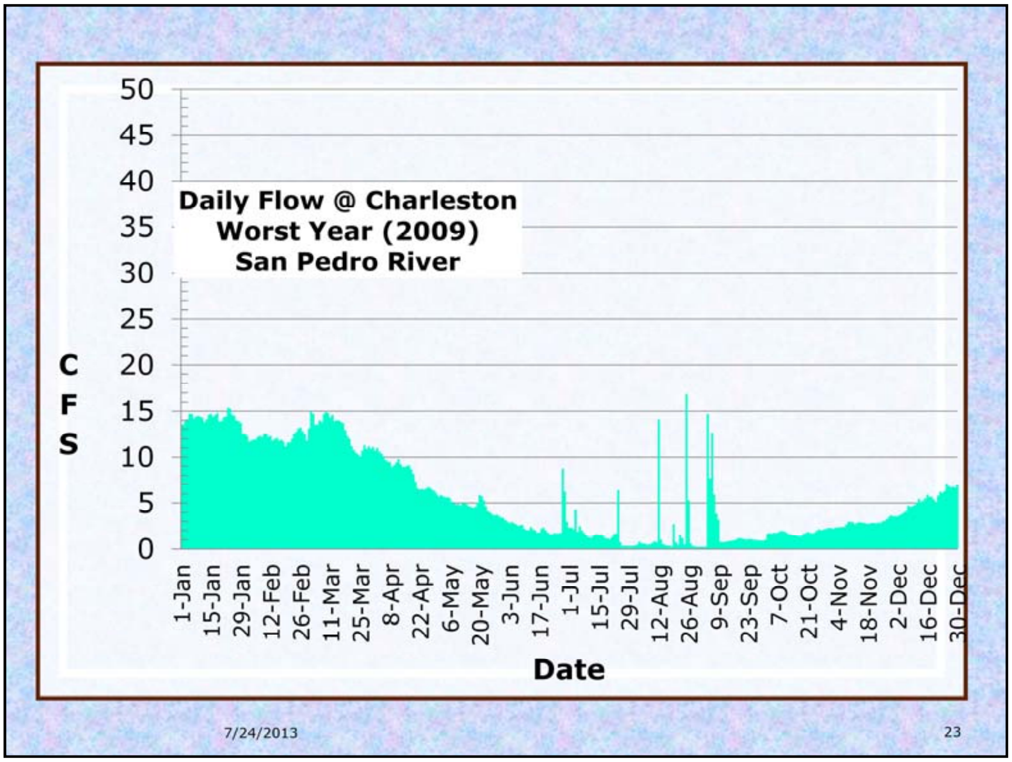
Source: USGS data



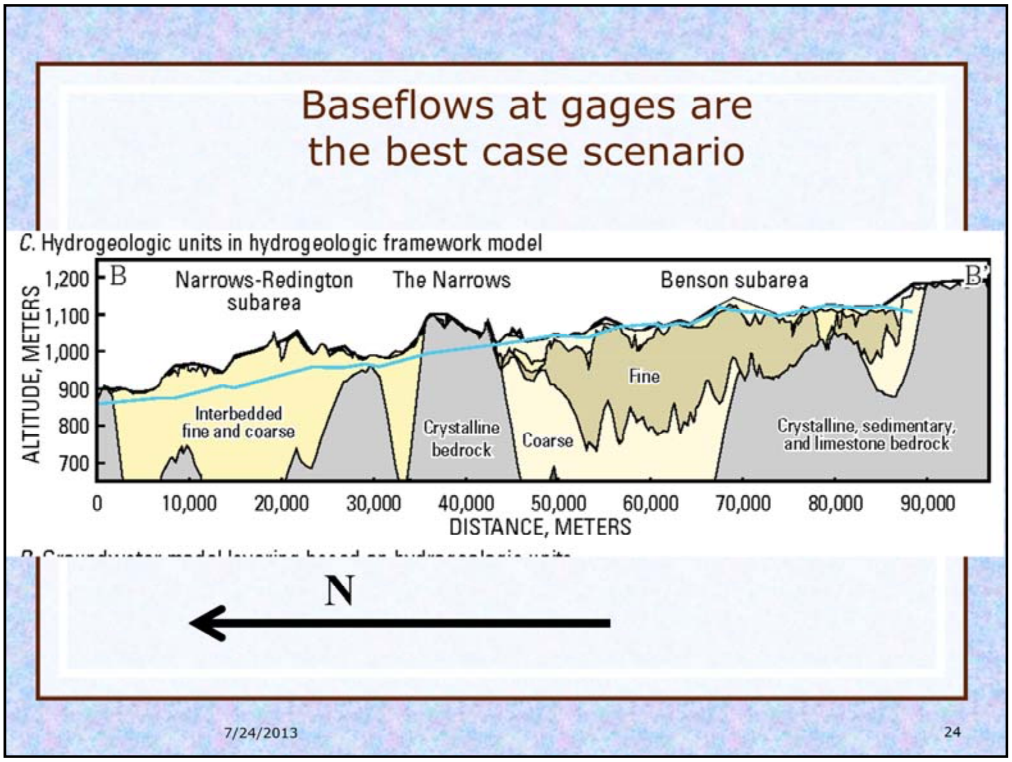
Daily Flow @ Charleston
Median Year (1953)
San Pedro River

7/24/2013

Source: USGS data

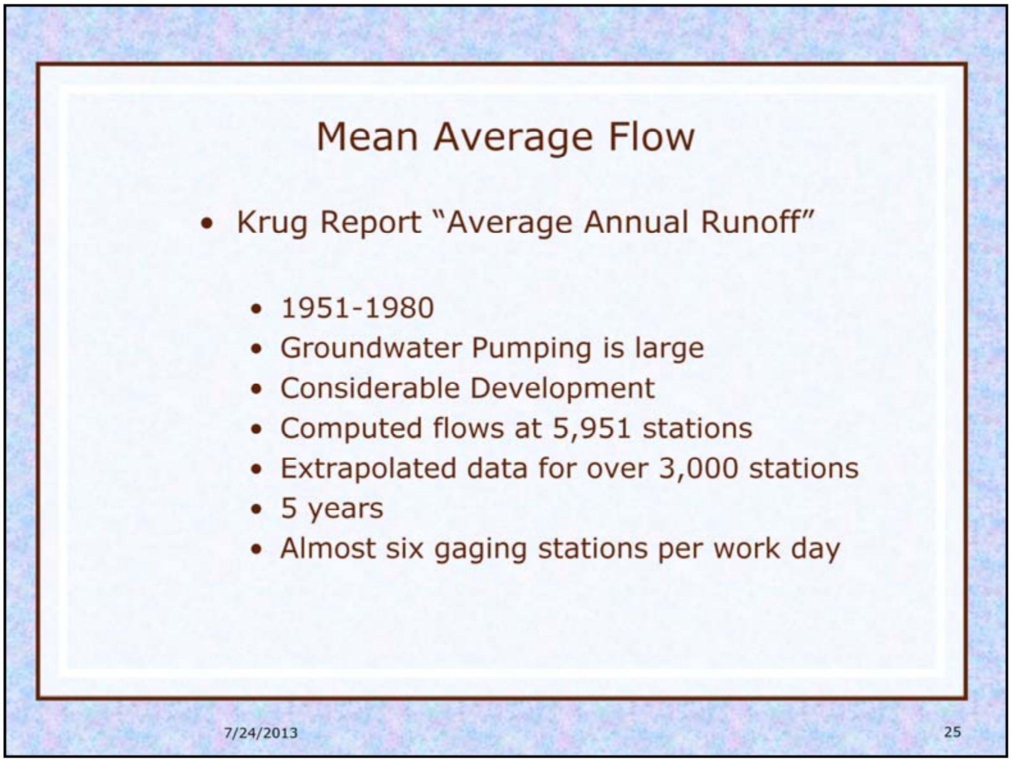


Source: USGS data



Baseflows at gages are the best case scenario

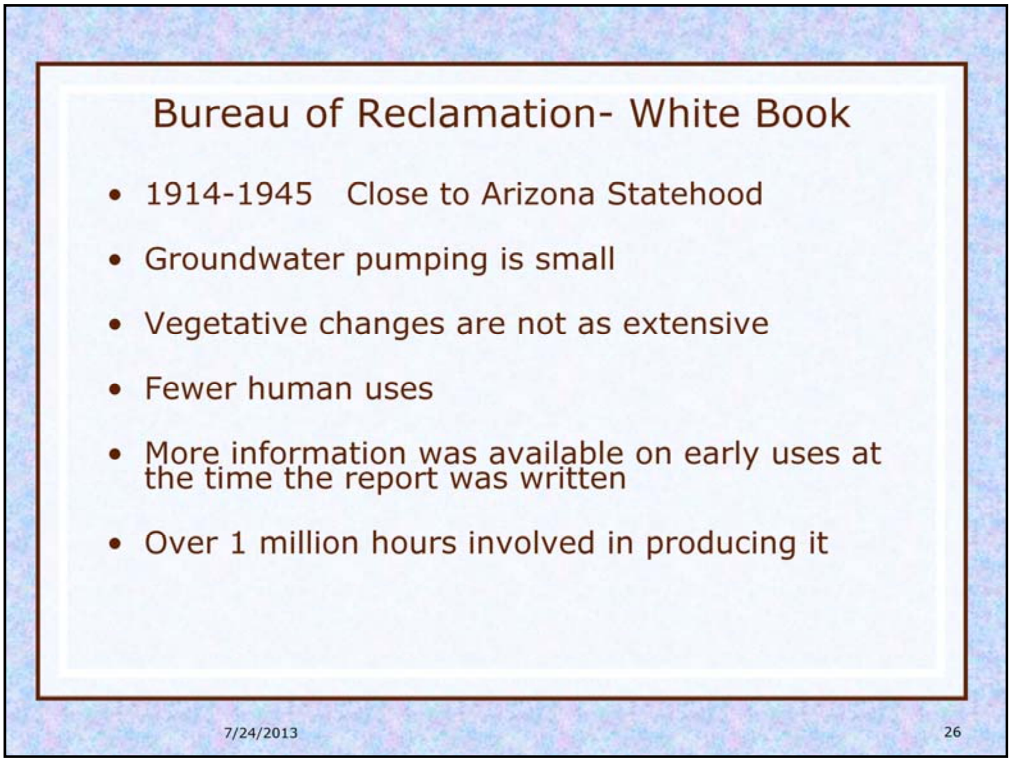
Source: Dickinson et. al. pg 17



Mean Average Flow

- Krug Report “Average Annual Runoff”
  - 1951-1980
  - Groundwater Pumping is large
  - Considerable Development
  - Computed flows at 5,951 stations
  - Extrapolated data for over 3,000 stations
  - 5 years
  - Almost six gaging stations per work day

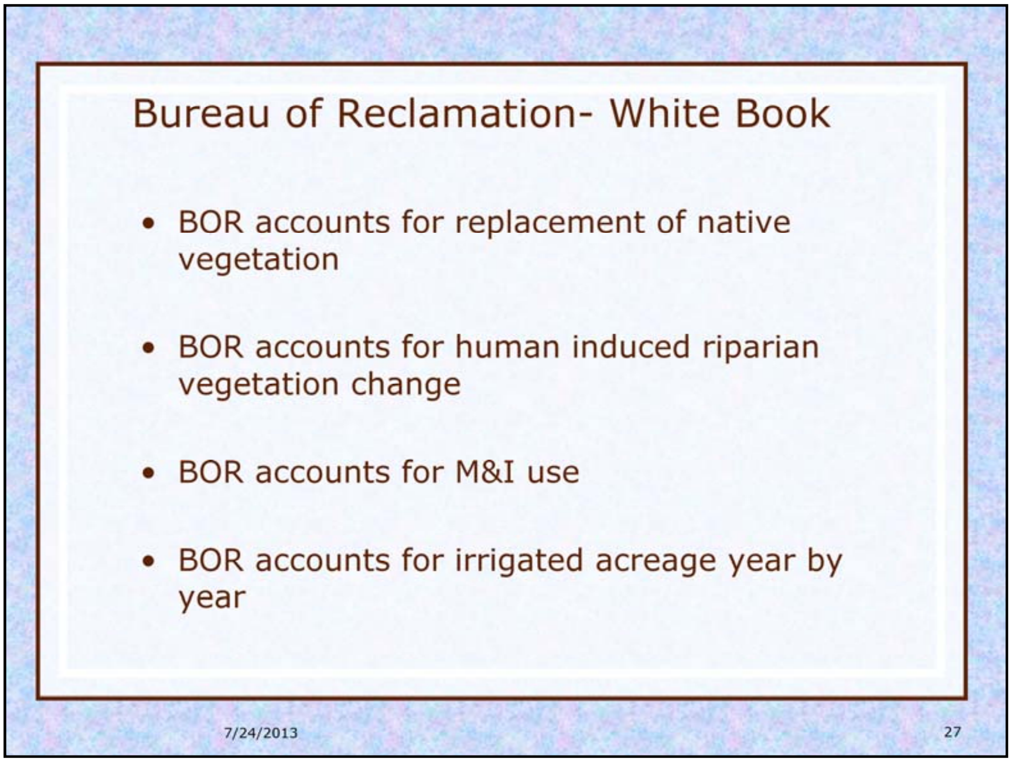
Source: Krug et. al.



Bureau of Reclamation- White Book

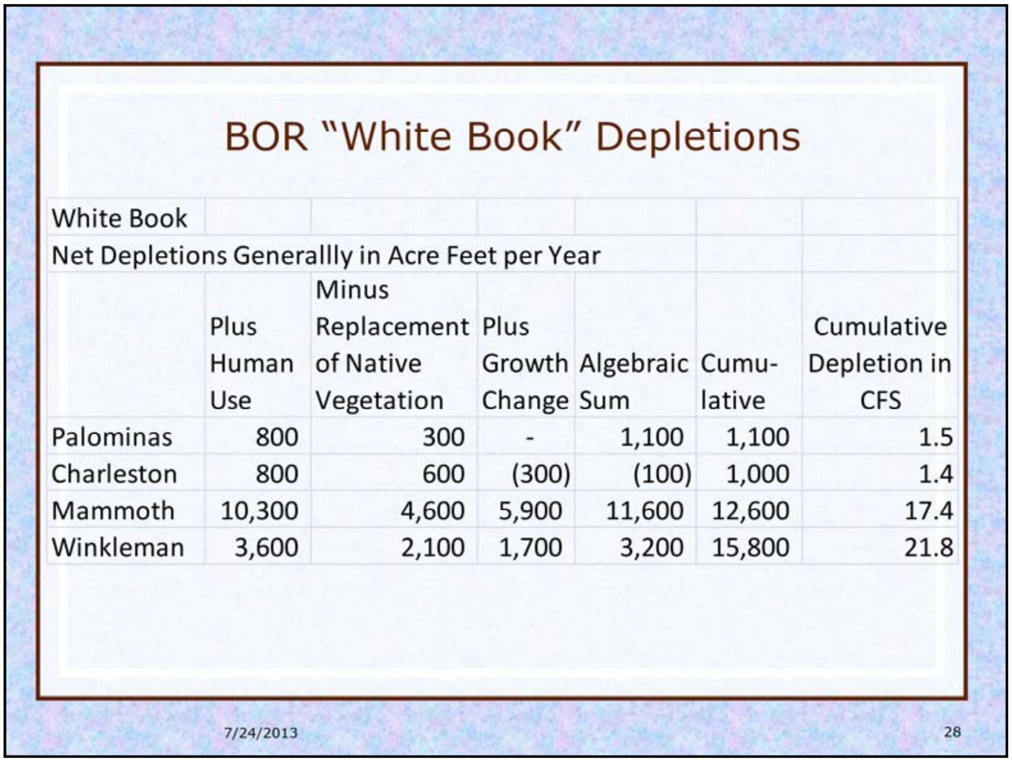
- 1914-1945 Close to Arizona Statehood
- Groundwater pumping is small
- Vegetative changes are not as extensive
- Fewer human uses
- More information was available on early uses at the time the report was written
- Over 1 million hours involved in producing it

Source: U.S. Bureau of Reclamation



Bureau of Reclamation- White Book

- BOR accounts for replacement of native vegetation
- BOR accounts for human induced riparian vegetation change
- BOR accounts for M&I use
- BOR accounts for irrigated acreage year by year



BOR “White Book” Depletions

White Book						
Net Depletions Generallly in Acre Feet per Year						
	Plus Human Use	Minus Replacement of Native Vegetation	Plus Growth Change	Algebraic Sum	Cumu-lative	Cumulative Depletion in CFS
Palominas	800	300	-	1,100	1,100	1.5
Charleston	800	600	(300)	(100)	1,000	1.4
Mammoth	10,300	4,600	5,900	11,600	12,600	17.4
Winkleman	3,600	2,100	1,700	3,200	15,800	21.8

7/24/2013

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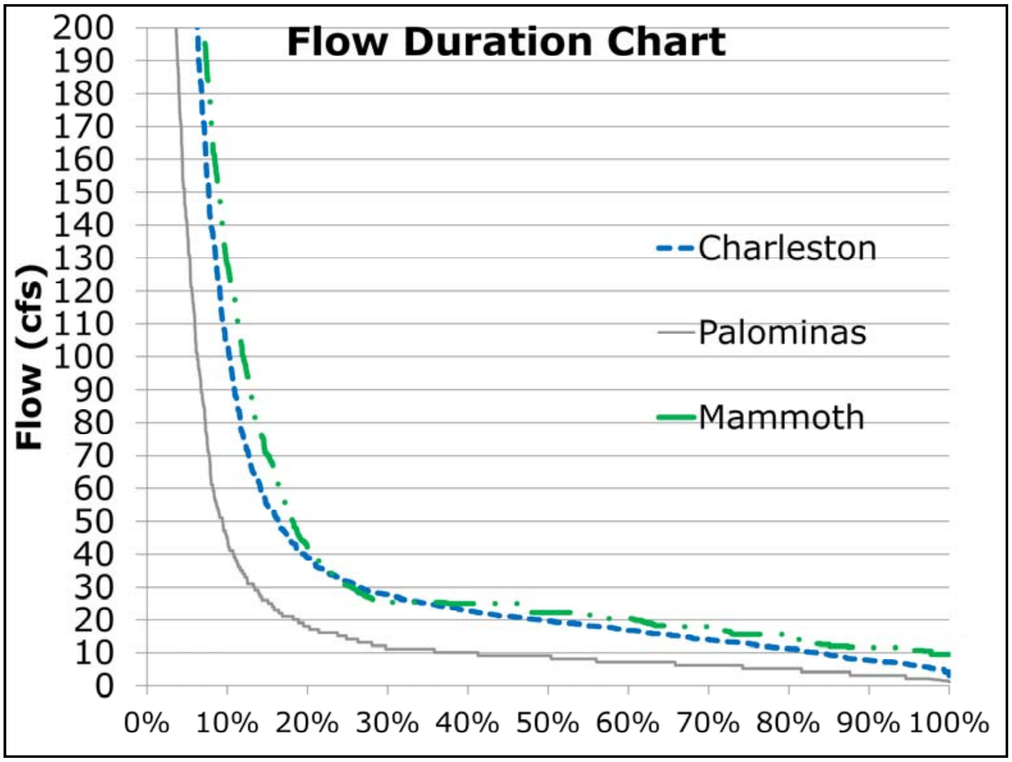
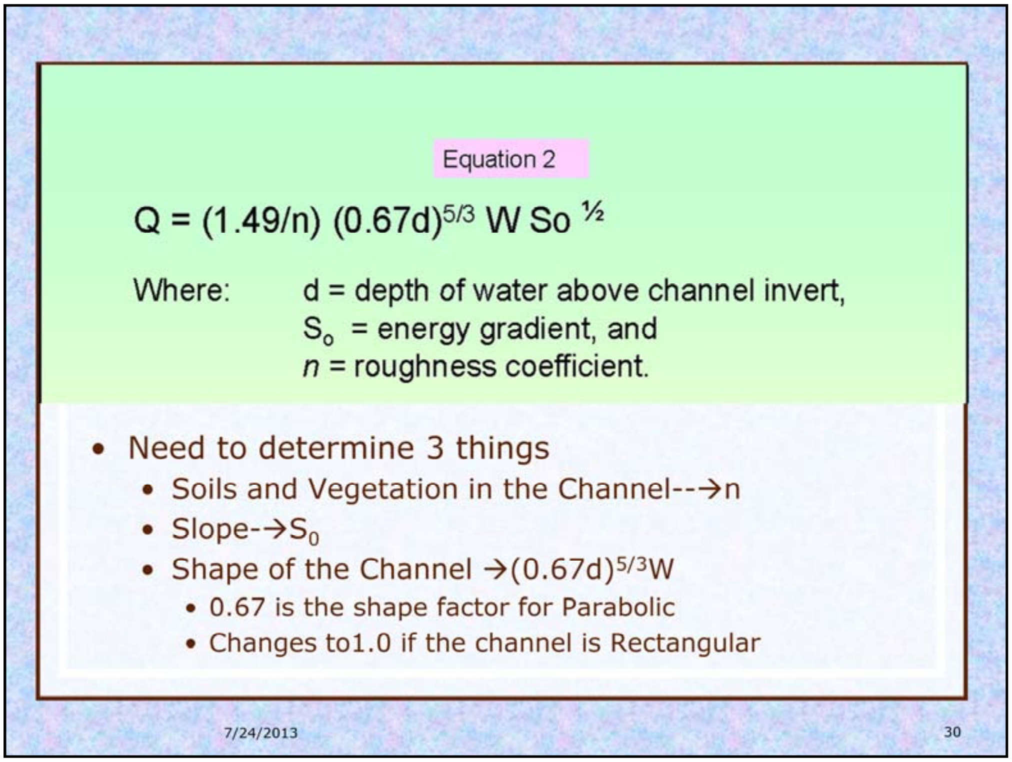
The Winkleman watershed was calculated separately for depletions. Those depletions were added to those of other watersheds for use at Kelvin due to there not being a gage at Winkleman during the period.


Flow Duration Chart
Flow (cfs)
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Charleston
Palominas
Mammoth



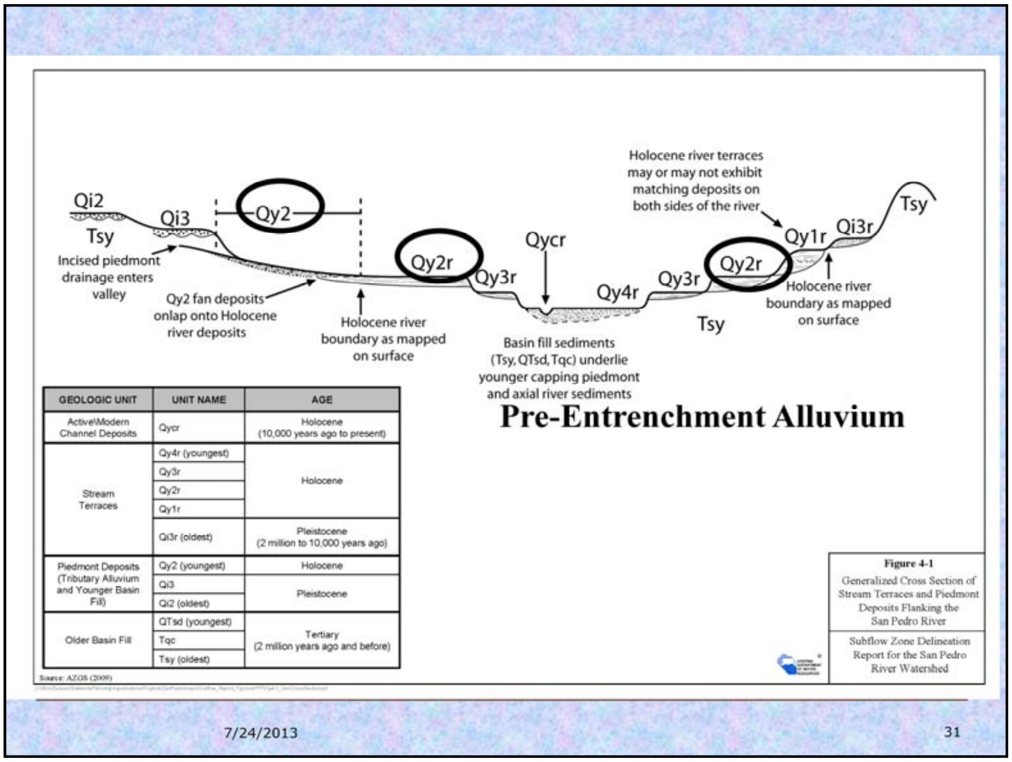
Equation 2

$$Q = (1.49/n)\,(0.67d)^{5/3}\,W\,So^{1/2}$$

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

- Need to determine 3 things
  - Soils and Vegetation in the Channel--→n
  - Slope-→S_0
  - Shape of the Channel →$(0.67d)^{5/3}W$
    - 0.67 is the shape factor for Parabolic
    - Changes to1.0 if the channel is Rectangular

Source of equation: Burkham



Holocene river terraces may or may not exhibit matching deposits on both sides of the river

Incised piedmont drainage enters valley

Qy2 fan deposits onlap onto Holocene river deposits

Holocene river boundary as mapped on surface

Basin fill sediments (Tsy, QTsd, Tqc) underlie younger capping piedmont and axial river sediments

Holocene river boundary as mapped on surface

Pre-Entrenchment Alluvium

GEOLOGIC UNIT	UNIT NAME	AGE
Active\Modern Channel Deposits	Qycr	Holocene (10,000 years ago to present)
Stream Terraces	Qy4r (youngest)	Holocene
	Qy3r	
	Qy2r	
	Qy1r	
	Qi3r (oldest)	Pleistocene (2 million to 10,000 years ago)
Piedmont Deposits (Tributary Alluvium and Younger Basin Fill)	Qy2 (youngest)	Holocene
	Qi3	Pleistocene
	Qi2 (oldest)	
Older Basin Fill	QTsd (youngest)	Tertiary (2 million years ago and before)
	Tqc	
	Tsy (oldest)	

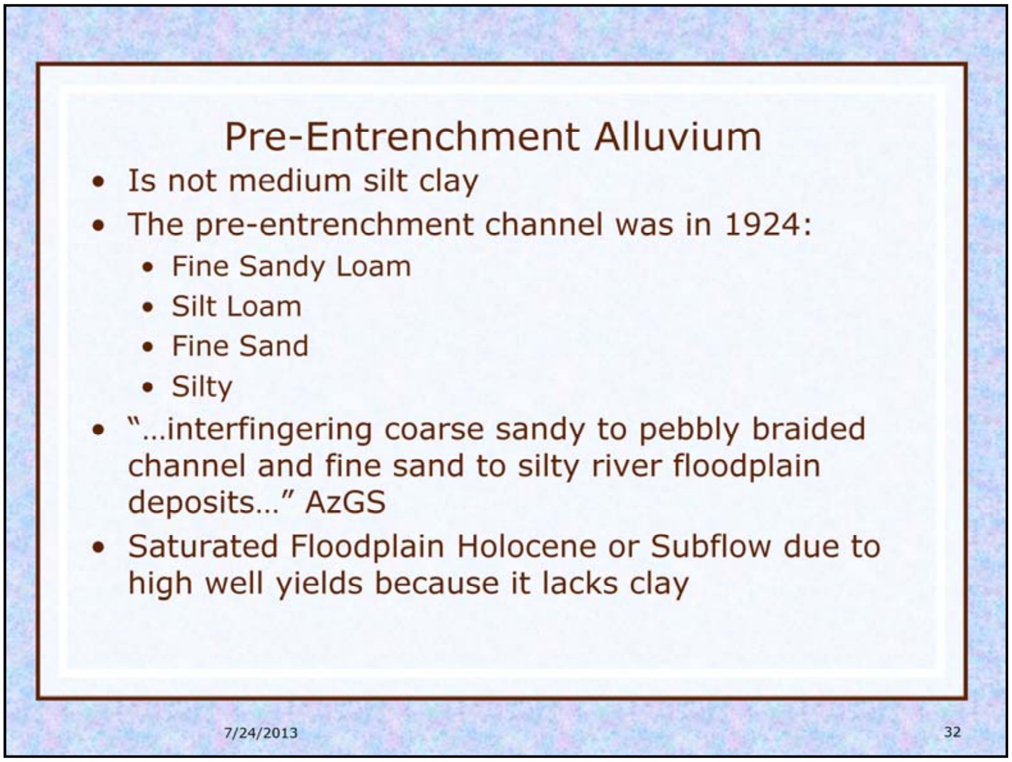
Source: AZGS (2009)

Figure 4-1

Generalized Cross Section of Stream Terraces and Piedmont Deposits Flanking the San Pedro River

Subflow Zone Delineation Report for the San Pedro River Watershed

Source: ADWR Fig 4-1



Pre-Entrenchment Alluvium

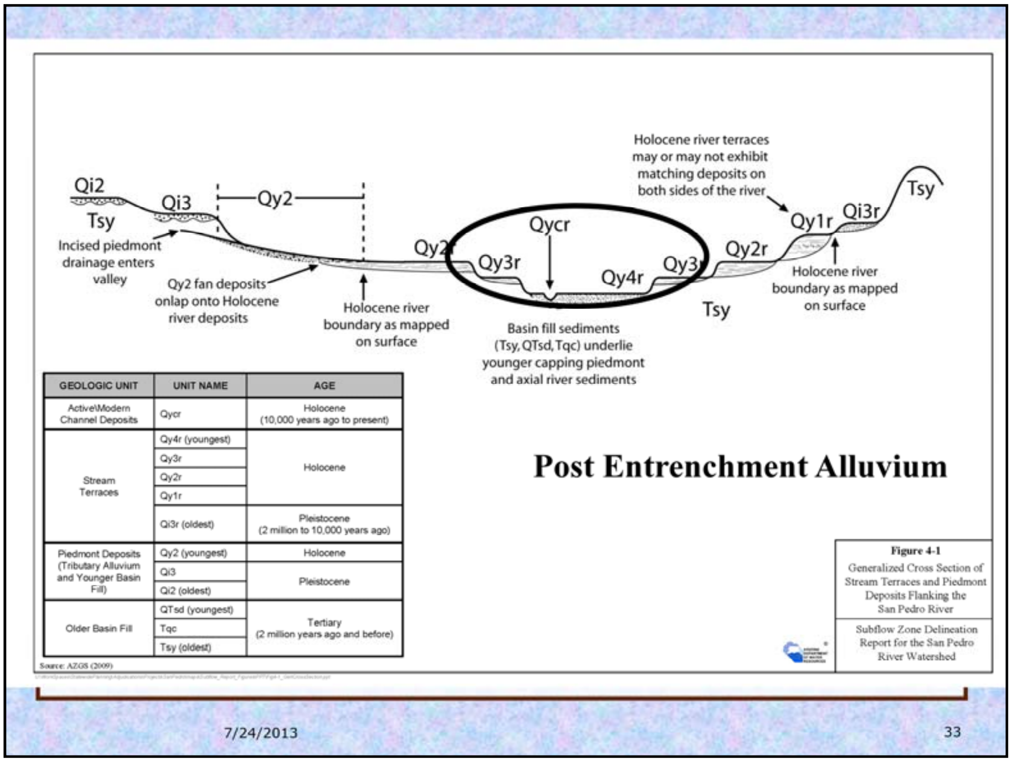
- Is not medium silt clay
- The pre-entrenchment channel was in 1924:
  - Fine Sandy Loam
  - Silt Loam
  - Fine Sand
  - Silty
- "…interfingering coarse sandy to pebbly braided channel and fine sand to silty river floodplain deposits…" AzGS
- Saturated Floodplain Holocene or Subflow due to high well yields because it lacks clay

7/24/2013

Source: Carpenter and Bransford pg 254, 271-2

Source: ADWR App C pg 43

See Appendix A - Pre-Entrenchment Soils



Post Entrenchment Alluvium

GEOLOGIC UNIT	UNIT NAME	AGE
Active\Modern Channel Deposits	Qycr	Holocene (10,000 years ago to present)
Stream Terraces	Qy4r (youngest)	Holocene
	Qy3r	
	Qy2r	
	Qy1r	
	Qi3r (oldest)	Pleistocene (2 million to 10,000 years ago)
Piedmont Deposits (Tributary Alluvium and Younger Basin Fill)	Qy2 (youngest)	Holocene
	Qi3	Pleistocene
	Qi2 (oldest)	
Older Basin Fill	QTsd (youngest)	Tertiary (2 million years ago and before)
	Tqc	
	Tsy (oldest)	

Source: AZGS (2009)

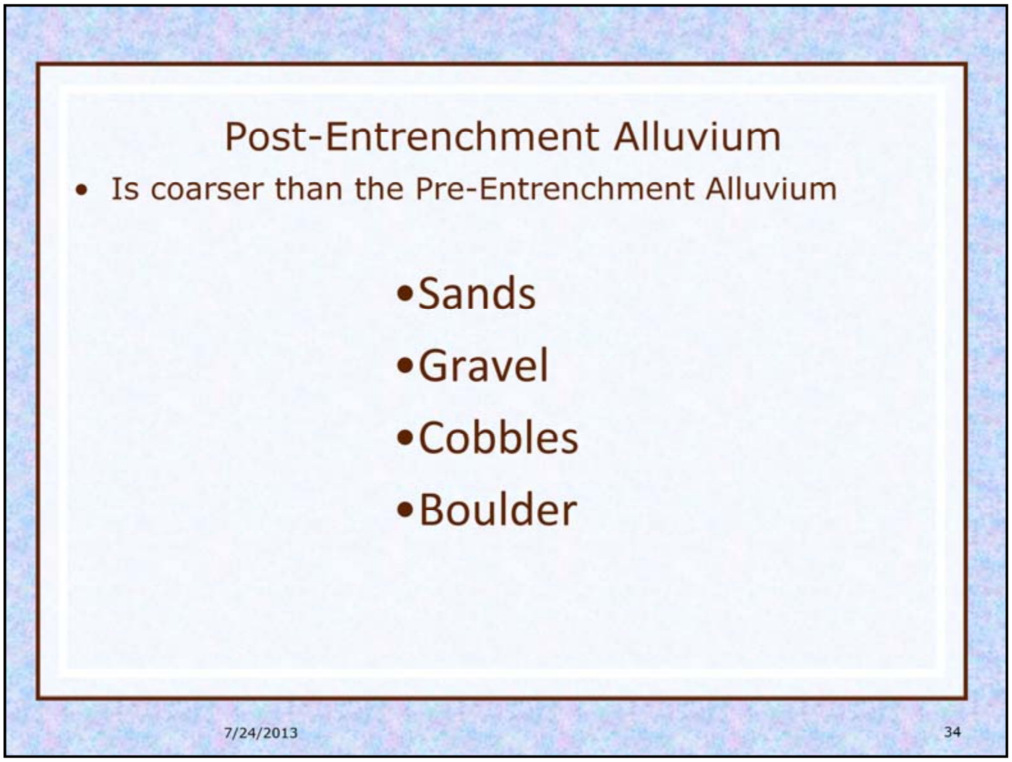
Figure 4-1
Generalized Cross Section of Stream Terraces and Piedmont Deposits Flanking the San Pedro River

Subflow Zone Delineation Report for the San Pedro River Watershed

7/24/2013

33

Source: ADWR Figure 4-1

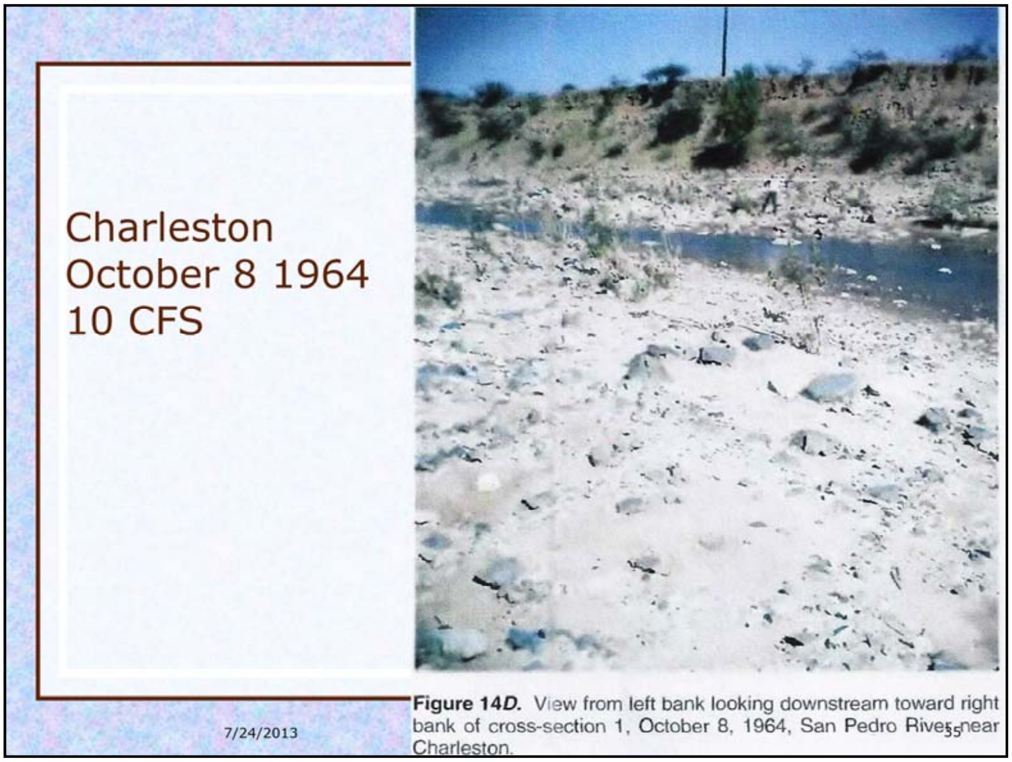


Post-Entrenchment Alluvium

- Is coarser than the Pre-Entrenchment Alluvium

- Sands
- Gravel
- Cobbles
- Boulder

See Appendix A – Post-Entrenchment Soils

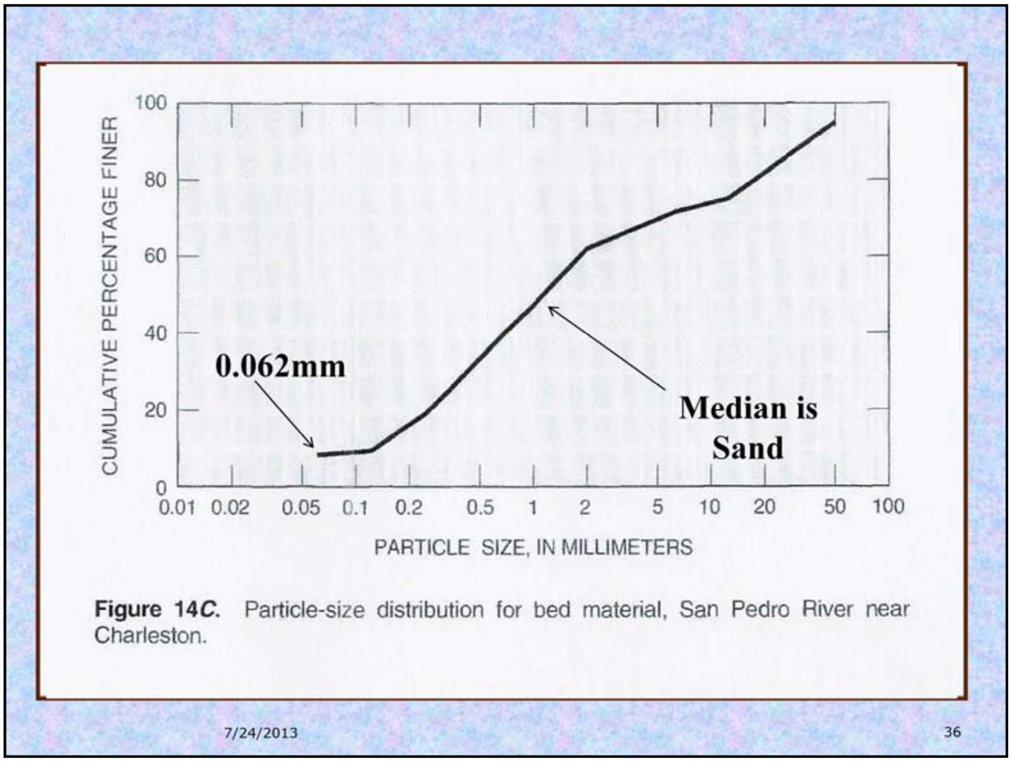


Charleston
October 8 1964
10 CFS

Figure 14*D*. View from left bank looking downstream toward right bank of cross-section 1, October 8, 1964, San Pedro River near Charleston.

7/24/2013

Source: Beaulieu et. al. pg 57



0.062mm

Median is Sand

Figure 14*C*. Particle-size distribution for bed material, San Pedro River near Charleston.

Source: Beaulieu et. al. pg 57

Soils .062mm or less are required for silty clay

Source: Osterkamp 1980 pg 190

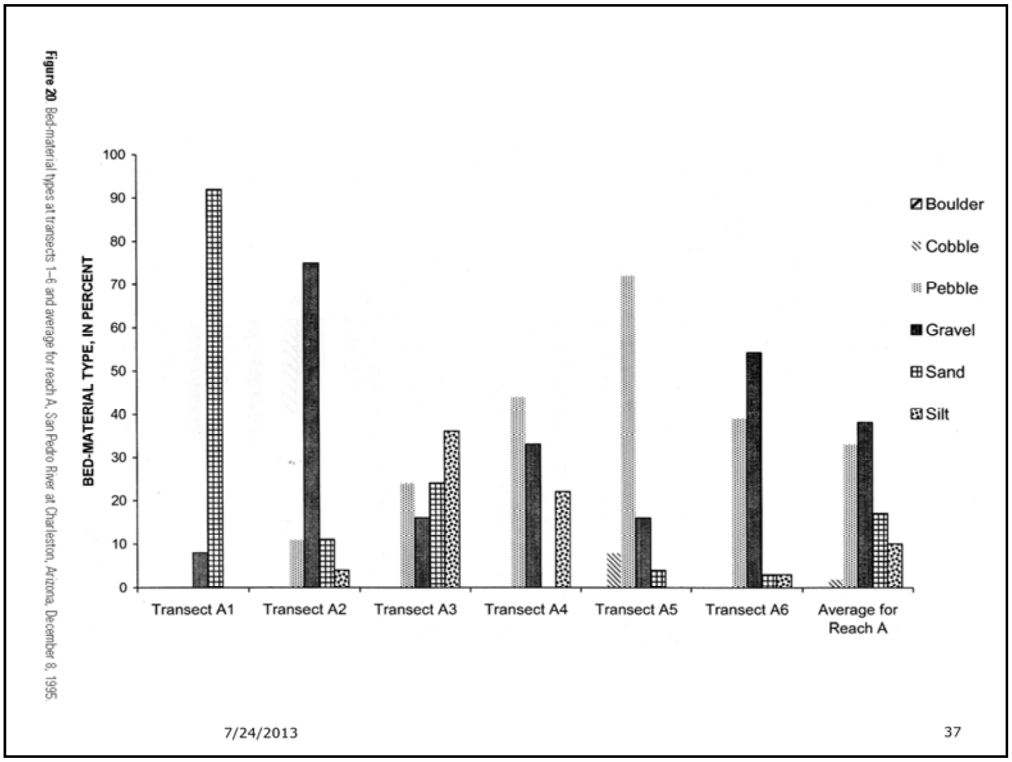
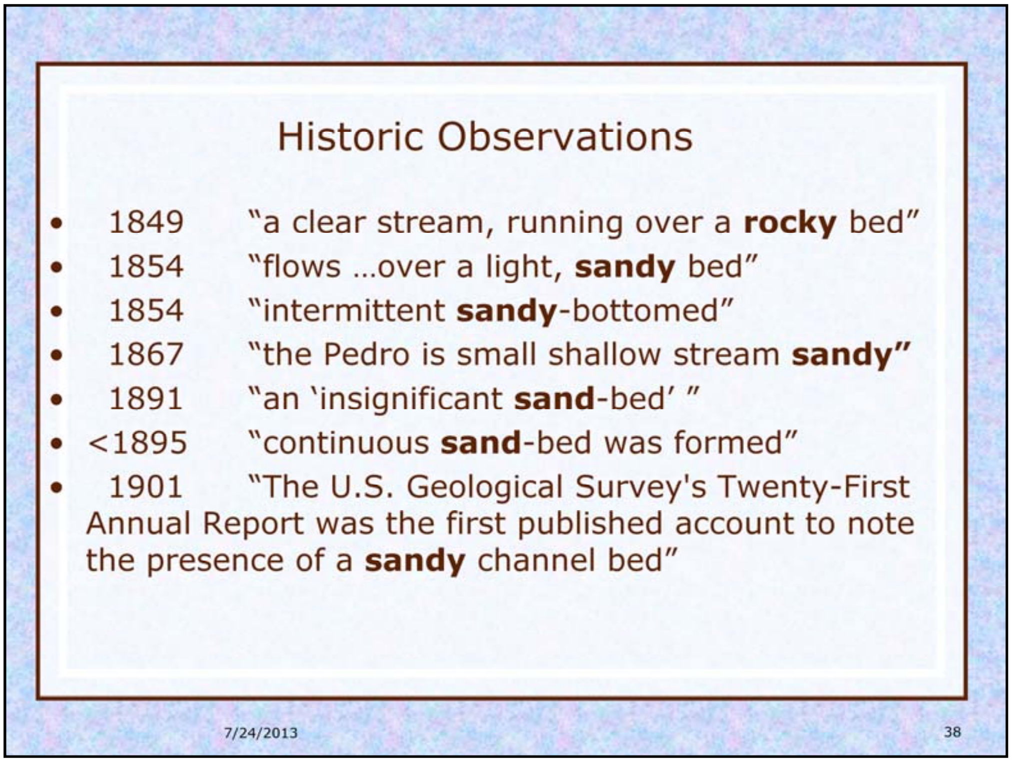


Figure 20. Bed-material types at transects 1–6 and average for reach A, San Pedro River at Charleston, Arizona, December 8, 1995.

7/24/2013

Source: Beaulieu et. al. pg 41



Historic Observations

- 1849 “a clear stream, running over a **rocky** bed”
- 1854 “flows …over a light, **sandy** bed”
- 1854 “intermittent **sandy**-bottomed”
- 1867 “the Pedro is small shallow stream **sandy”**
- 1891 “an ‘insignificant **sand**-bed’ ”
- <1895 “continuous **sand**-bed was formed”
- 1901 “The U.S. Geological Survey's Twenty-First Annual Report was the first published account to note the presence of a **sandy** channel bed”

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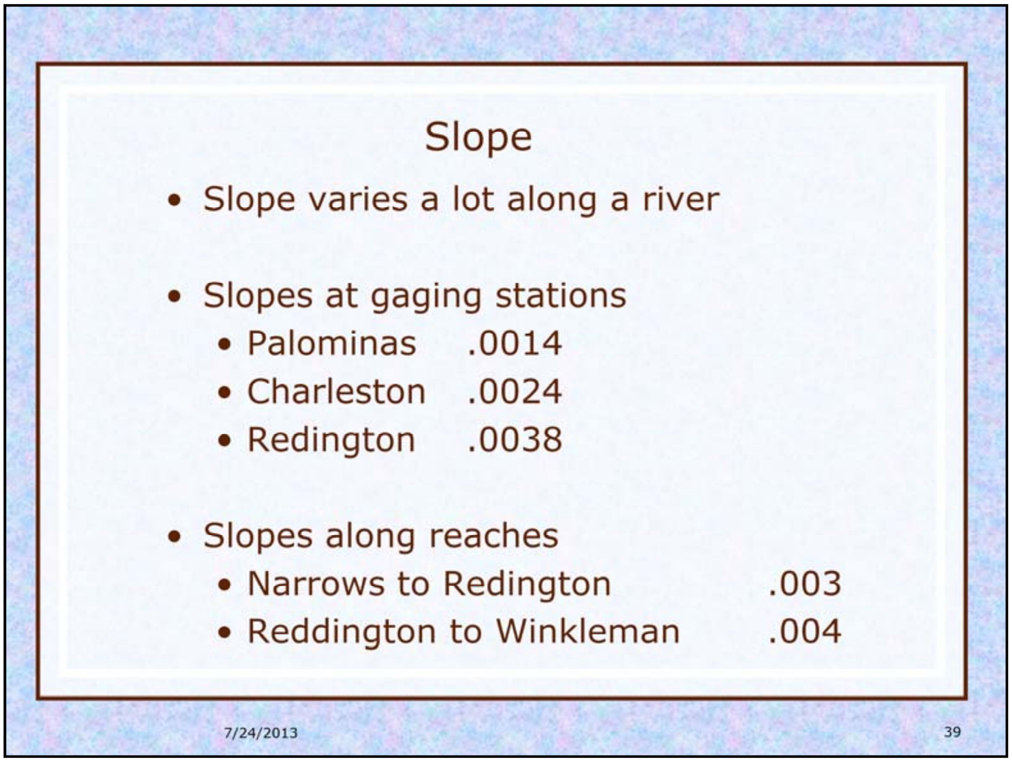
1849	Source: Fuller pg 3-15
1854 (1st)	Source: Fuller pg 3-17
1854 (2nd)	Source: NRCS pg 14
1867	Source: Dobyns 1995 pg 32
1891	Source: Fuller pg 3-19
<1895	Source: Wood pg 23
1901	Source: Wood pg 22

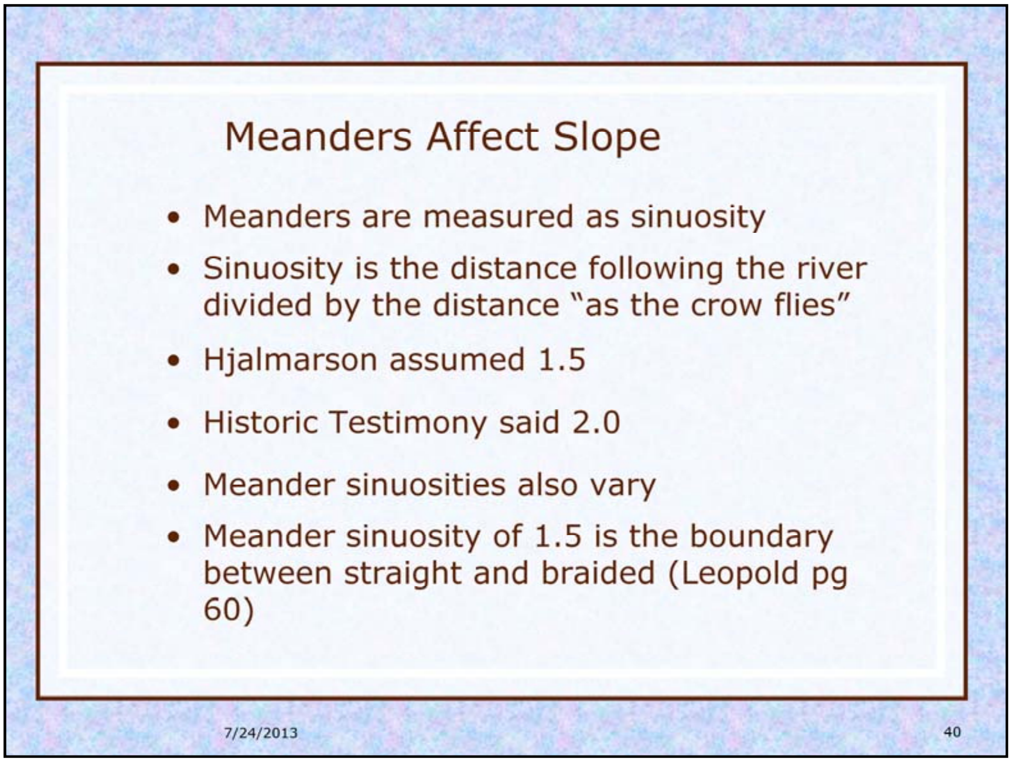


Slope

- Slope varies a lot along a river
- Slopes at gaging stations
  - Palominas .0014
  - Charleston .0024
  - Redington .0038
- Slopes along reaches
  - Narrows to Redington .003
  - Reddington to Winkleman .004

Source: Osterkamp et. al., 1982 Table 1 for gaging stations

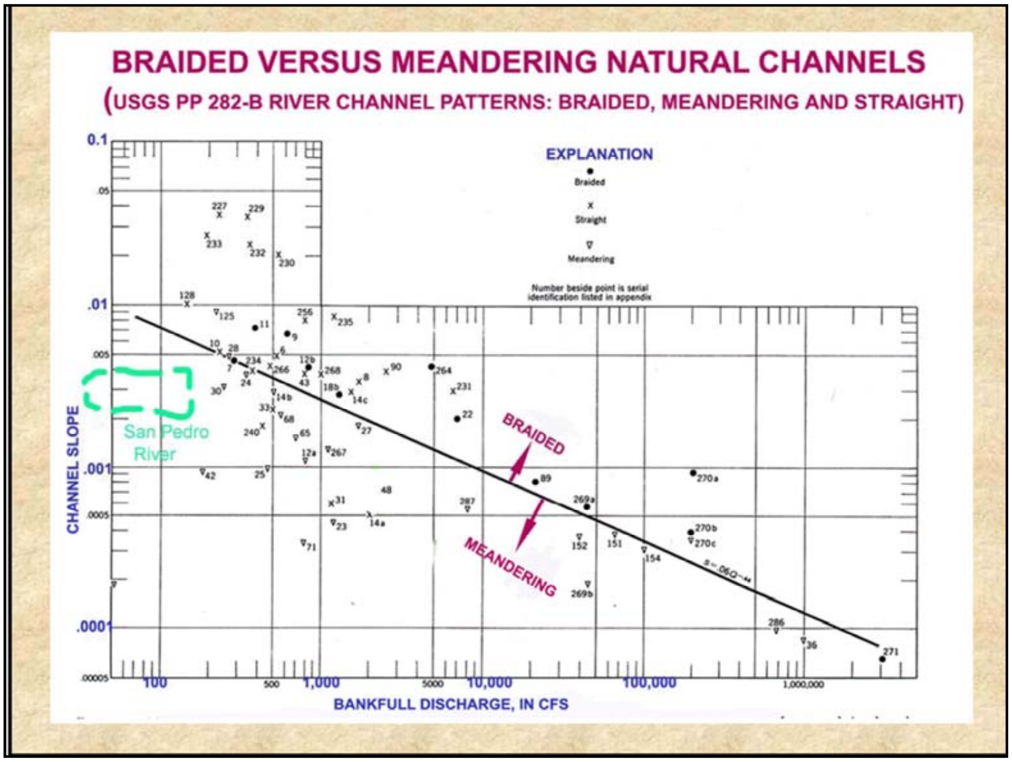
Source: Fuller pg 5-8 for reaches



Meanders Affect Slope

- Meanders are measured as sinuosity
- Sinuosity is the distance following the river divided by the distance "as the crow flies"
- Hjalmarson assumed 1.5
- Historic Testimony said 2.0
- Meander sinuosities also vary
- Meander sinuosity of 1.5 is the boundary between straight and braided (Leopold pg 60)

Source: Dobyns 1995 pg 22-23 for Historic Testimony



BRAIDED VERSUS MEANDERING NATURAL CHANNELS

(USGS PP 282-B RIVER CHANNEL PATTERNS: BRAIDED, MEANDERING AND STRAIGHT)

Source: Hjalmarson 2013 slide 106

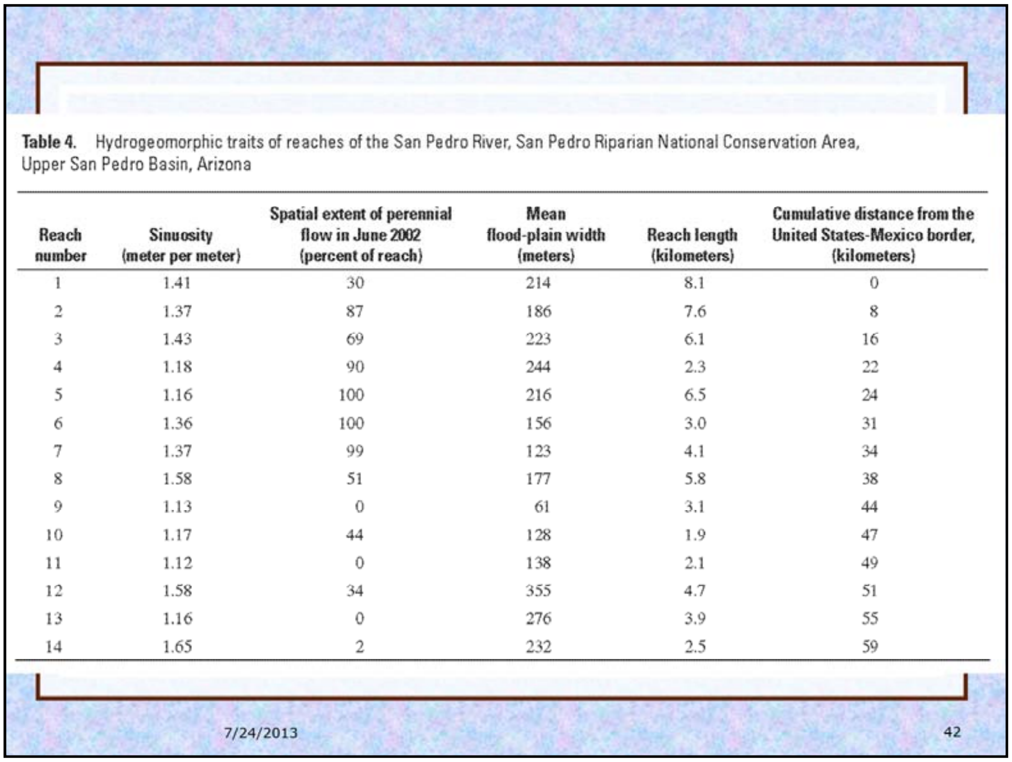
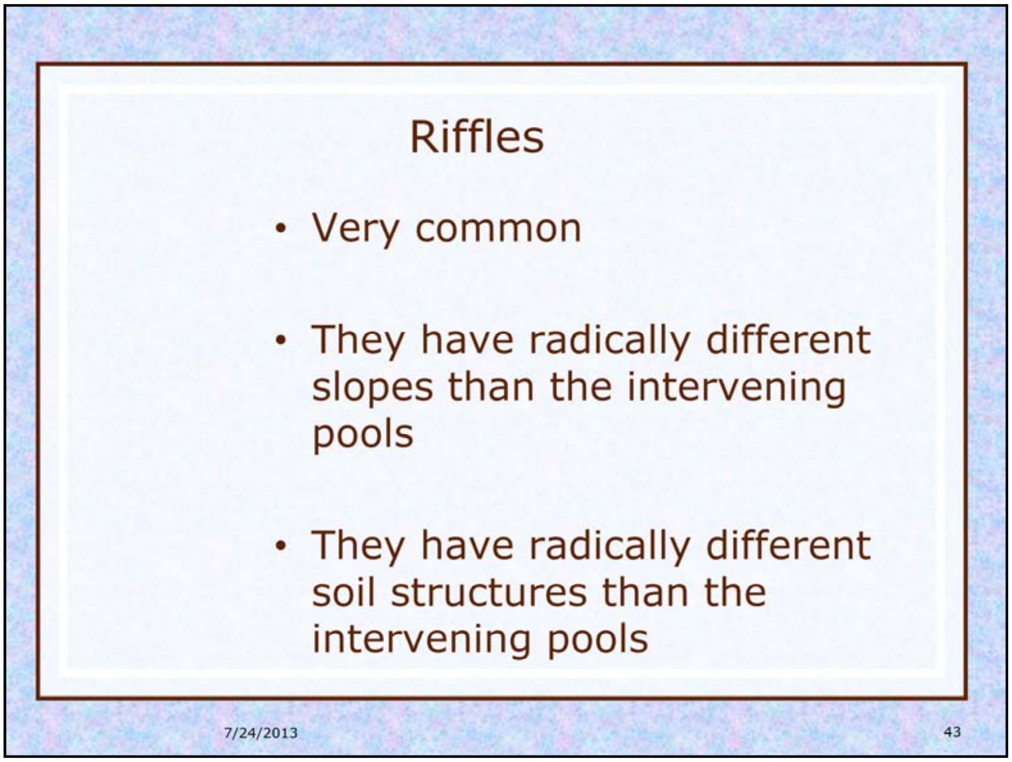


Table 4. Hydrogeomorphic traits of reaches of the San Pedro River, San Pedro Riparian National Conservation Area, Upper San Pedro Basin, Arizona

Reach number	Sinuosity (meter per meter)	Spatial extent of perennial flow in June 2002 (percent of reach)	Mean flood-plain width (meters)	Reach length (kilometers)	Cumulative distance from the United States-Mexico border, (kilometers)
1	1.41	30	214	8.1	0
2	1.37	87	186	7.6	8
3	1.43	69	223	6.1	16
4	1.18	90	244	2.3	22
5	1.16	100	216	6.5	24
6	1.36	100	156	3.0	31
7	1.37	99	123	4.1	34
8	1.58	51	177	5.8	38
9	1.13	0	61	3.1	44
10	1.17	44	128	1.9	47
11	1.12	0	138	2.1	49
12	1.58	34	355	4.7	51
13	1.16	0	276	3.9	55
14	1.65	2	232	2.5	59

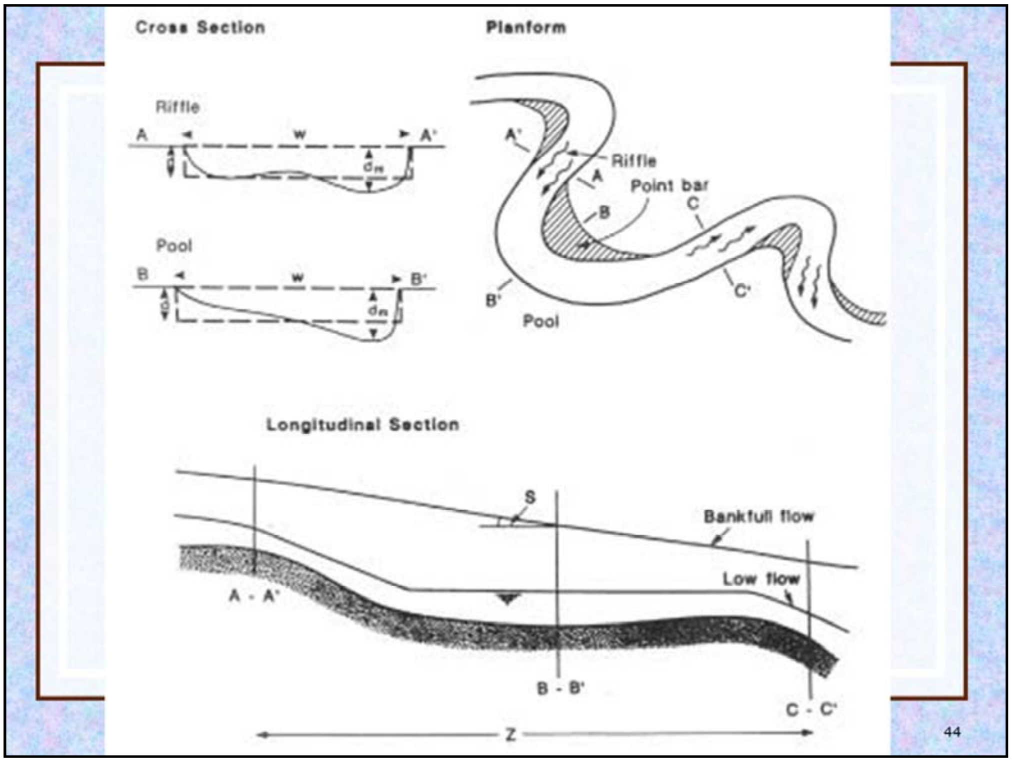
Source: Leenhouts, et.al. pg 18



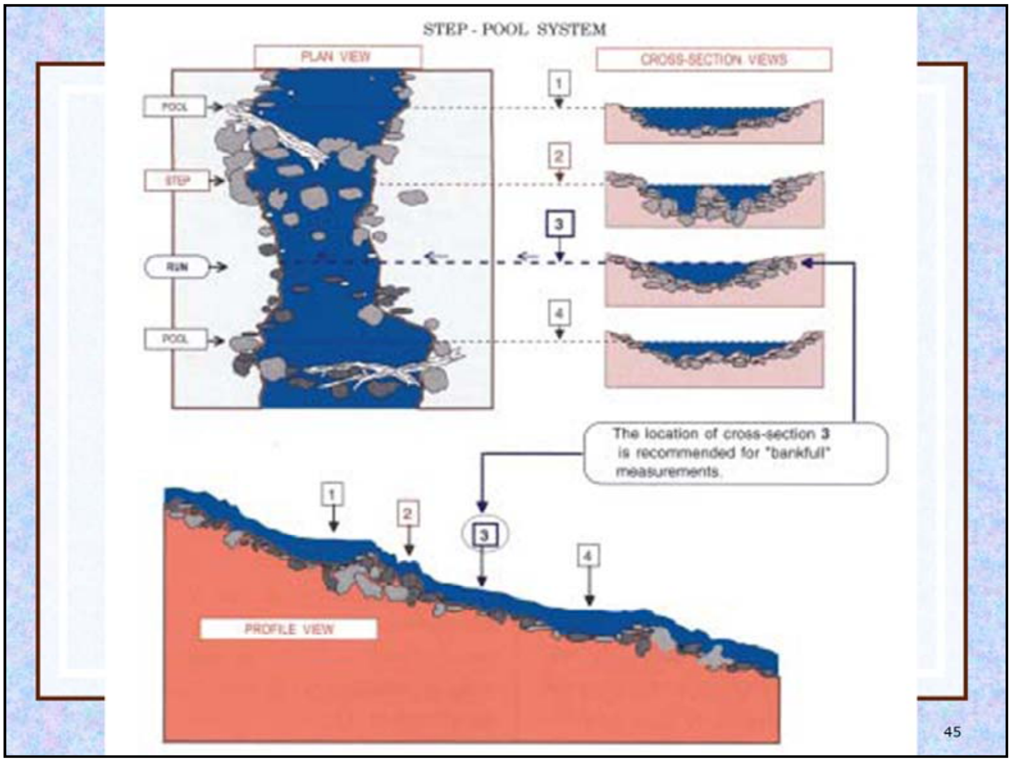
Riffles

- Very common
- They have radically different slopes than the intervening pools
- They have radically different soil structures than the intervening pools

See Appendix A - Riffles



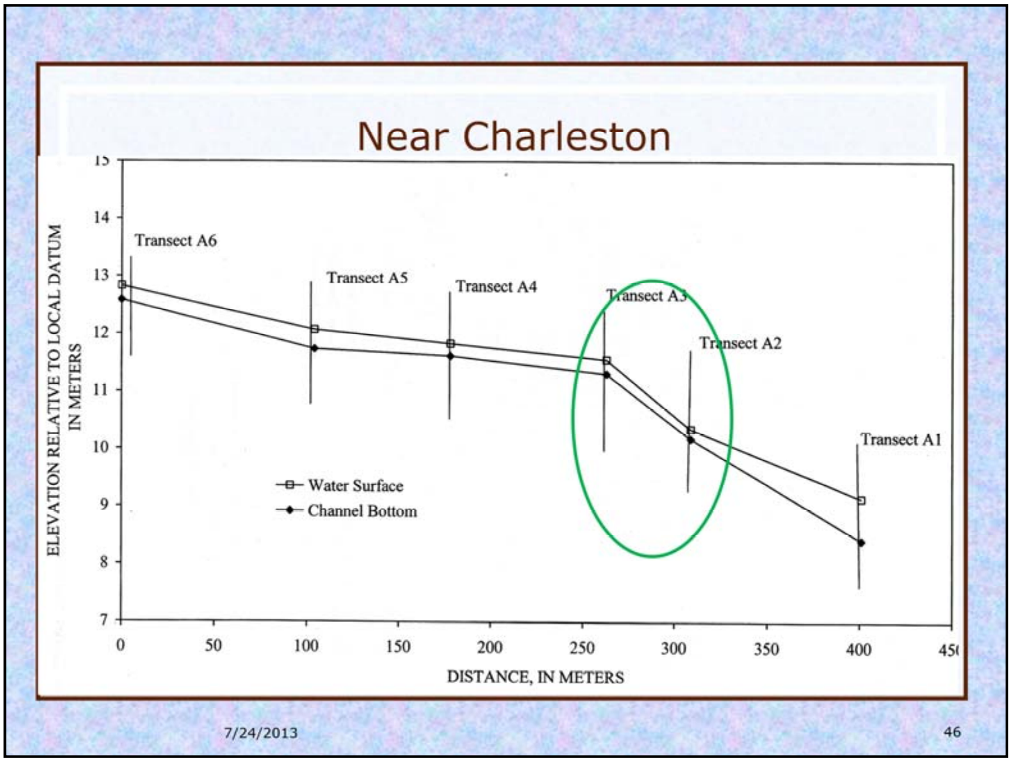
Source: N. Carolina Stream Restoration Institute pg 11



STEP - POOL SYSTEM

The location of cross-section **3** is recommended for "bankfull" measurements.

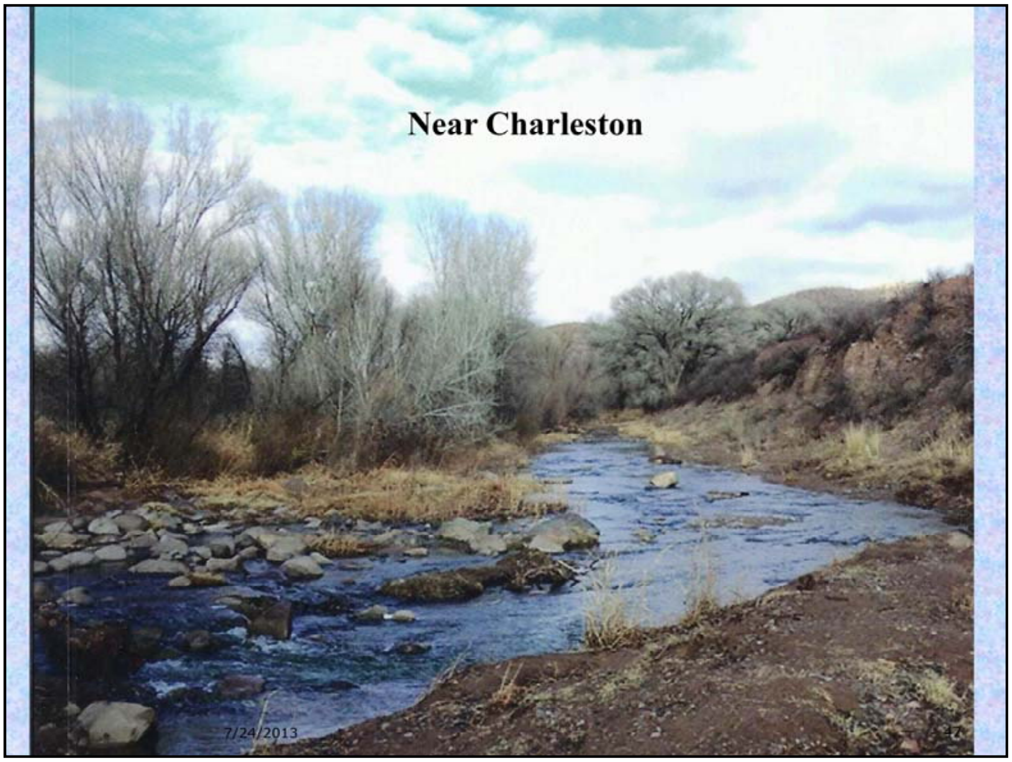
Source: N. Carolina Stream Restoration Institute pg 11



Near Charleston

7/24/2013

Source: Beaulieu et.al. pg 34

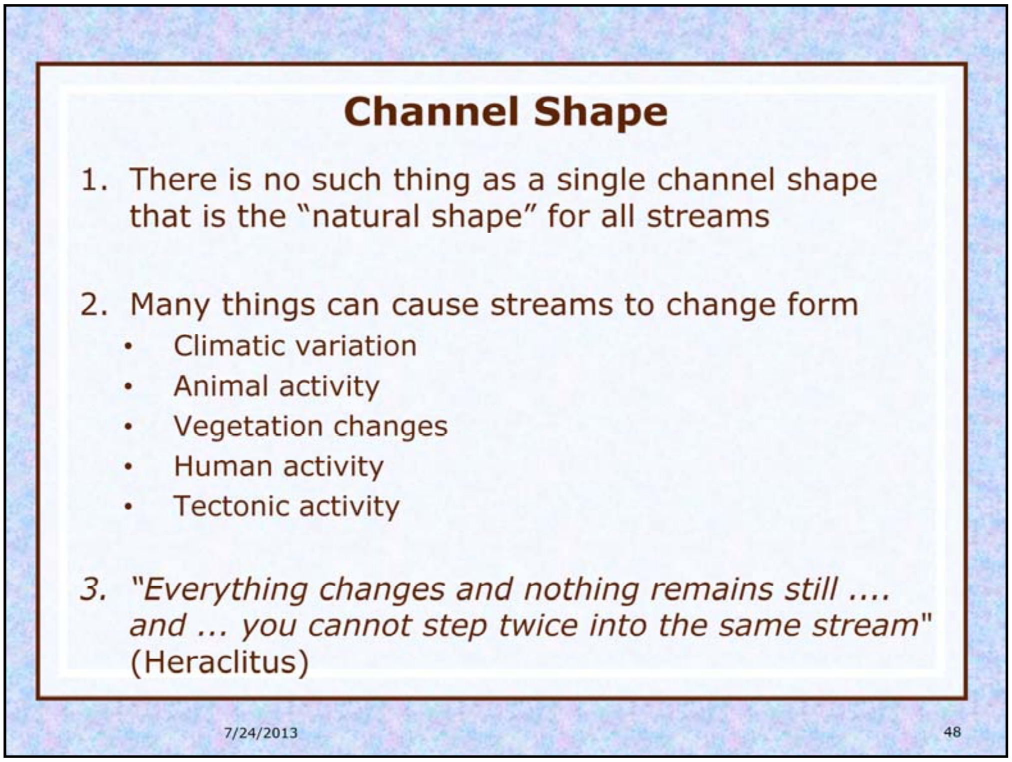


Near Charleston

7/24/2013

17

Source: Rose Cover Photo, no date of photo provided



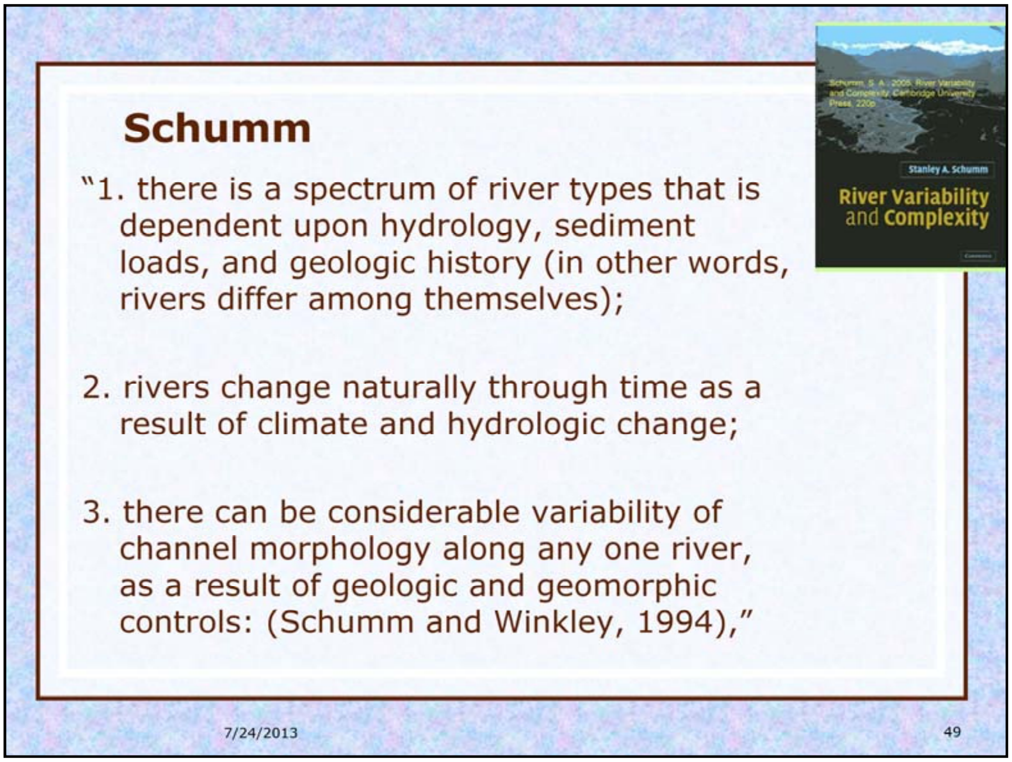
Channel Shape

1. There is no such thing as a single channel shape that is the "natural shape" for all streams

2. Many things can cause streams to change form
   - Climatic variation
   - Animal activity
   - Vegetation changes
   - Human activity
   - Tectonic activity

3. *"Everything changes and nothing remains still .... and ... you cannot step twice into the same stream"* (Heraclitus)

See Appendix A - River Variability



Schumm, S. A., 2005, River Variability and Complexity, Cambridge University Press, 220p.

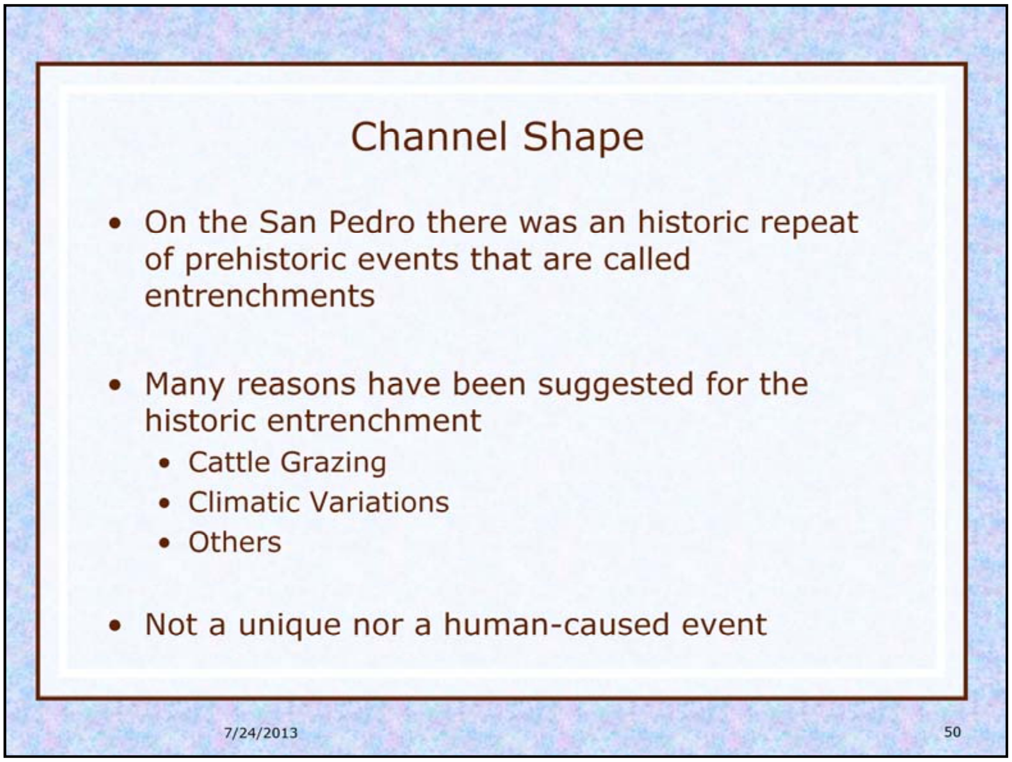
Schumm

"1. there is a spectrum of river types that is dependent upon hydrology, sediment loads, and geologic history (in other words, rivers differ among themselves);

2. rivers change naturally through time as a result of climate and hydrologic change;

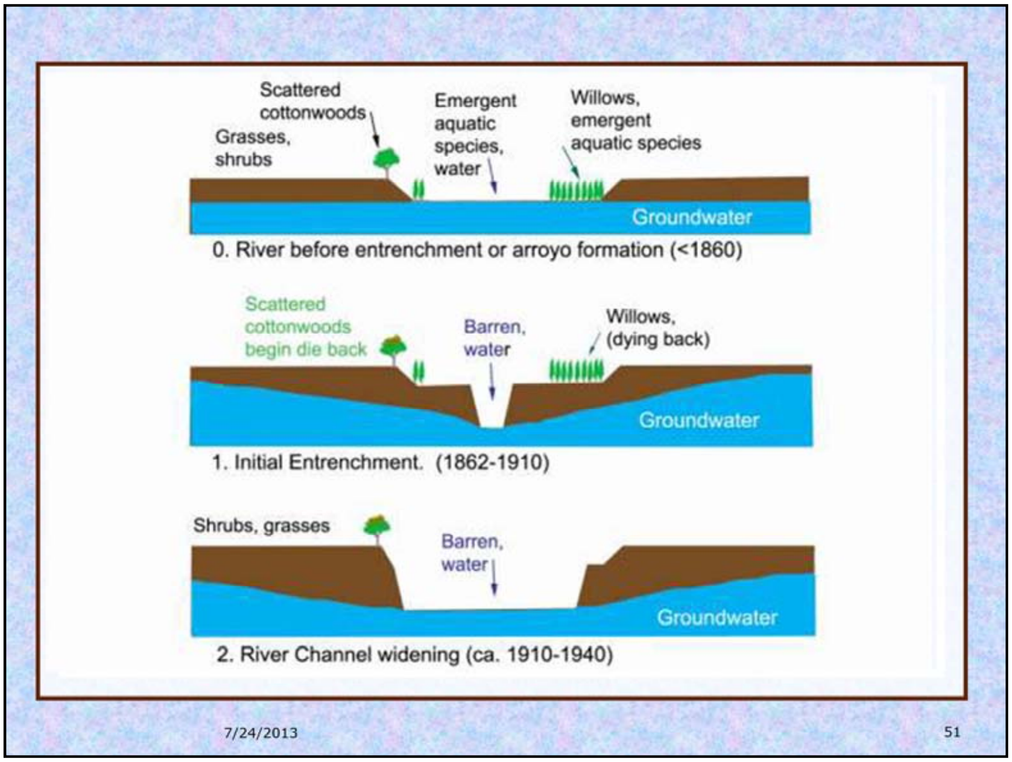
3. there can be considerable variability of channel morphology along any one river, as a result of geologic and geomorphic controls: (Schumm and Winkley, 1994),"

Source: Schumm pg 4



Channel Shape

- On the San Pedro there was an historic repeat of prehistoric events that are called entrenchments
- Many reasons have been suggested for the historic entrenchment
  - Cattle Grazing
  - Climatic Variations
  - Others
- Not a unique nor a human-caused event

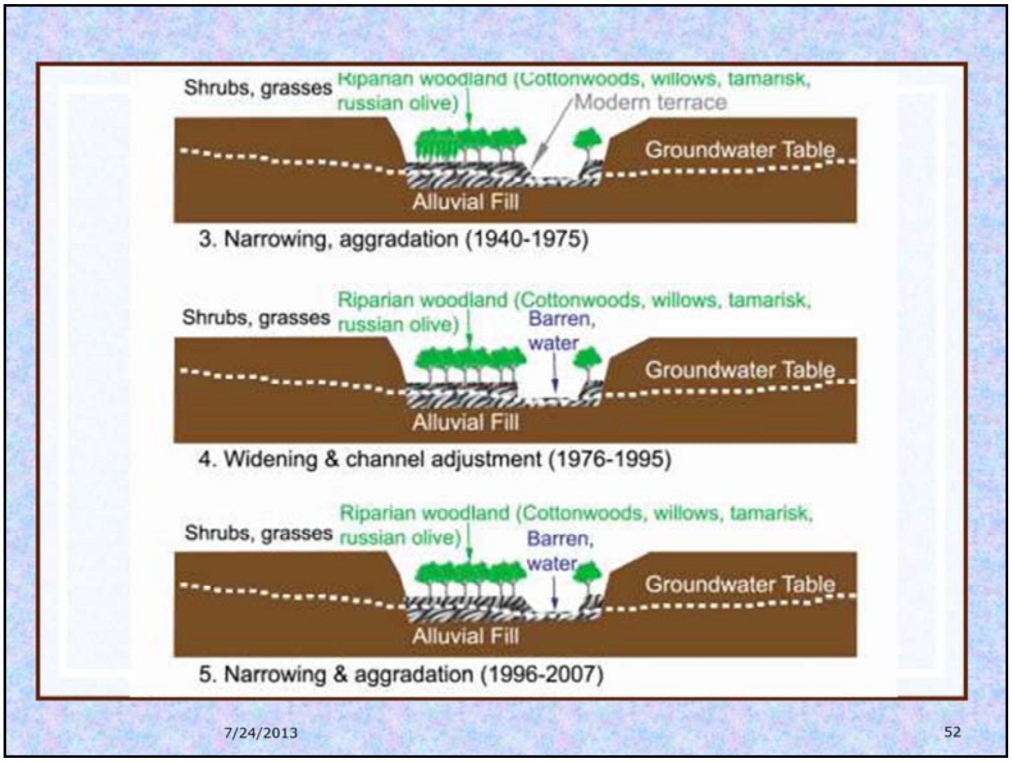


0. River before entrenchment or arroyo formation (<1860)

1. Initial Entrenchment. (1862-1910)

2. River Channel widening (ca. 1910-1940)

Source: Noonan pg 53

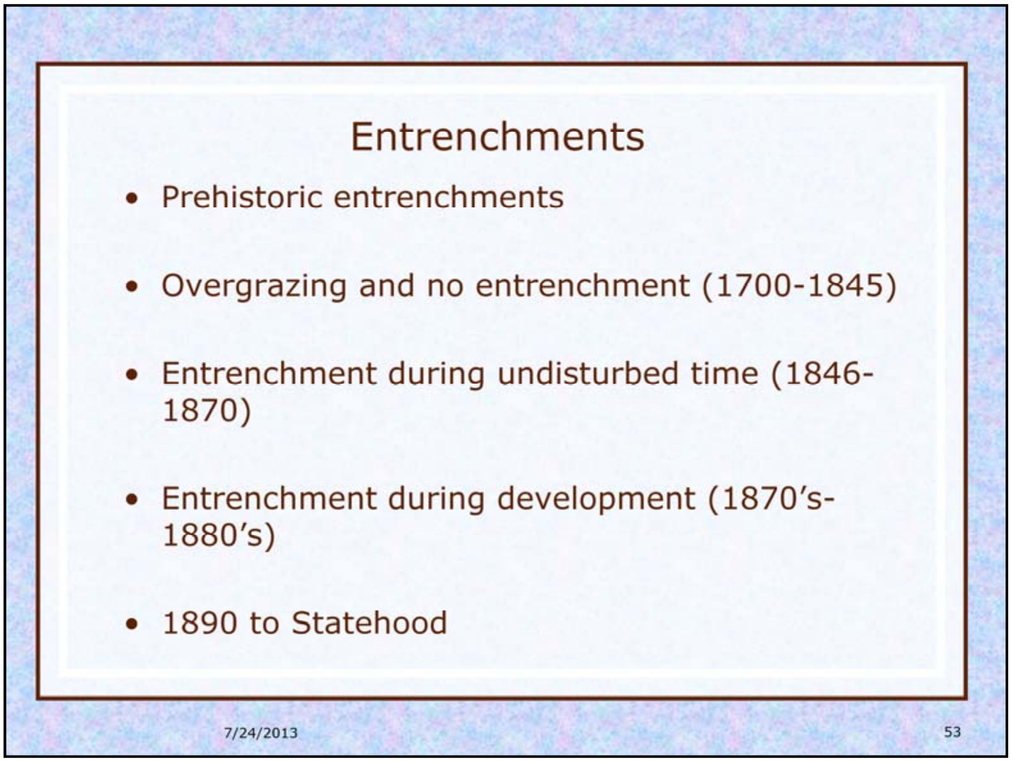


3. Narrowing, aggradation (1940-1975)

4. Widening & channel adjustment (1976-1995)

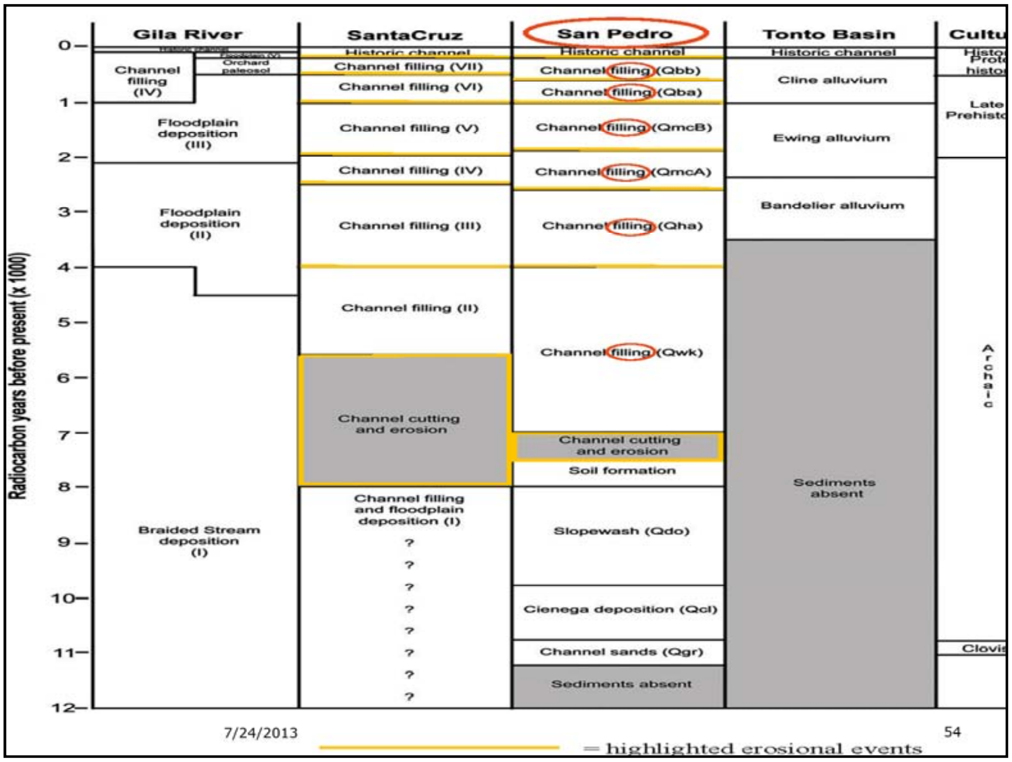
5. Narrowing & aggradation (1996-2007)

Source: Noonan pg 53



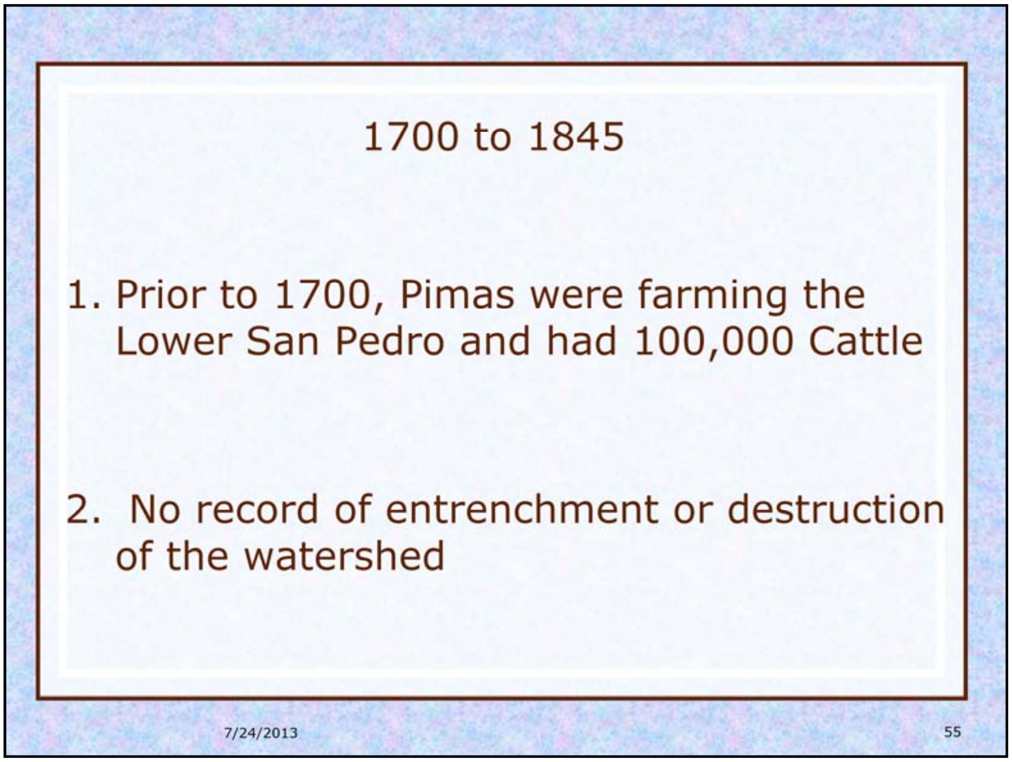
Entrenchments

- Prehistoric entrenchments
- Overgrazing and no entrenchment (1700-1845)
- Entrenchment during undisturbed time (1846-1870)
- Entrenchment during development (1870's-1880's)
- 1890 to Statehood



Source: Waters pg 338

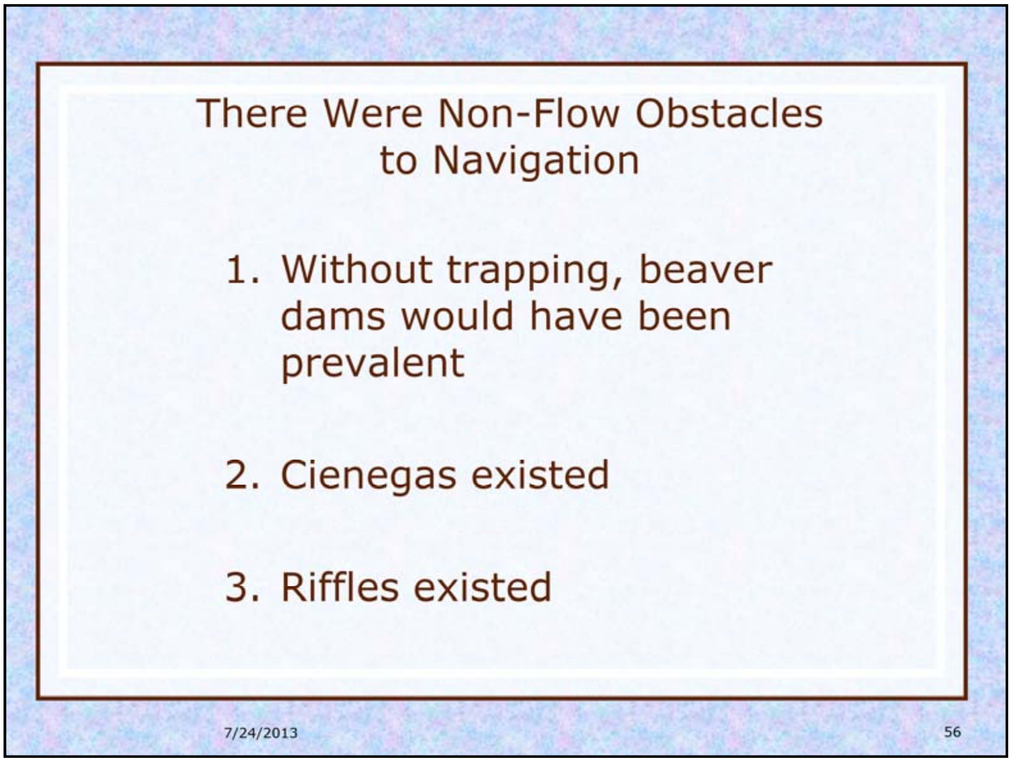
See Appendix A - Prehistoric Entrenchments



1700 to 1845

1. Prior to 1700, Pimas were farming the Lower San Pedro and had 100,000 Cattle
2. No record of entrenchment or destruction of the watershed

Source: ANSAC pg 21 & Fuller pg 3-7 for Item 1



There Were Non-Flow Obstacles to Navigation

1. Without trapping, beaver dams would have been prevalent
2. Cienegas existed
3. Riffles existed

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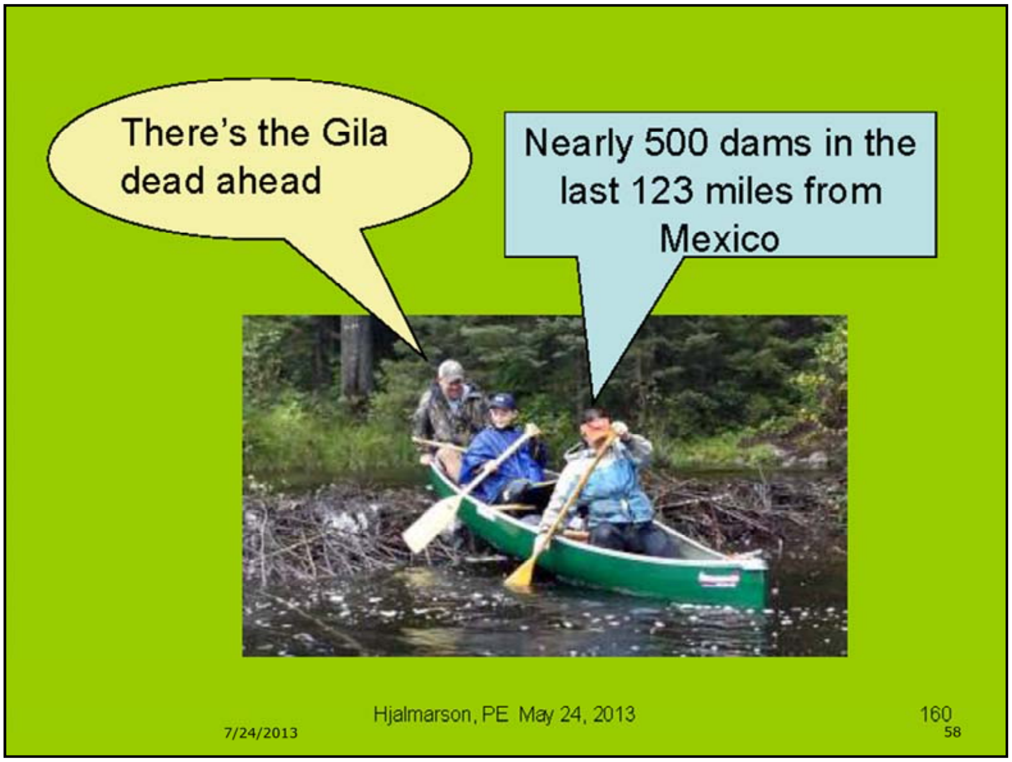
Source: Lomeli



There's the Gila dead ahead

Nearly 500 dams in the last 123 miles from Mexico

Hjalmarson, PE May 24, 2013

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7/24/2013

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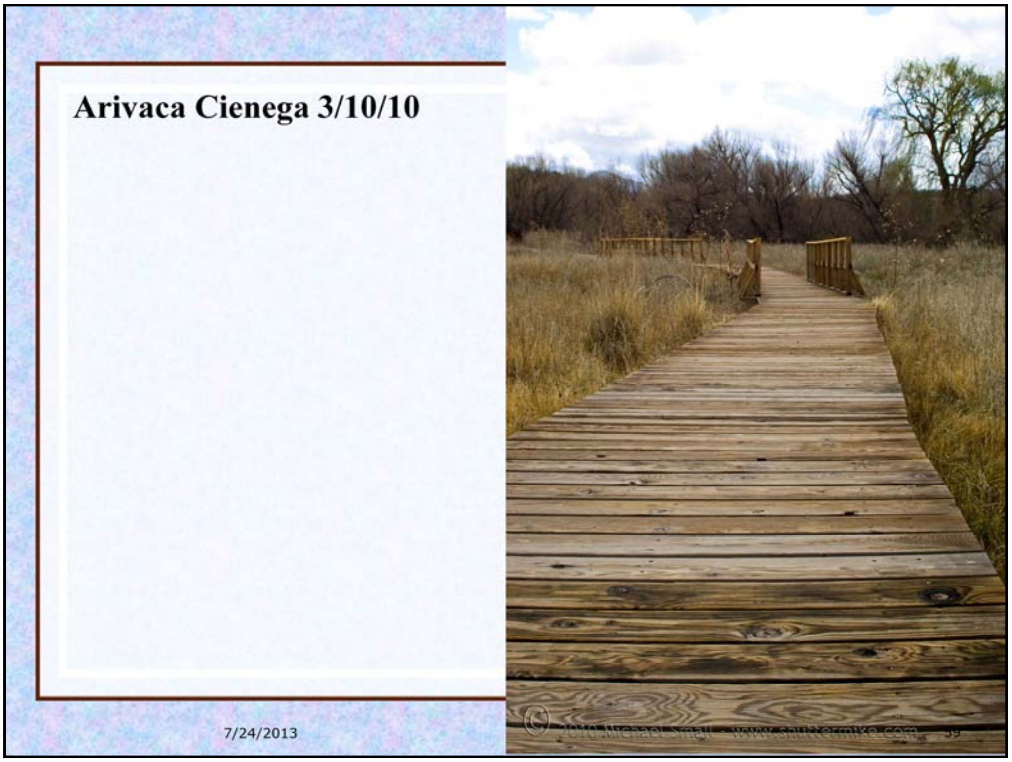
Source: Hjalmarson 2013 Slide 160

See Appendix A - Beavers
140 miles *1.6 Km per mile*.5 colonies per km = 112 dams
140 miles *1.6 Km per mile* 7.5 colonies per km=1680 dams

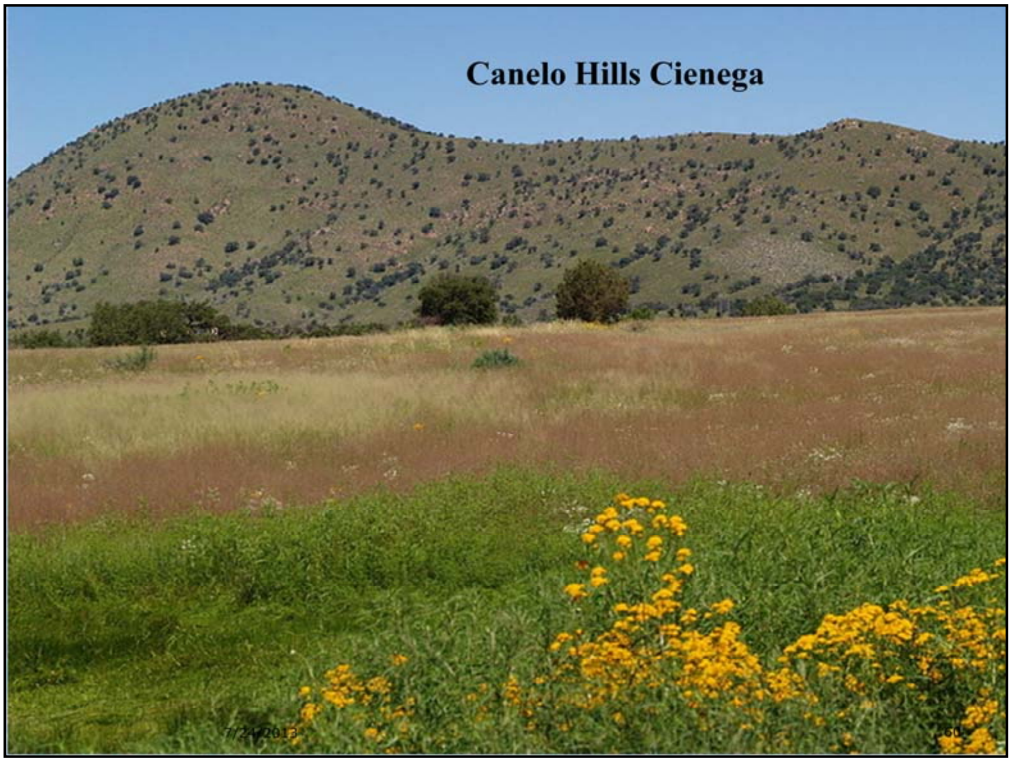
This river was named “Beaver Creek” by Pattie



Arivaca Cienega 3/10/10

7/24/2013

See Appendix A - Cienegas



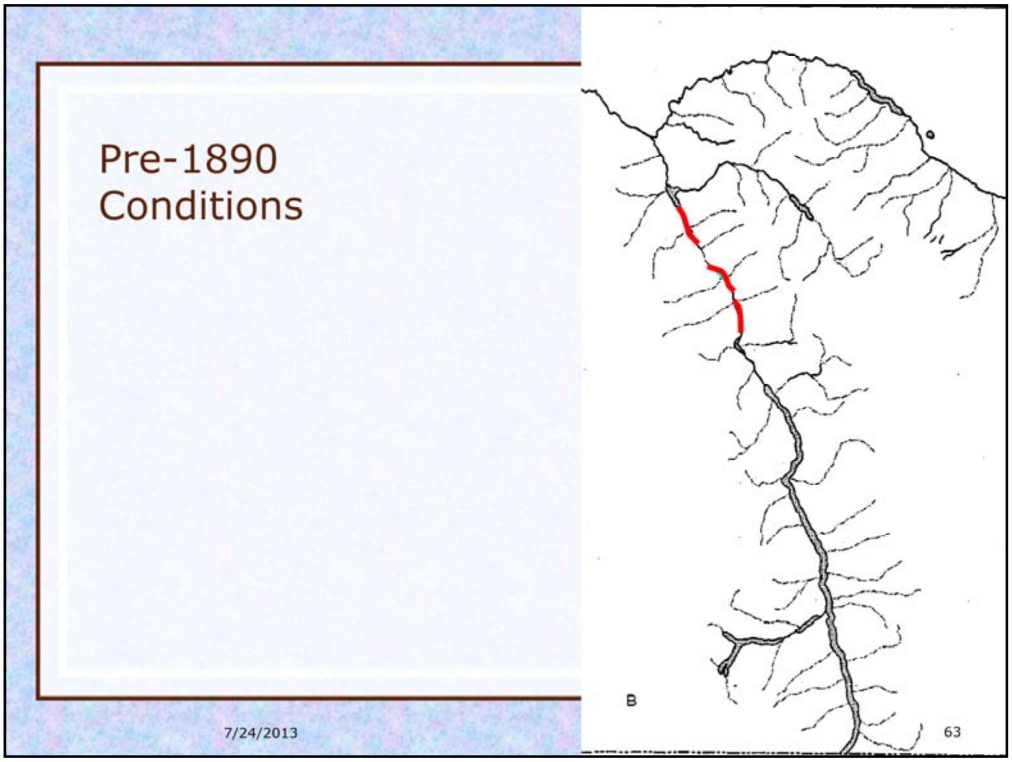
Canelo Hills Cienega

7/24/2013

Appendix B Figure 1. Bingham Cienega sampling point, 6/9/2000.

Source: Pima Association of Governments

St. David Cienega



Pre-1890 Conditions

7/24/2013

Source: Hendrickson and Minckley Figure 9b

Dashed Lines are ephemeral flow.
These reaches are highlighted in red.
Note the map has no category for intermittent flow.

Wide areas on river are cienega/marsh

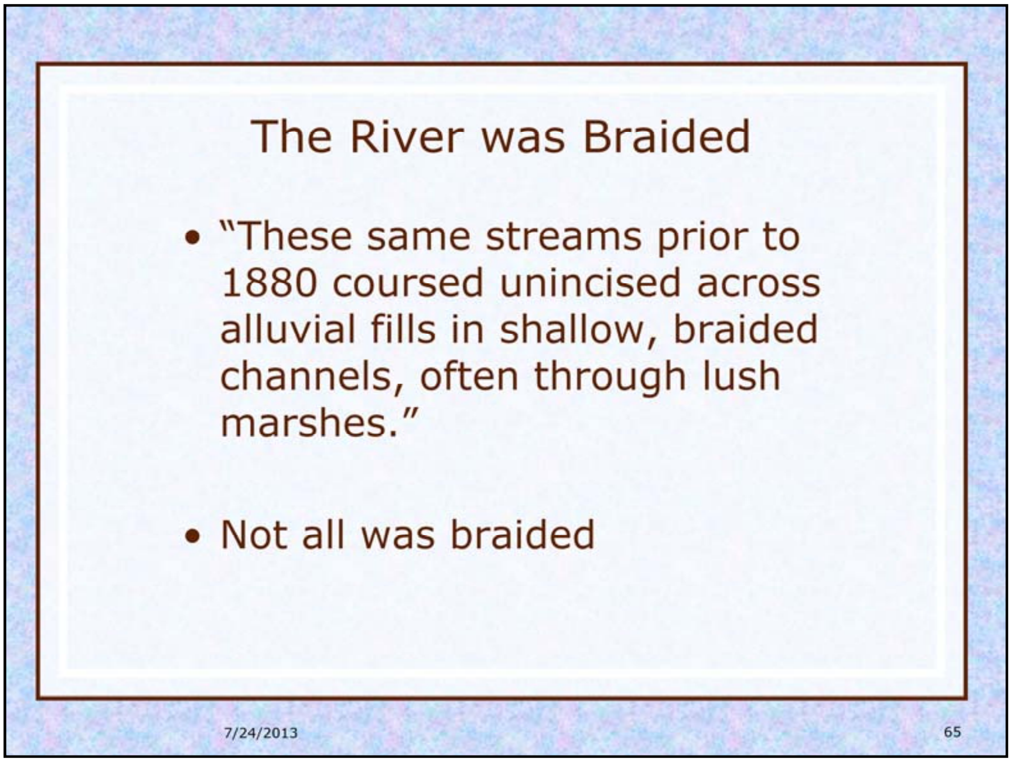
1846-1870

1. Human influences were about a low as they can get.
2. Grasslands were in excellent condition
3. The cattle were disappearing
4. But entrenchment began

See Appendix A - The Abundance of Grass 1846-1870 for item 2

See Appendix A - The Cattle Were Disappearing for item 3

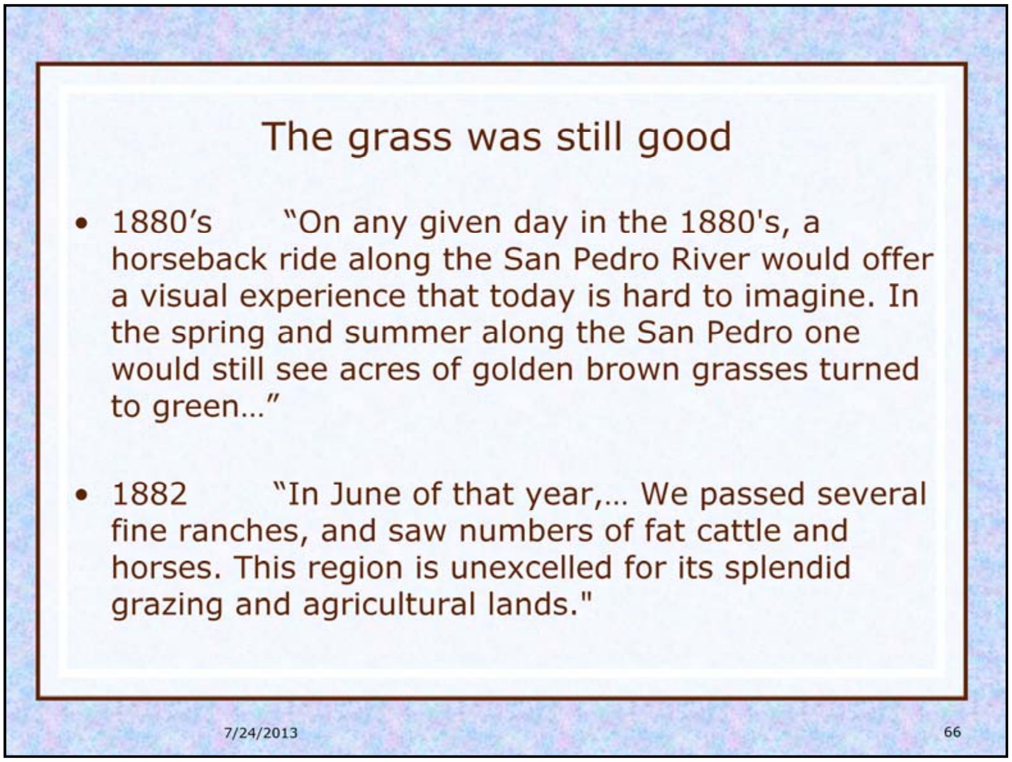
See Appendix A – The First Historic Entrenchment for item 4



The River was Braided

- "These same streams prior to 1880 coursed unincised across alluvial fills in shallow, braided channels, often through lush marshes."
- Not all was braided

Source: Hendrickson and Minckley 1984 pg 131



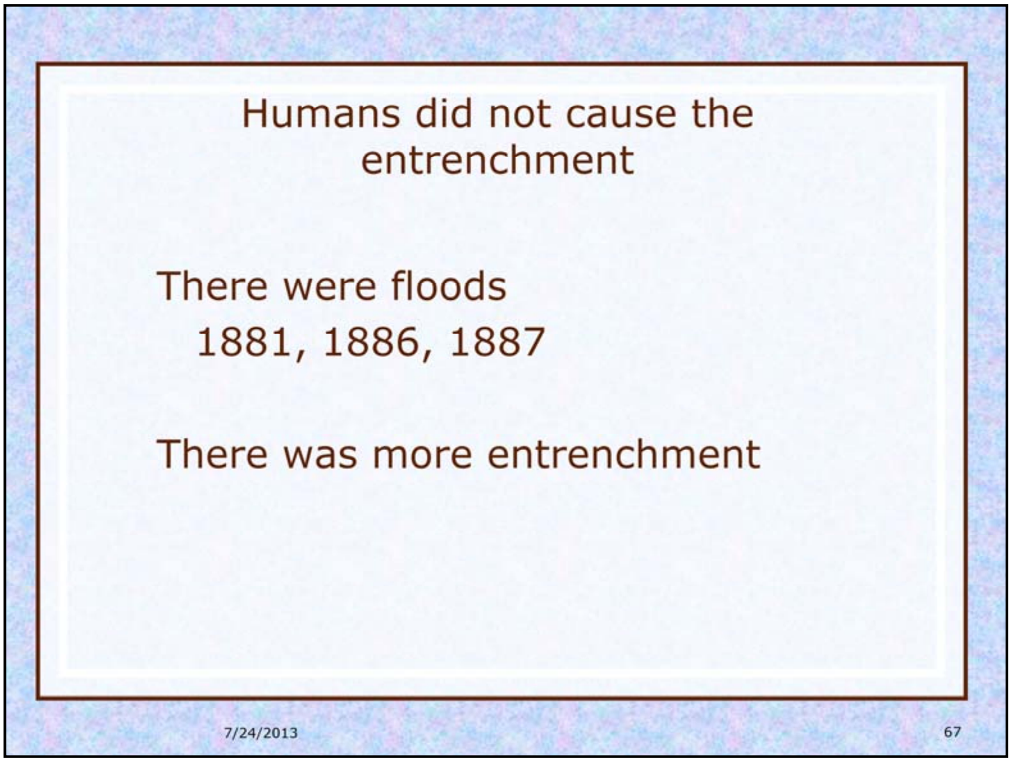
The grass was still good

- 1880’s “On any given day in the 1880's, a horseback ride along the San Pedro River would offer a visual experience that today is hard to imagine. In the spring and summer along the San Pedro one would still see acres of golden brown grasses turned to green…”
- 1882 “In June of that year,… We passed several fine ranches, and saw numbers of fat cattle and horses. This region is unexcelled for its splendid grazing and agricultural lands."

7/24/2013

Source: Rose pg 3 for 1880’s

Source: Dobyns 1995 pg 49 for 1882

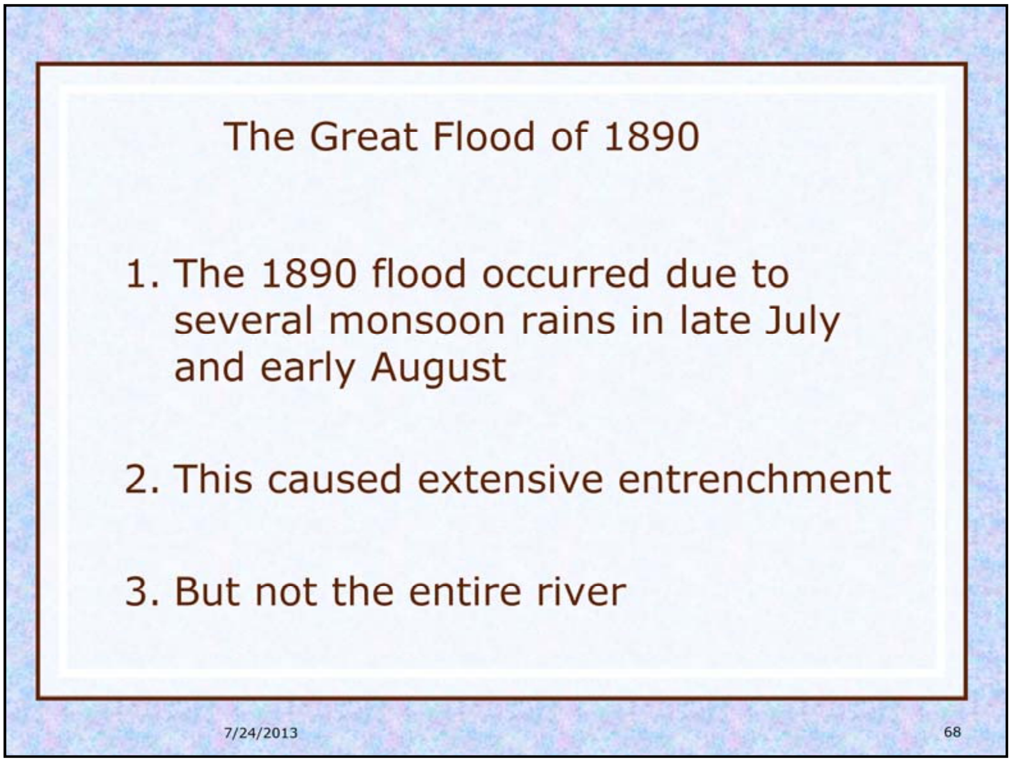


Humans did not cause the entrenchment

There were floods
1881, 1886, 1887

There was more entrenchment

See Appendix A – The 1880’s Entrenchment



The Great Flood of 1890

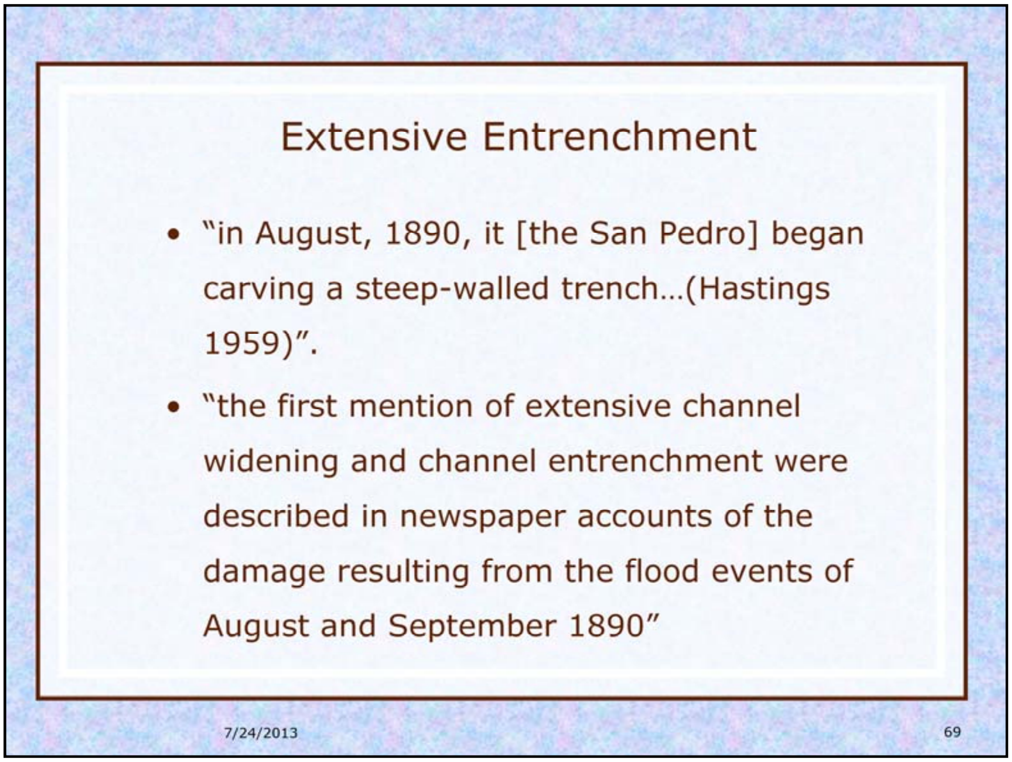
1. The 1890 flood occurred due to several monsoon rains in late July and early August
2. This caused extensive entrenchment
3. But not the entire river

7/24/2013

Source: Dobyns 1995 pg 67-72 for item 1

See Appendix A – The 1890 Entrenchment for item 2

See Appendix A – Reaches Not Entrenched in 1890 for item 3



Extensive Entrenchment

- "in August, 1890, it [the San Pedro] began carving a steep-walled trench…(Hastings 1959)".
- "the first mention of extensive channel widening and channel entrenchment were described in newspaper accounts of the damage resulting from the flood events of August and September 1890"

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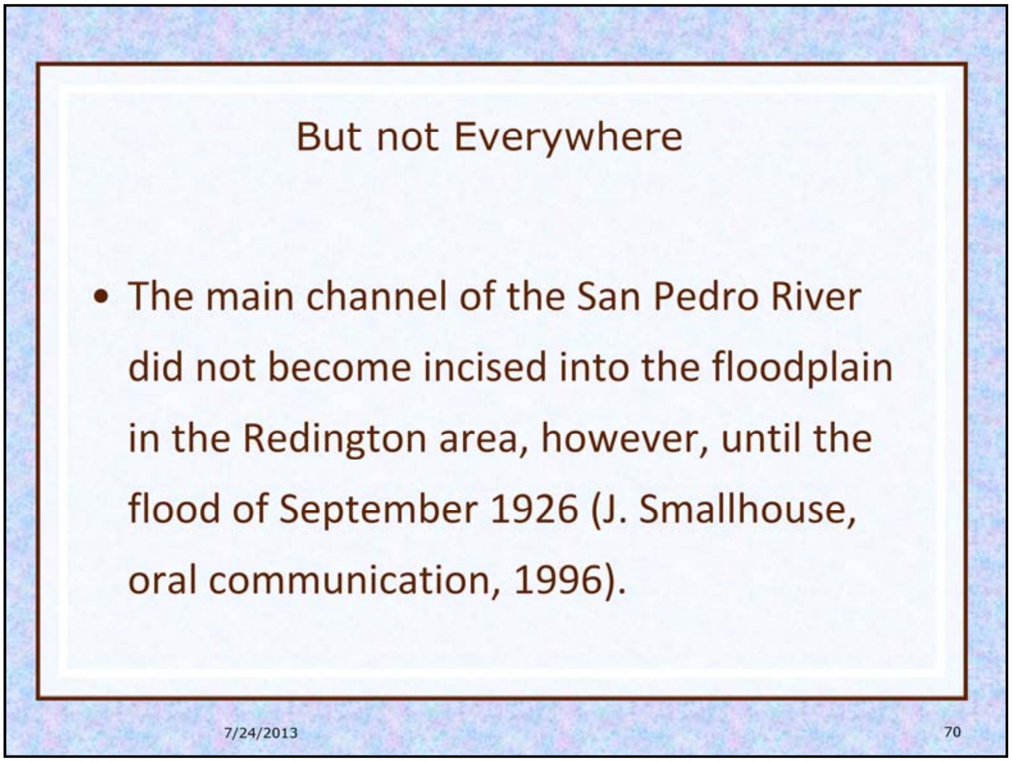
Source: Fuller pg 3-20, 21

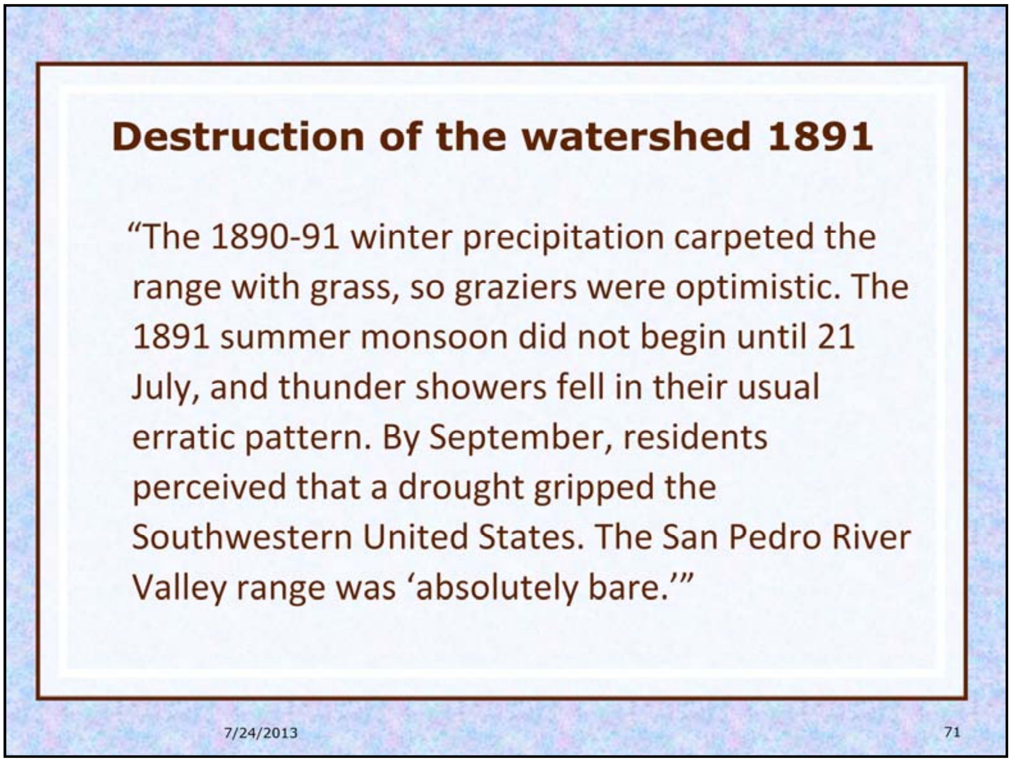
Source: Wood pg 24



But not Everywhere

- The main channel of the San Pedro River did not become incised into the floodplain in the Redington area, however, until the flood of September 1926 (J. Smallhouse, oral communication, 1996).

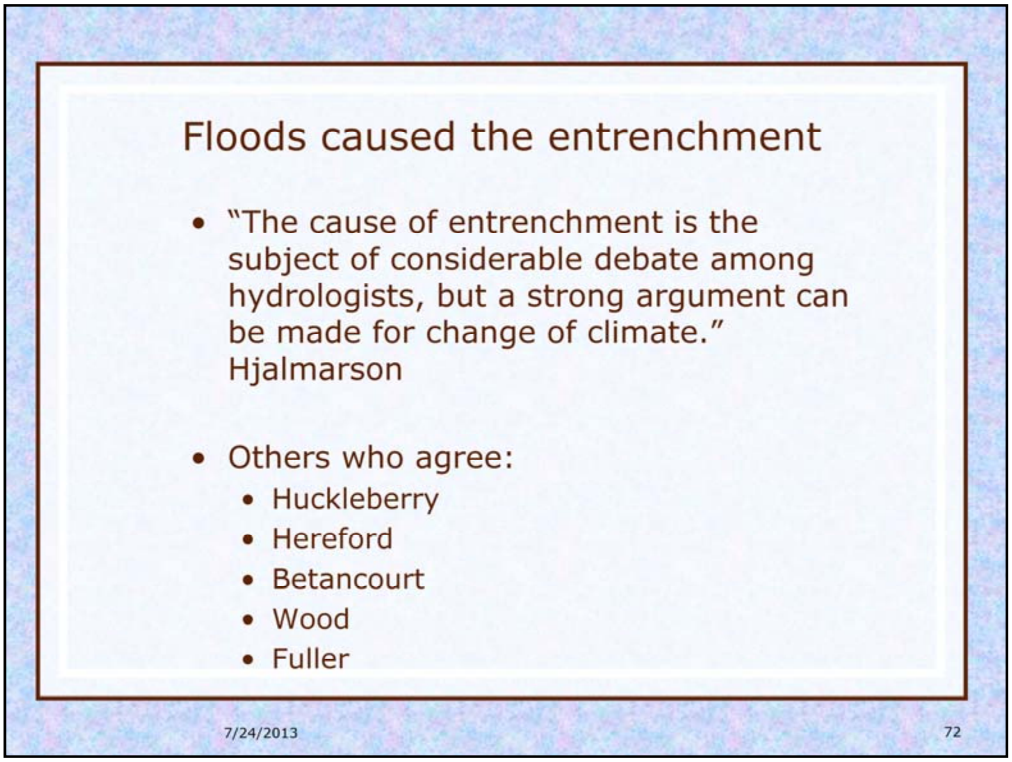
Source: Fuller pg 5-14



Destruction of the watershed 1891

"The 1890-91 winter precipitation carpeted the range with grass, so graziers were optimistic. The 1891 summer monsoon did not begin until 21 July, and thunder showers fell in their usual erratic pattern. By September, residents perceived that a drought gripped the Southwestern United States. The San Pedro River Valley range was 'absolutely bare.'"

Source: Dobyns 1995 pg 74

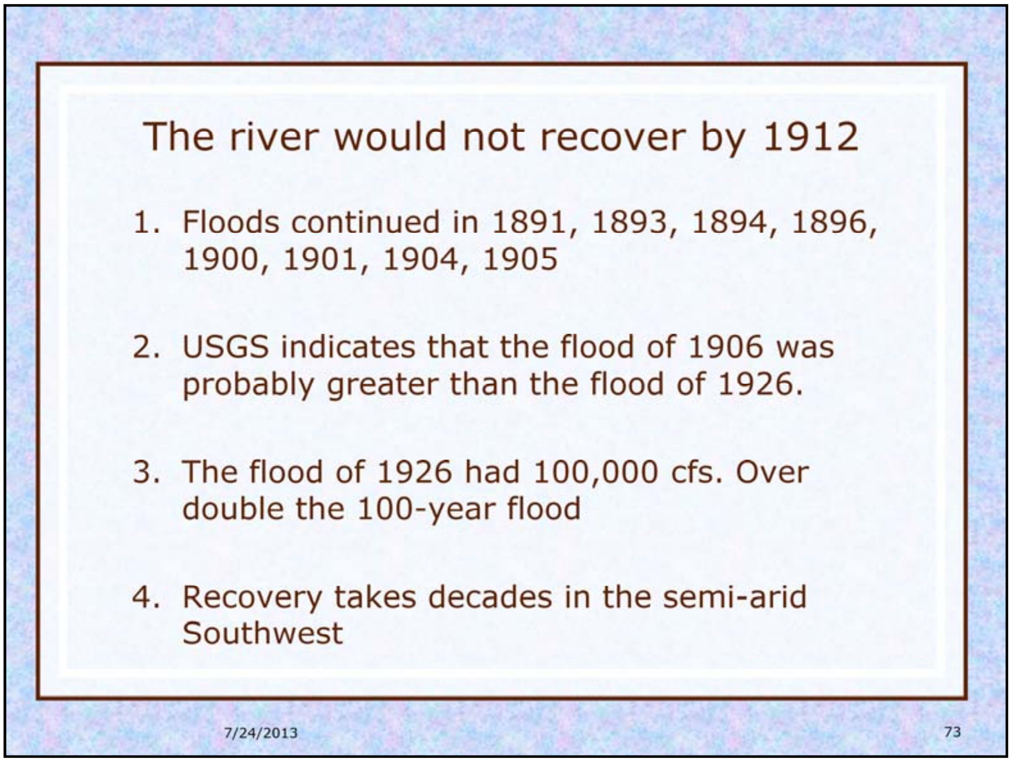


Floods caused the entrenchment

- "The cause of entrenchment is the subject of considerable debate among hydrologists, but a strong argument can be made for change of climate." Hjalmarson
- Others who agree:
  - Huckleberry
  - Hereford
  - Betancourt
  - Wood
  - Fuller

Source: Hjalmarson 1988 pg 1

See Appendix A - Floods and Entrenchment



The river would not recover by 1912

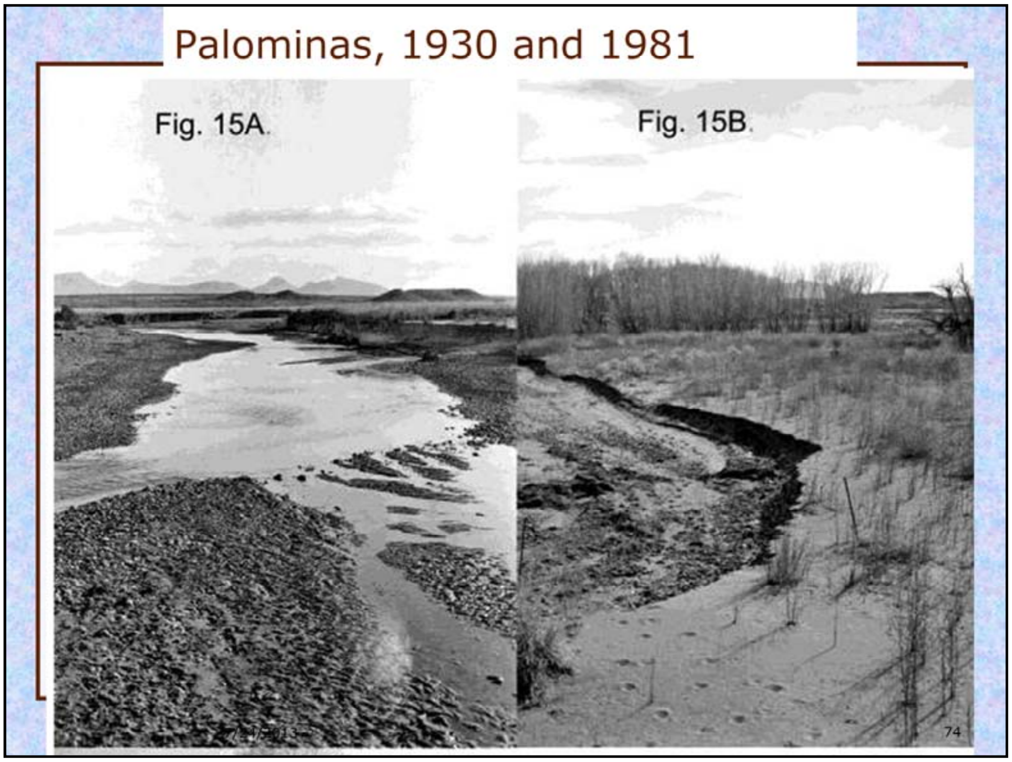
1. Floods continued in 1891, 1893, 1894, 1896, 1900, 1901, 1904, 1905
2. USGS indicates that the flood of 1906 was probably greater than the flood of 1926.
3. The flood of 1926 had 100,000 cfs. Over double the 100-year flood
4. Recovery takes decades in the semi-arid Southwest

7/24/2013

Source: Wood pg 5 for item 1

Source: Pope et. al. pg 389 for items 2 & 3

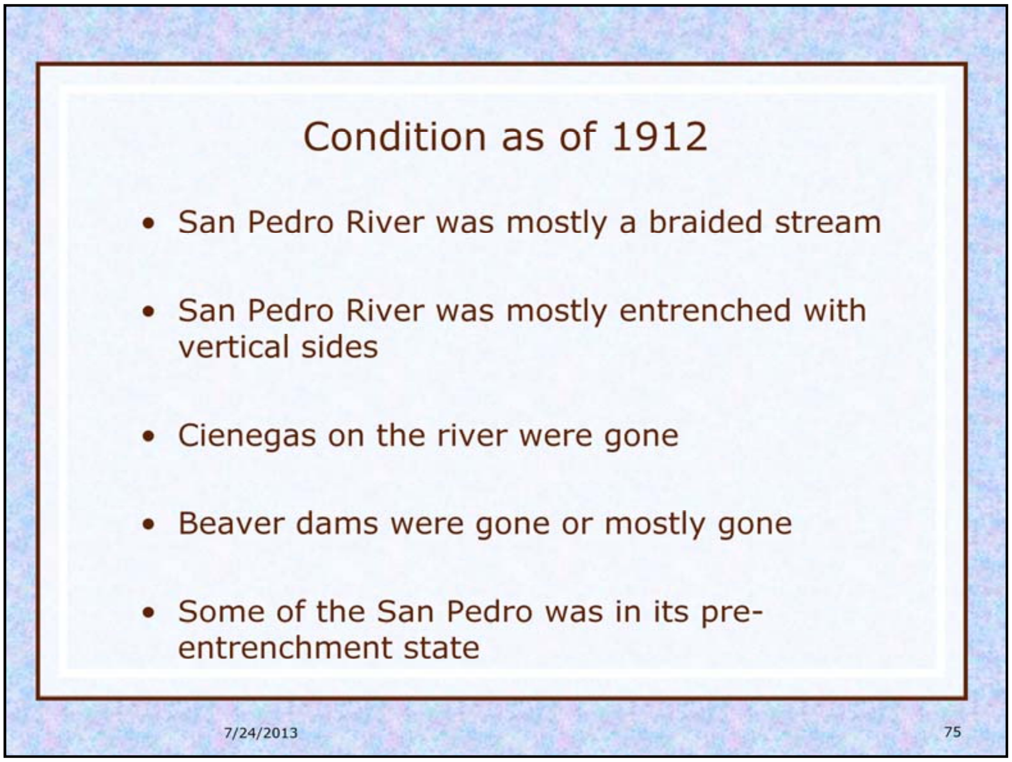
See Appendix A - Stream Recovery for item 4



Palominas, 1930 and 1981

Fig. 15A.

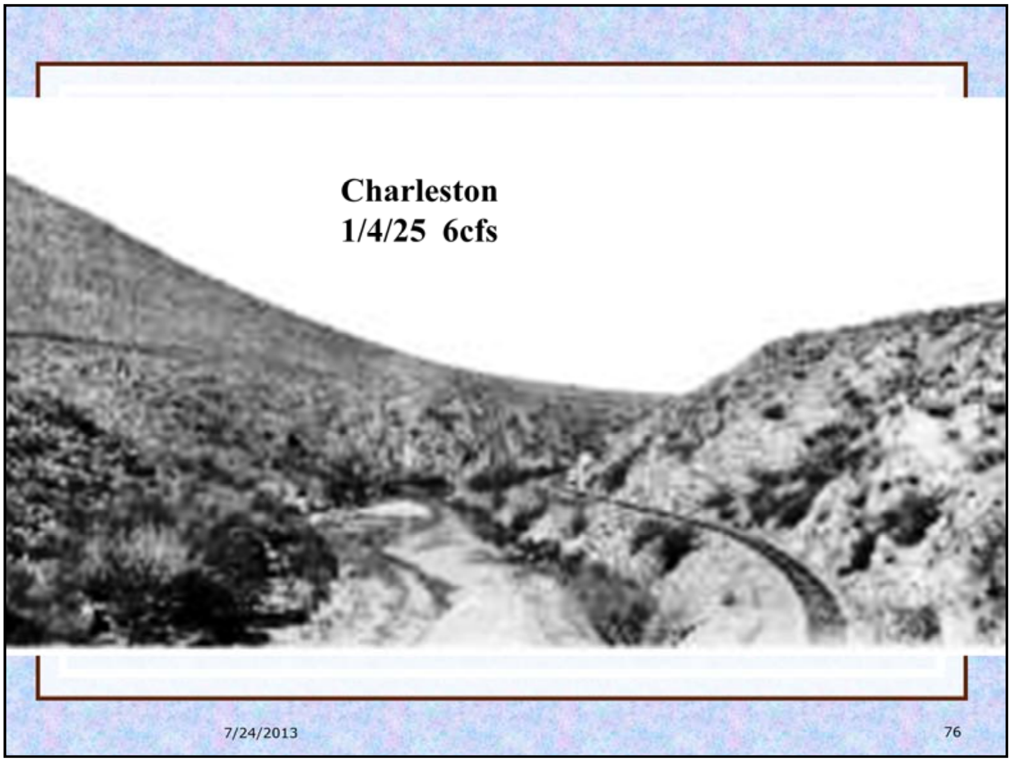
Fig. 15B.



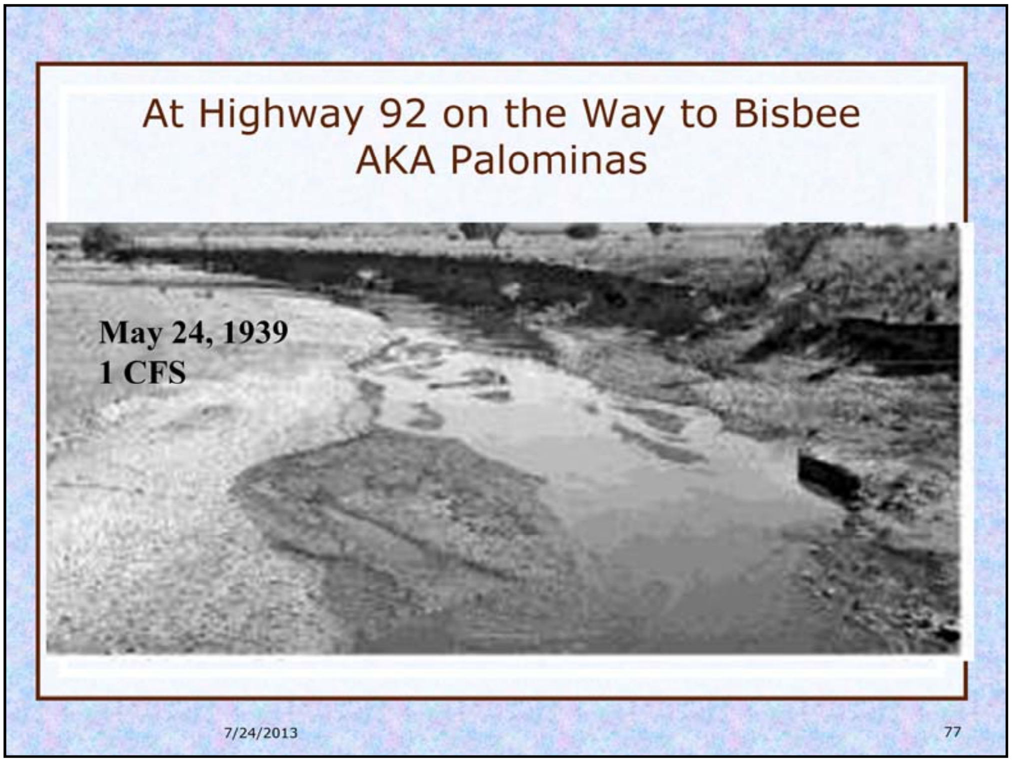
Condition as of 1912

- San Pedro River was mostly a braided stream
- San Pedro River was mostly entrenched with vertical sides
- Cienegas on the river were gone
- Beaver dams were gone or mostly gone
- Some of the San Pedro was in its pre-entrenchment state

See Appendix A - Statehood Condition

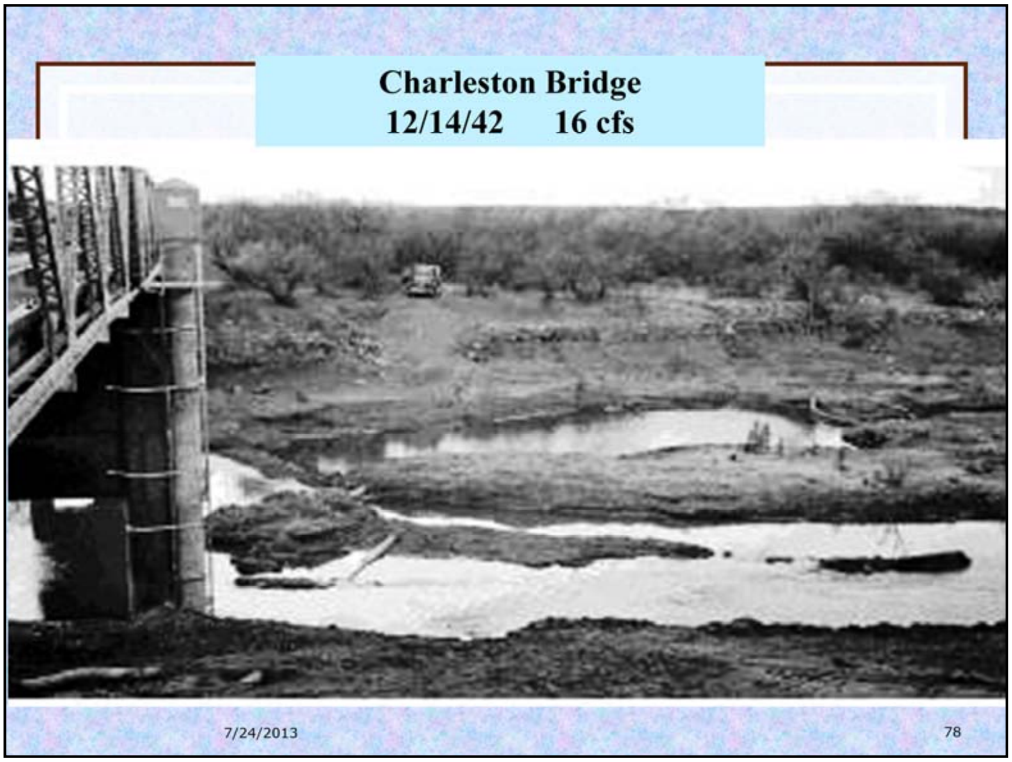


Charleston
1/4/25 6cfs

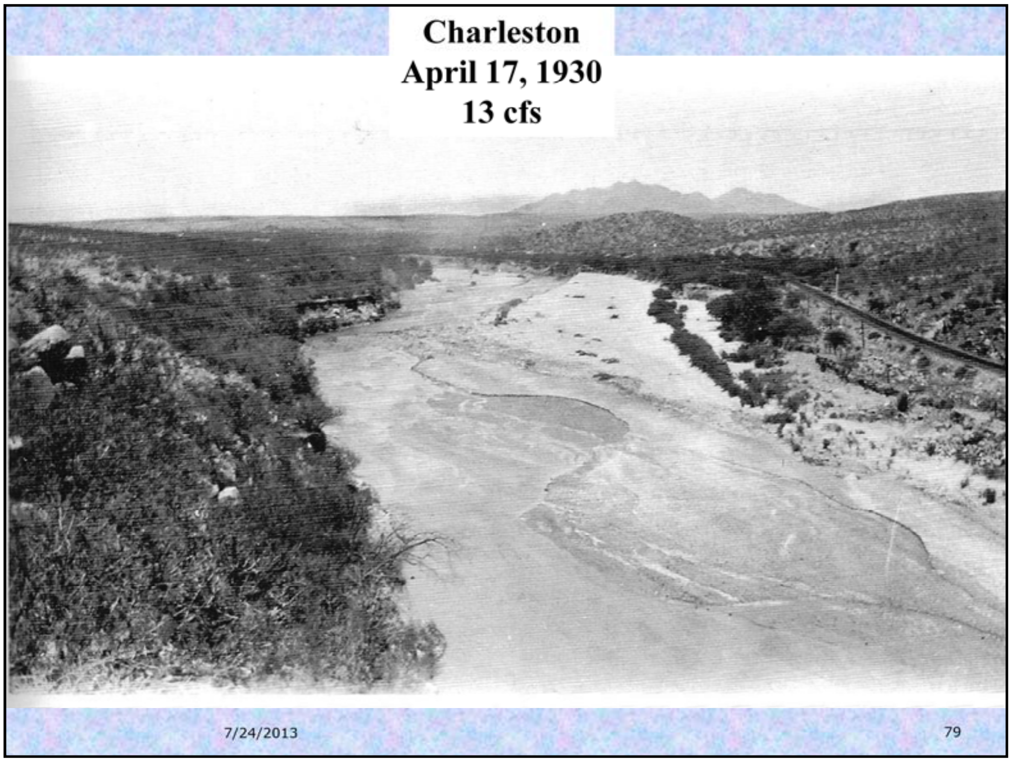


At Highway 92 on the Way to Bisbee AKA Palominas

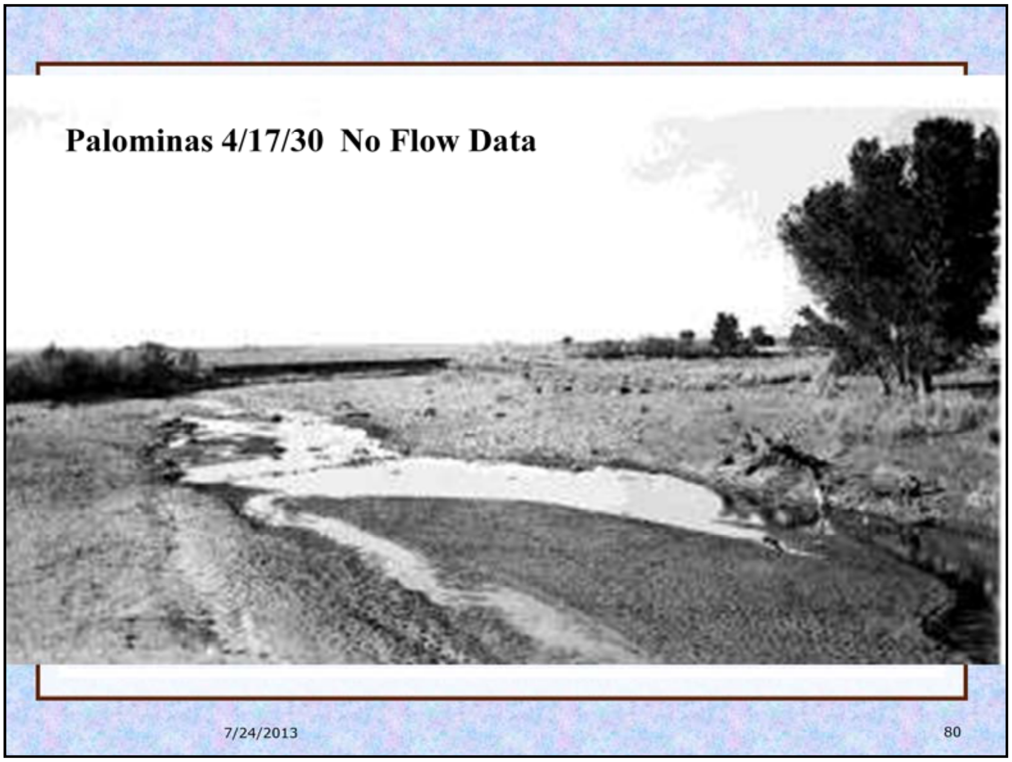
May 24, 1939
1 CFS



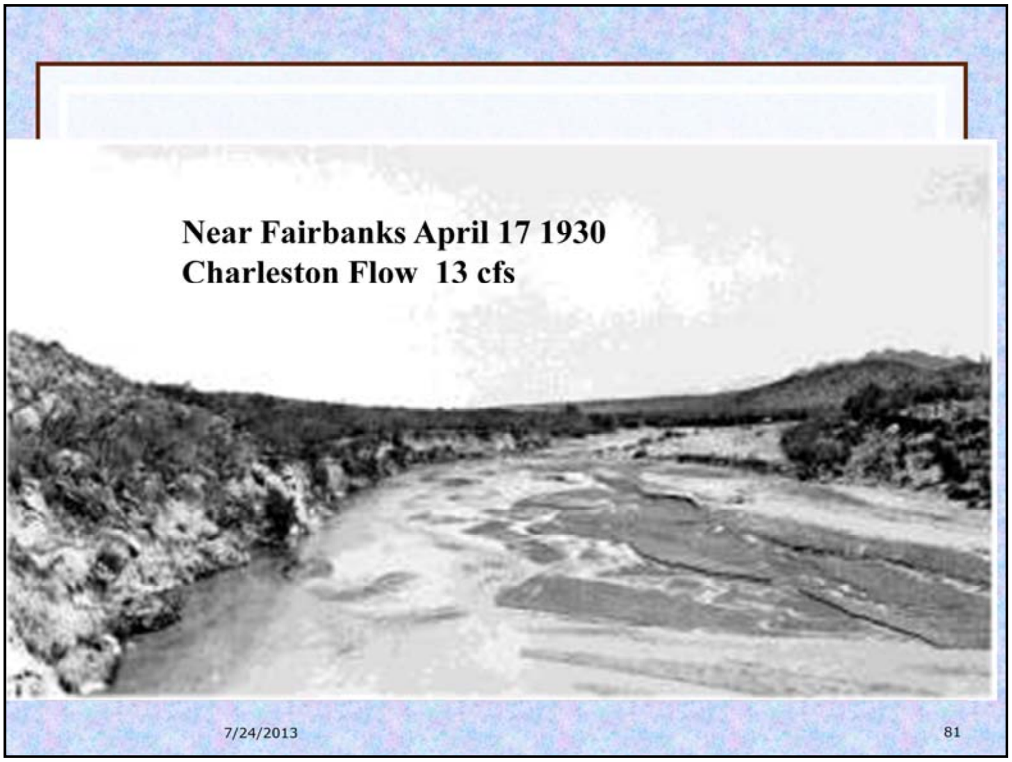
Charleston Bridge
12/14/42 16 cfs



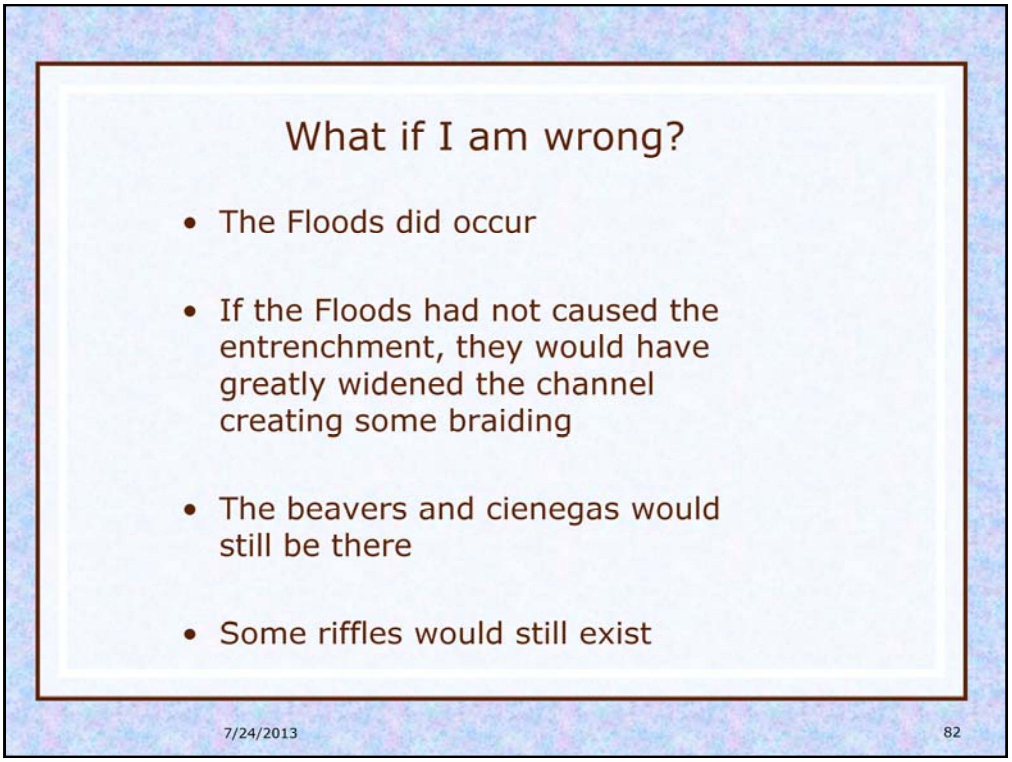
Charleston
April 17, 1930
13 cfs



Palominas 4/17/30 No Flow Data

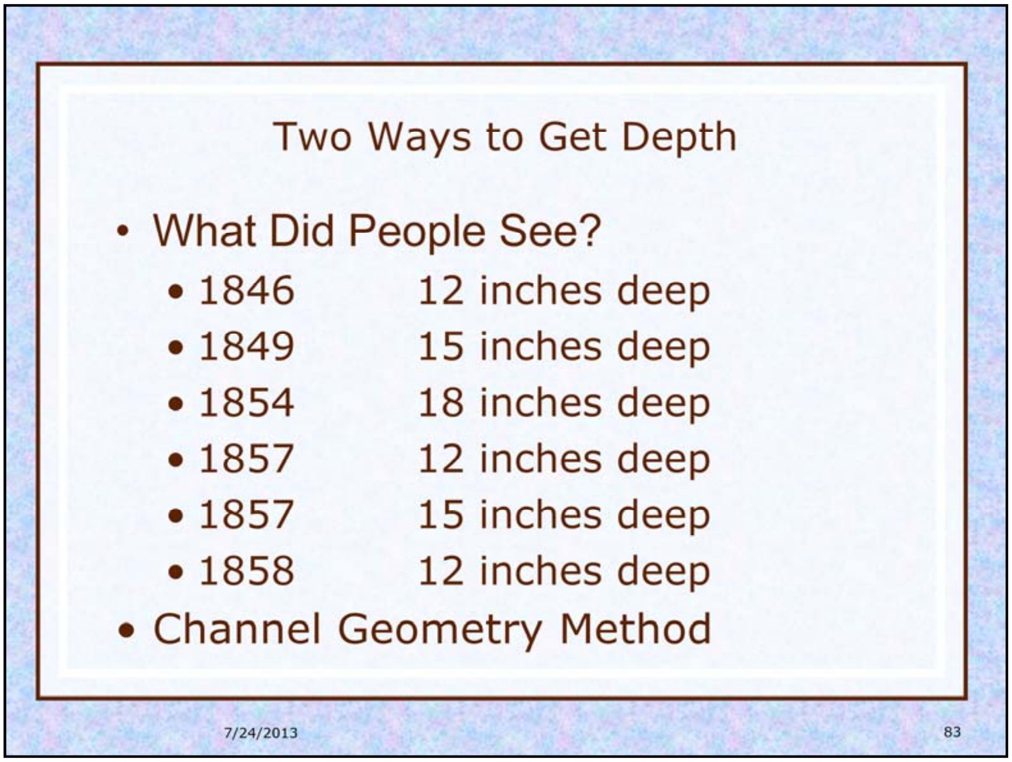


Near Fairbanks April 17 1930
Charleston Flow 13 cfs



What if I am wrong?

- The Floods did occur
- If the Floods had not caused the entrenchment, they would have greatly widened the channel creating some braiding
- The beavers and cienegas would still be there
- Some riffles would still exist



Two Ways to Get Depth

- What Did People See?
  - 1846 12 inches deep
  - 1849 15 inches deep
  - 1854 18 inches deep
  - 1857 12 inches deep
  - 1857 15 inches deep
  - 1858 12 inches deep
- Channel Geometry Method

Source: Fuller pg 5-13 for 1846

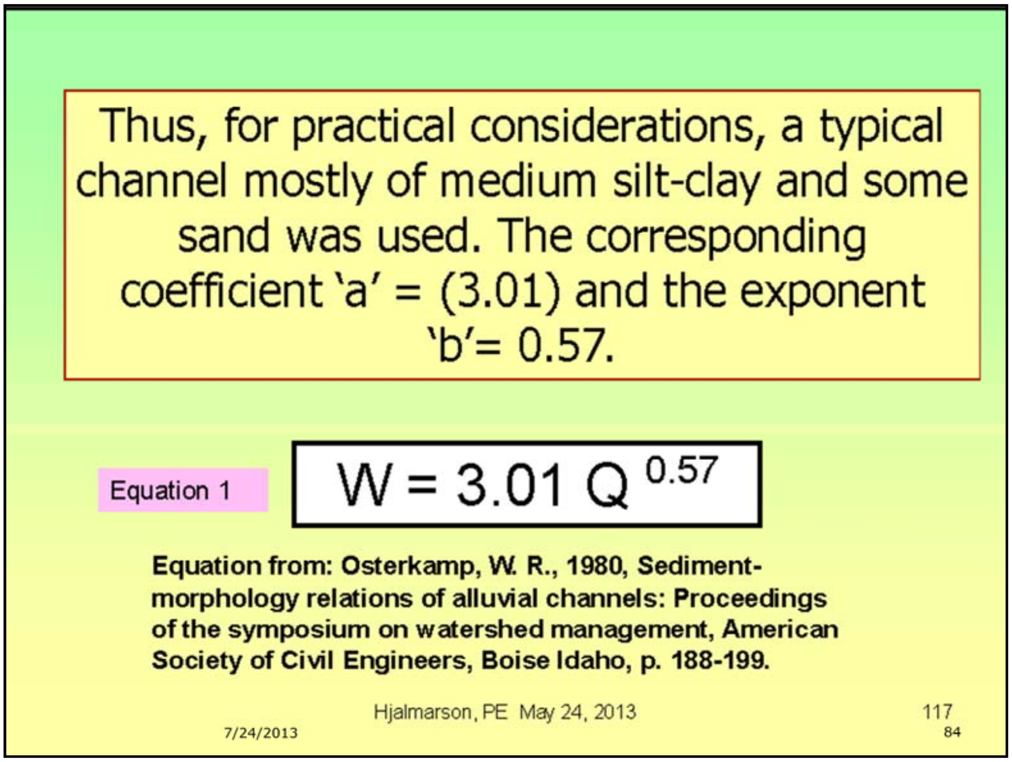
Source: Fuller pg 3-17 for 1849

Source: Fuller pg 3-17 for 1854

Source: Fuller pg 3-18 for 1857 (1st)

Source: Hereford and Betancourt pg 136 for 1857 (2nd)

Source: Fuller pg 3-18 for 1858



Thus, for practical considerations, a typical channel mostly of medium silt-clay and some sand was used. The corresponding coefficient ‘a’ = (3.01) and the exponent ‘b’= 0.57.

Equation 1

$$\boxed{W = 3.01\,Q^{0.57}}$$

Equation from: 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.

Hjalmarson, PE May 24, 2013

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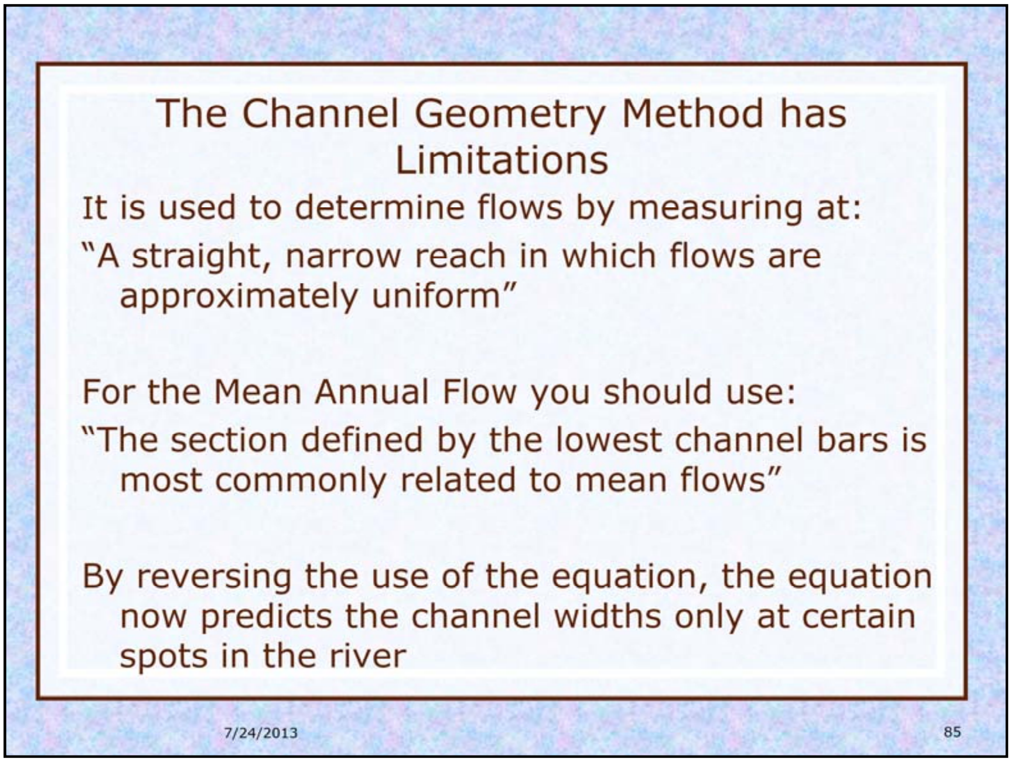
7/24/2013

84

Source: Hjalmarson Slide 117



The Channel Geometry Method has Limitations

It is used to determine flows by measuring at:

“A straight, narrow reach in which flows are approximately uniform”

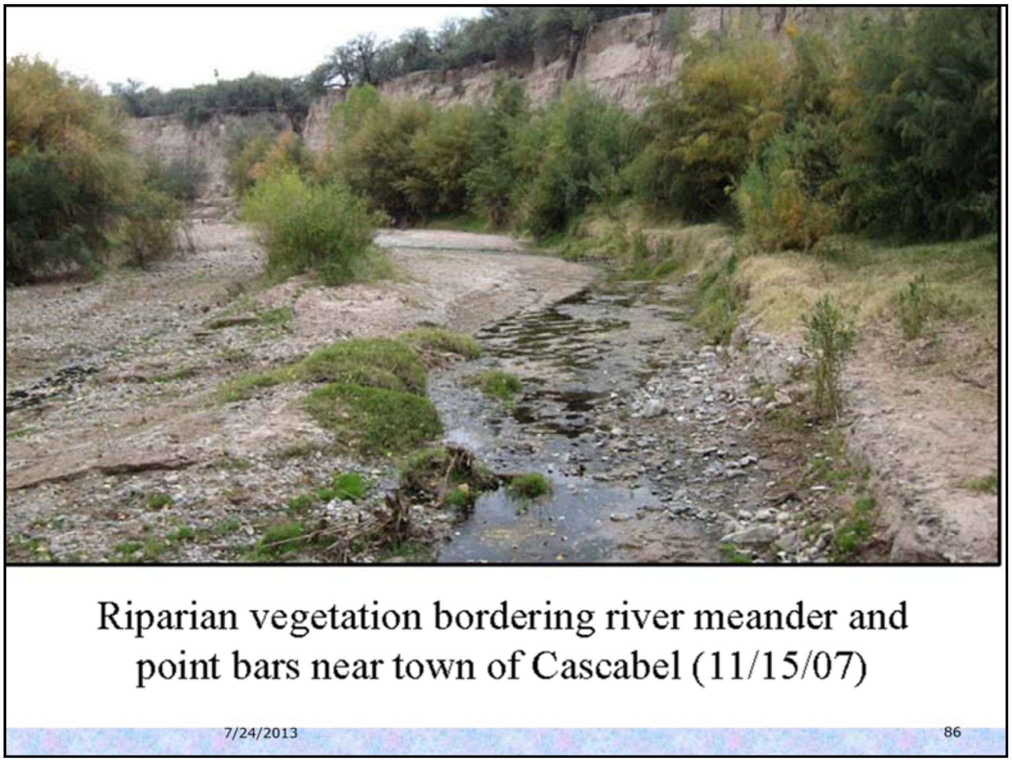
For the Mean Annual Flow you should use:

“The section defined by the lowest channel bars is most commonly related to mean flows”

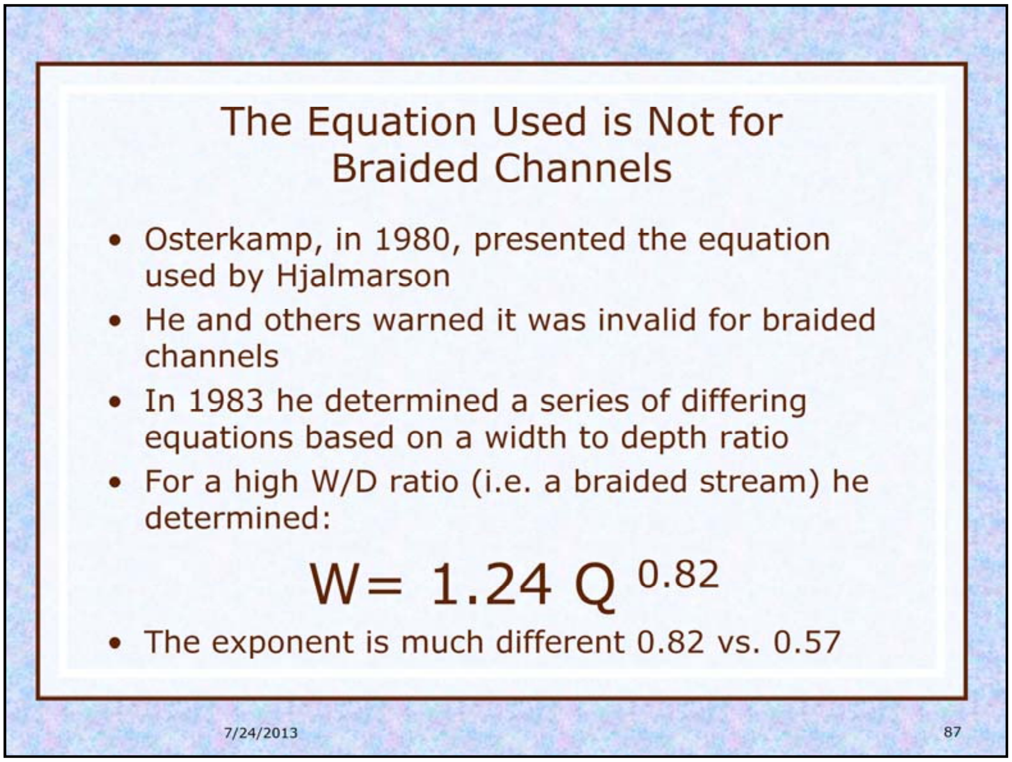
By reversing the use of the equation, the equation now predicts the channel widths only at certain spots in the river

7/24/2013

Source: Barnes, Jr. No Pg



Riparian vegetation bordering river meander and point bars near town of Cascabel (11/15/07)



The Equation Used is Not for Braided Channels

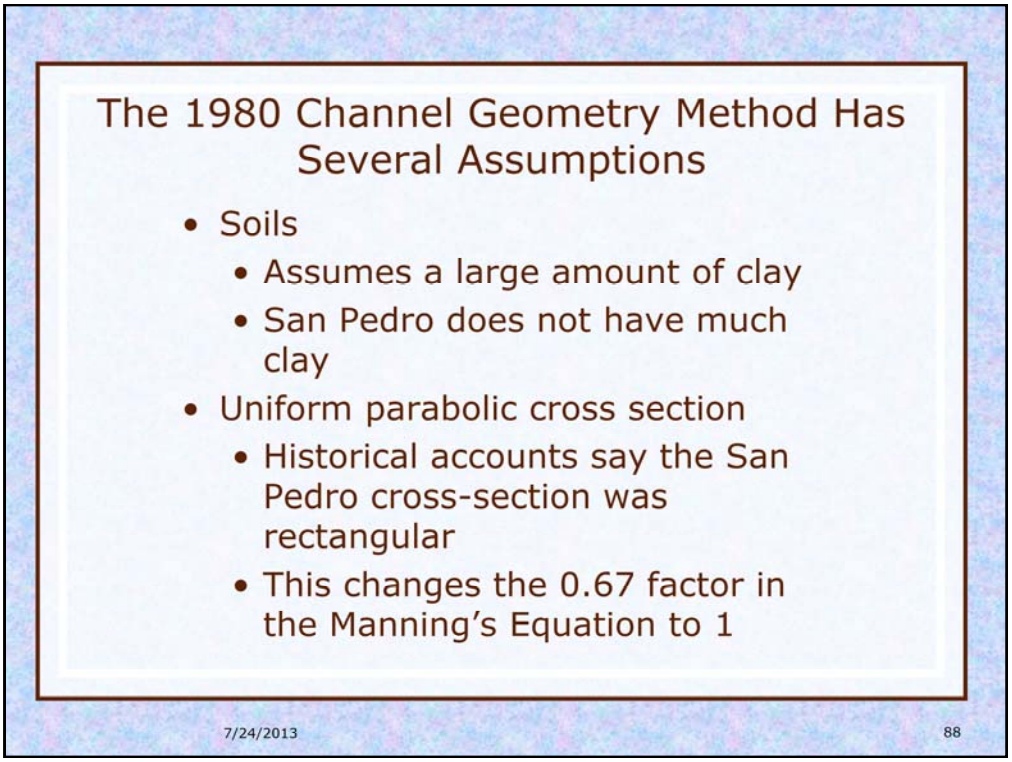
- Osterkamp, in 1980, presented the equation used by Hjalmarson
- He and others warned it was invalid for braided channels
- In 1983 he determined a series of differing equations based on a width to depth ratio
- For a high W/D ratio (i.e. a braided stream) he determined:

$$W= 1.24\ Q^{0.82}$$

- The exponent is much different 0.82 vs. 0.57

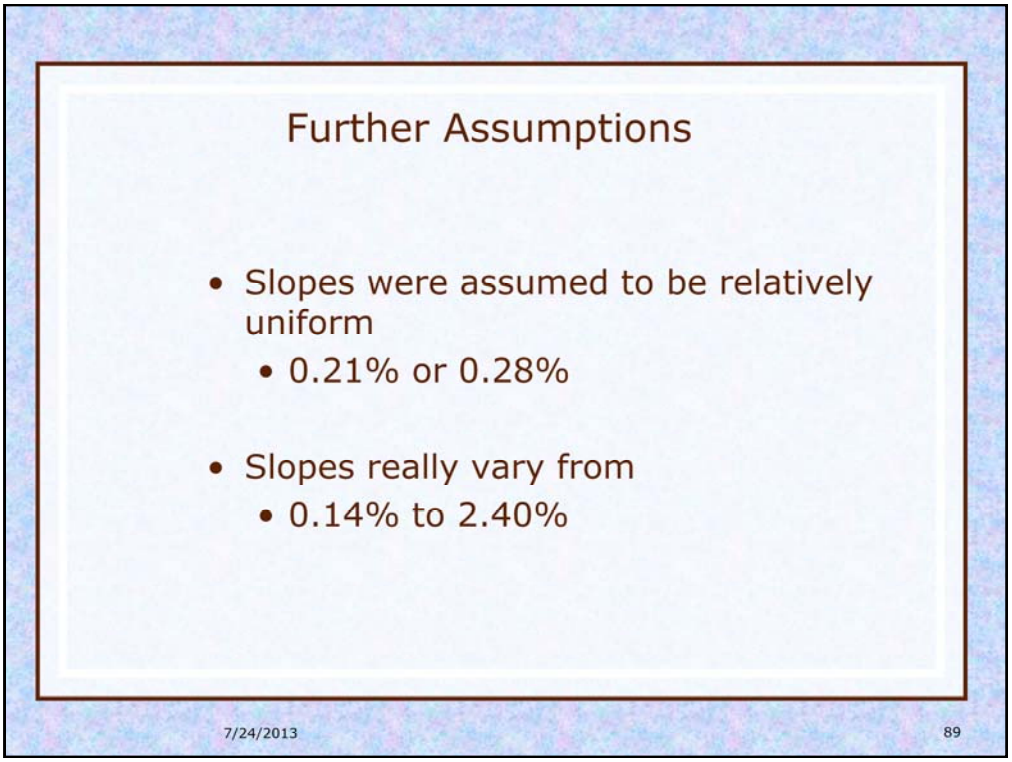
Source: Osterkamp et.al. 1983 pg 7 for formula (converted to U. S. Units)

See Appendix A - Channel Geometry Method – Braiding and Flooding



The 1980 Channel Geometry Method Has Several Assumptions

- Soils
  - Assumes a large amount of clay
  - San Pedro does not have much clay
- Uniform parabolic cross section
  - Historical accounts say the San Pedro cross-section was rectangular
  - This changes the 0.67 factor in the Manning's Equation to 1



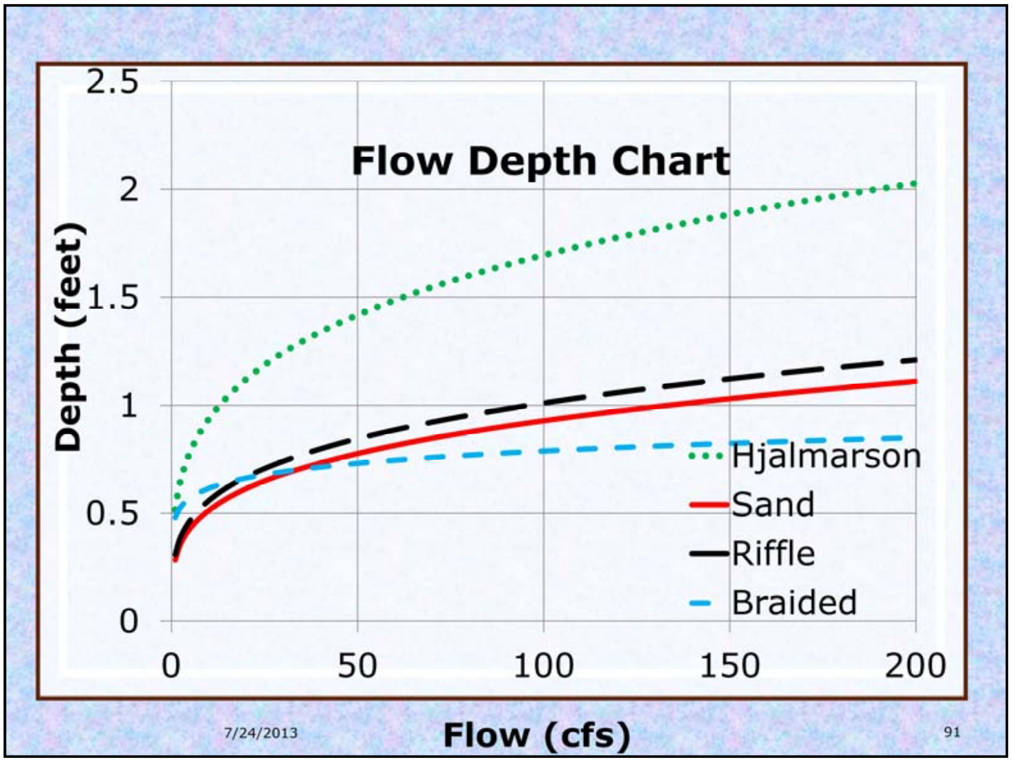
Further Assumptions

- Slopes were assumed to be relatively uniform
    - 0.21% or 0.28%

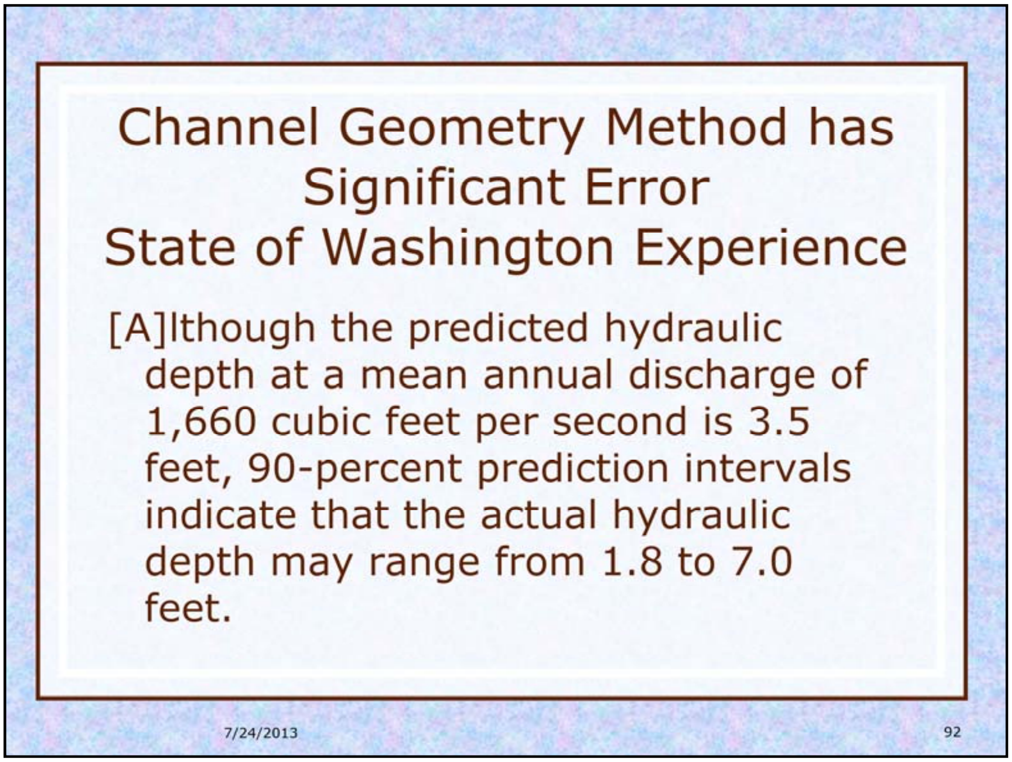
- Slopes really vary from
    - 0.14% to 2.40%

Ignores Natural Obstacles

- Riffles
- Beaver Dams
- Cienegas


Flow Depth Chart
Depth (feet)
2.5
2
1.5
1
0.5
0
0
50
100
150
200
Flow (cfs)
Hjalmarson
Sand
Riffle
Braided

7/24/2013



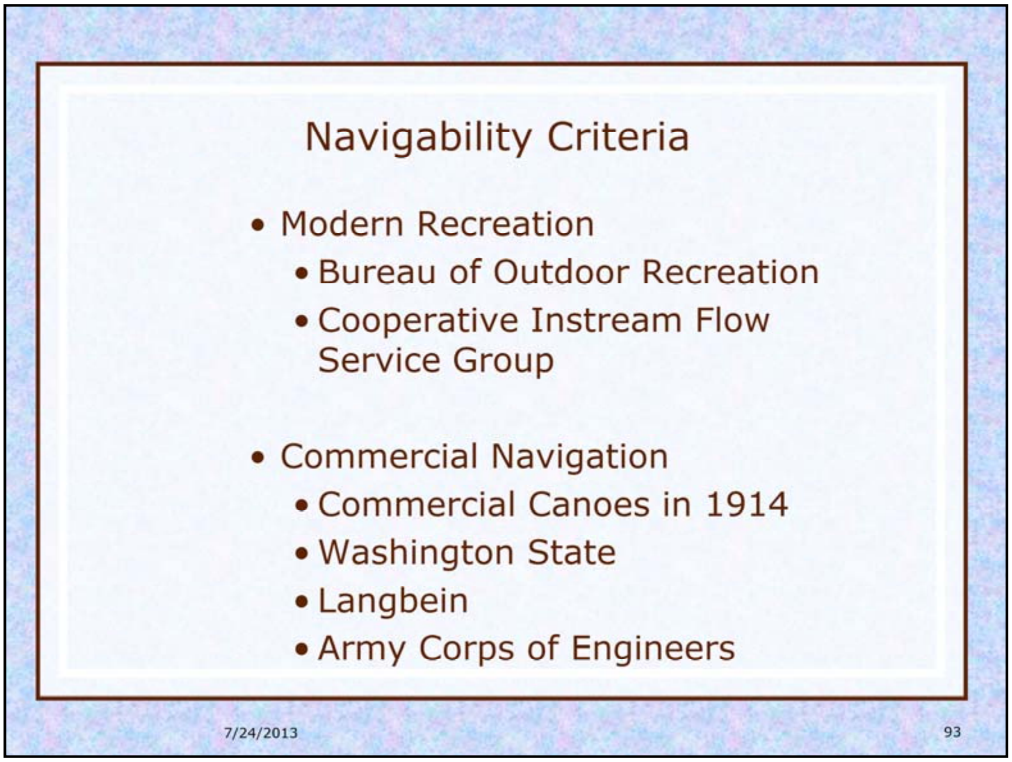
Channel Geometry Method has Significant Error
State of Washington Experience

[A]lthough the predicted hydraulic depth at a mean annual discharge of 1,660 cubic feet per second is 3.5 feet, 90-percent prediction intervals indicate that the actual hydraulic depth may range from 1.8 to 7.0 feet.

7/24/2013

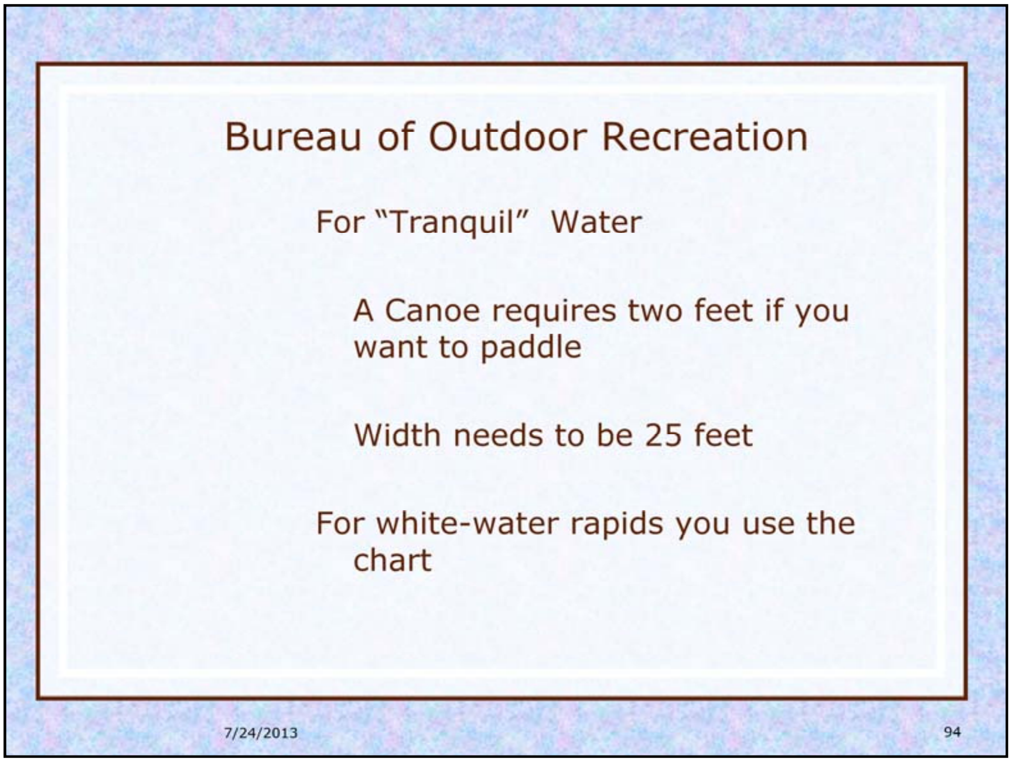
Source: Magirl and Olsen pg 1

See Appendix A - Channel Geometry Method – Error



Navigability Criteria

- Modern Recreation
  - Bureau of Outdoor Recreation
  - Cooperative Instream Flow Service Group
- Commercial Navigation
  - Commercial Canoes in 1914
  - Washington State
  - Langbein
  - Army Corps of Engineers



Bureau of Outdoor Recreation

- For “Tranquil” Water
  - A Canoe requires two feet if you want to paddle
  - Width needs to be 25 feet
- For white-water rapids you use the chart

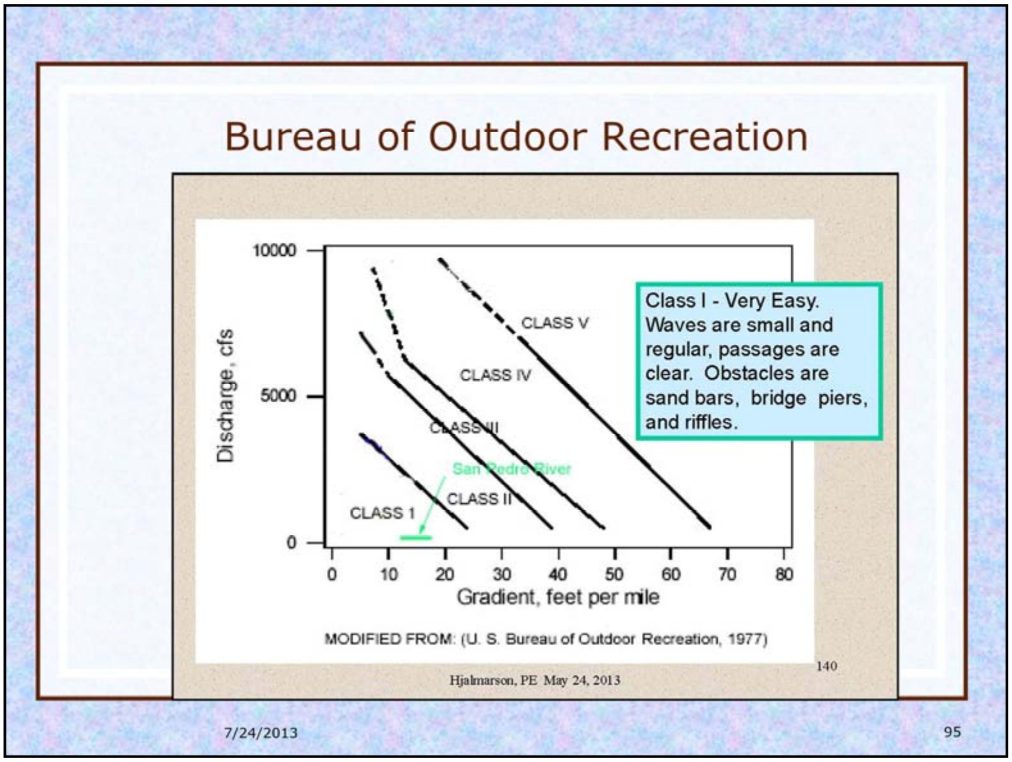
Source: Hjalmarson 2013 slides 139-140

Source: Cortell pg 14 for two foot requirement

Based on Hjalmarson model depth requires 191cfs

Source: Cortell pg 21 for Width

Based on Hjalmarson model width requires 41 cfs



Bureau of Outdoor Recreation

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

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

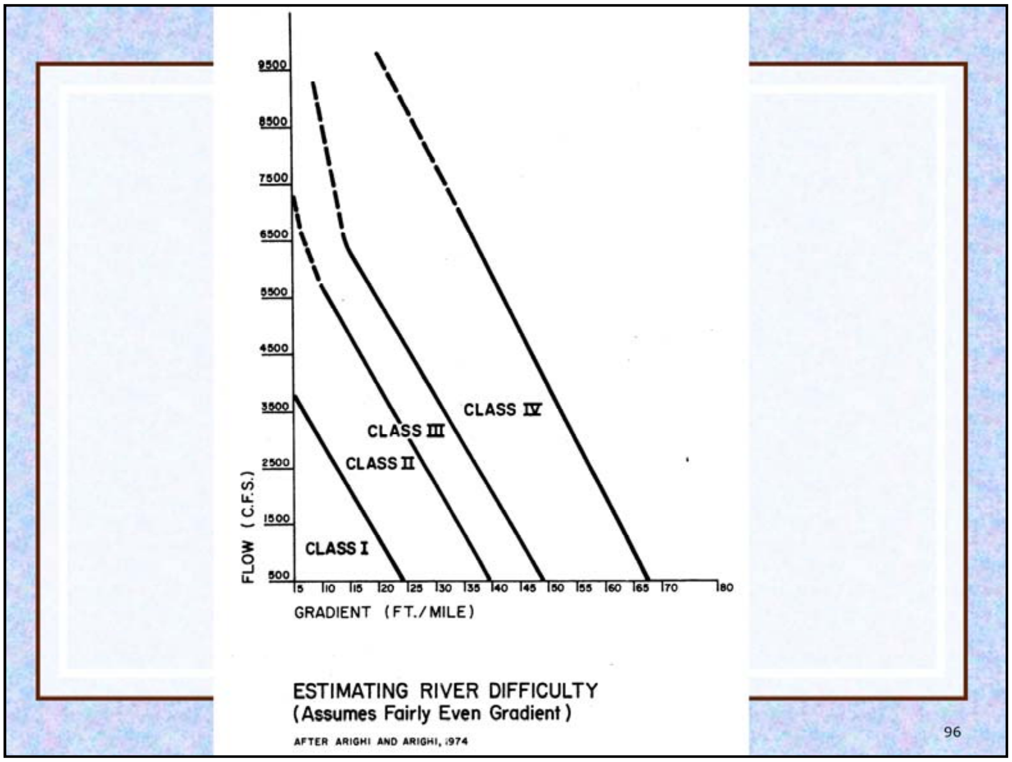
140

Hjalmarson, PE May 24, 2013

7/24/2013

95

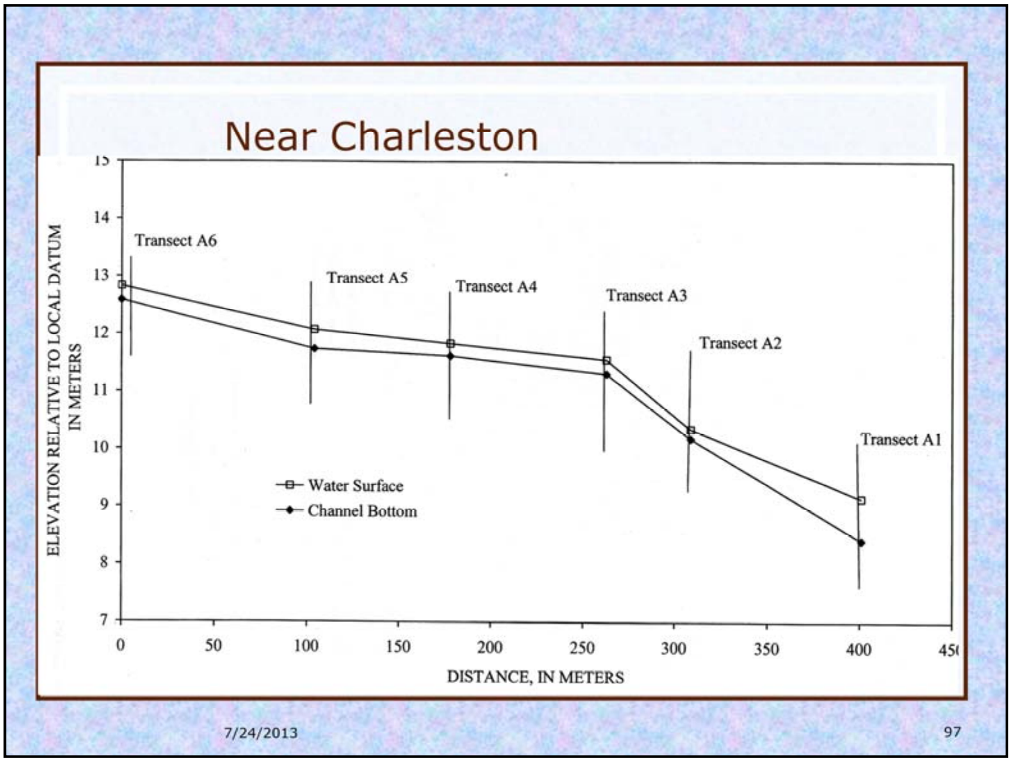
Source: Hjalmarson slide 140



ESTIMATING RIVER DIFFICULTY
(Assumes Fairly Even Gradient)

AFTER ARIGHI AND ARIGHI, 1974

Source: Cortell pg 18



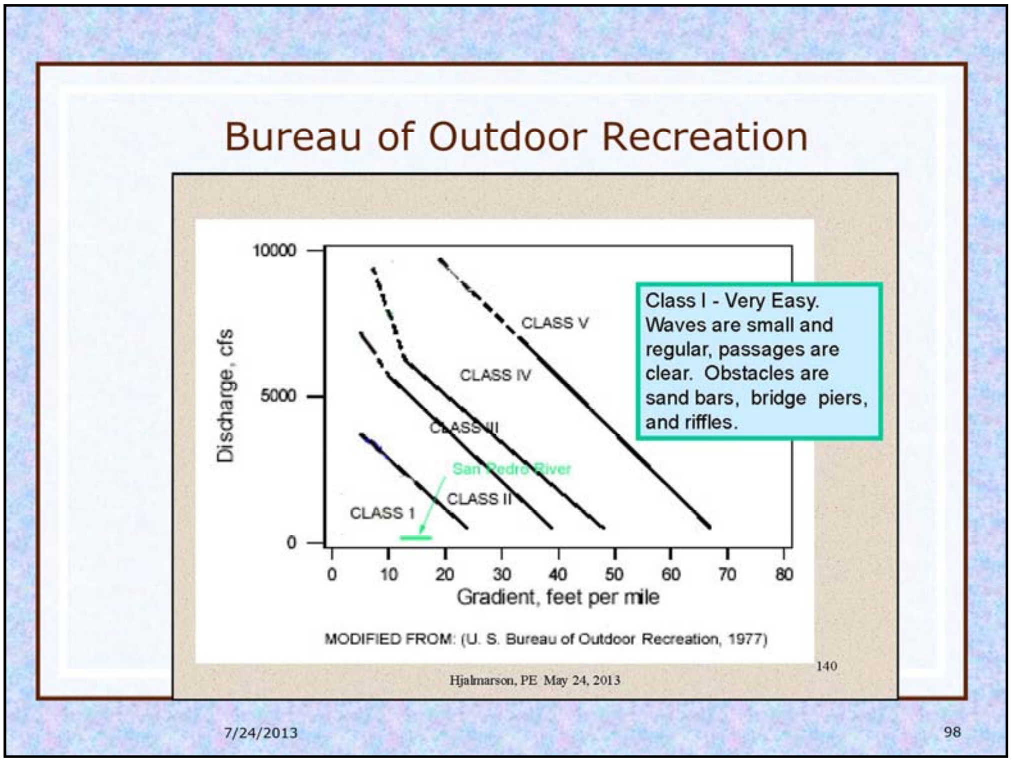
Near Charleston

7/24/2013

97

Source: Beaulieu and others pg 34

Slope between Transect A2 and A3 is 125 feet per mile



Bureau of Outdoor Recreation

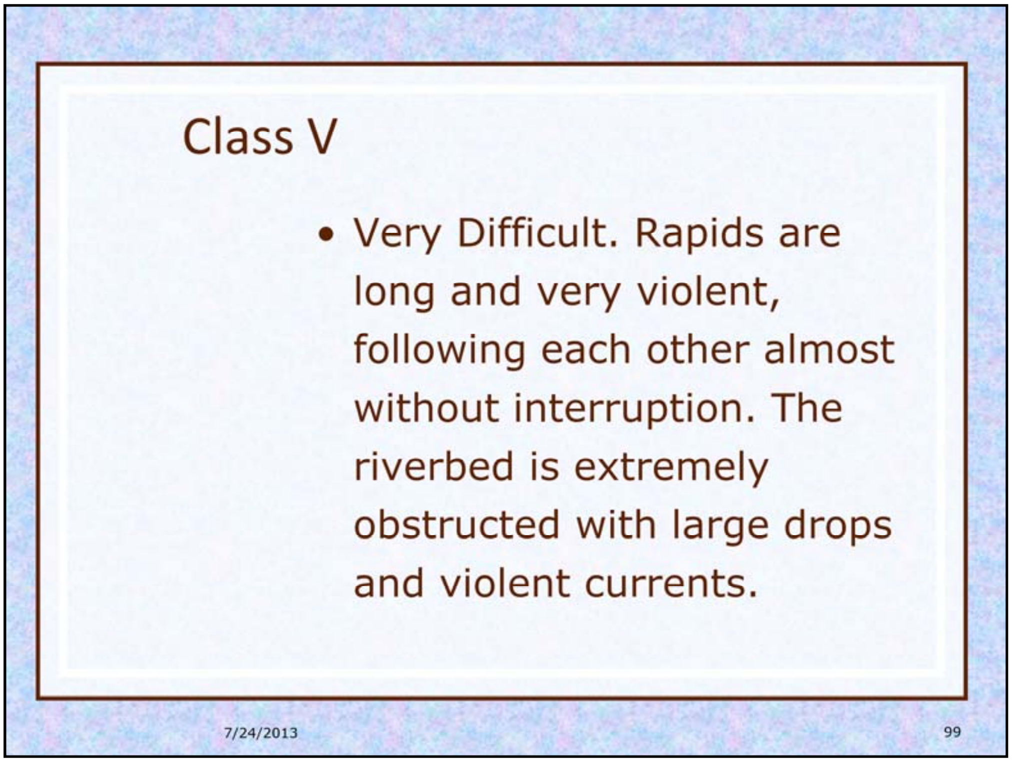
Class I - Very Easy. Waves are small and regular, passages are clear. Obstacles are sand bars, bridge piers, and riffles.

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

Hjalmarson, PE May 24, 2013

Source: Hjalmarson slide 140

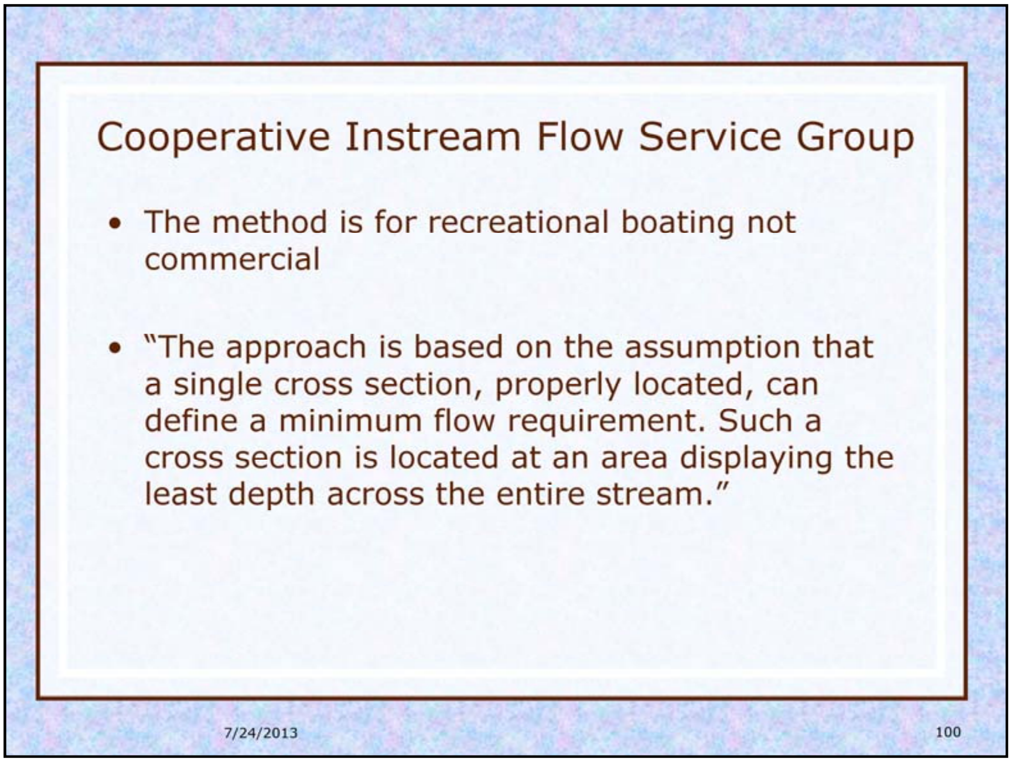
Slope between Transect A2 and A3 is 125 feet per mile



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.

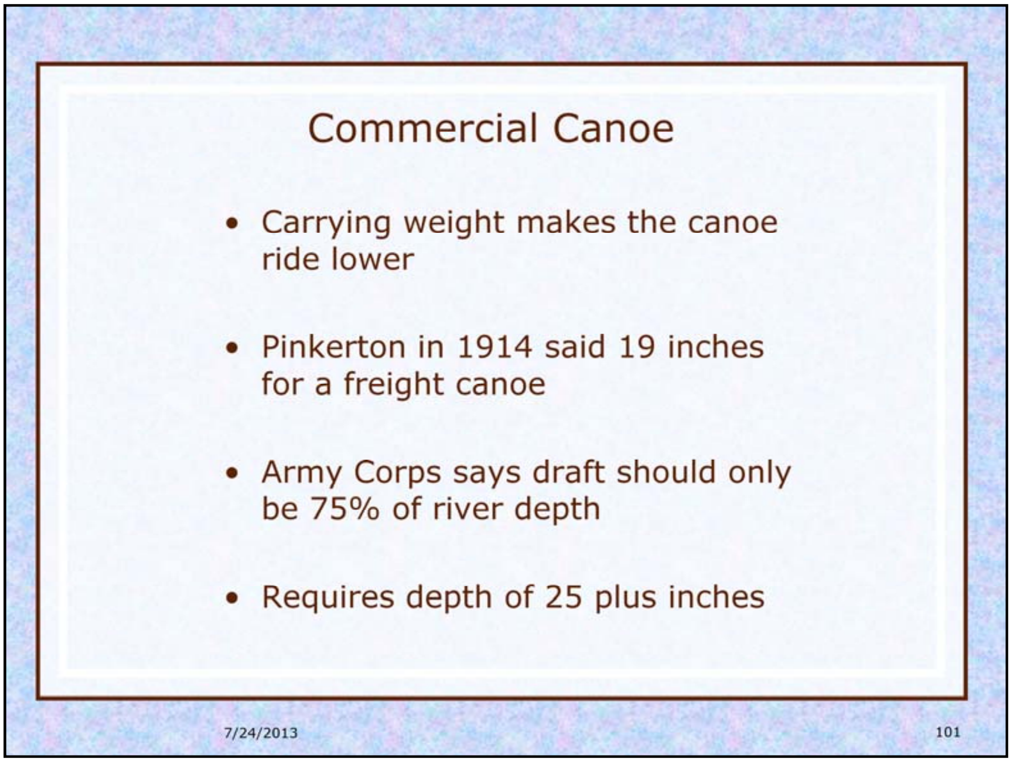
Source: Cortell pg 16



Cooperative Instream Flow Service Group

- The method is for recreational boating not commercial
- “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.”

Source: Cooperative Instream Flow Service Group

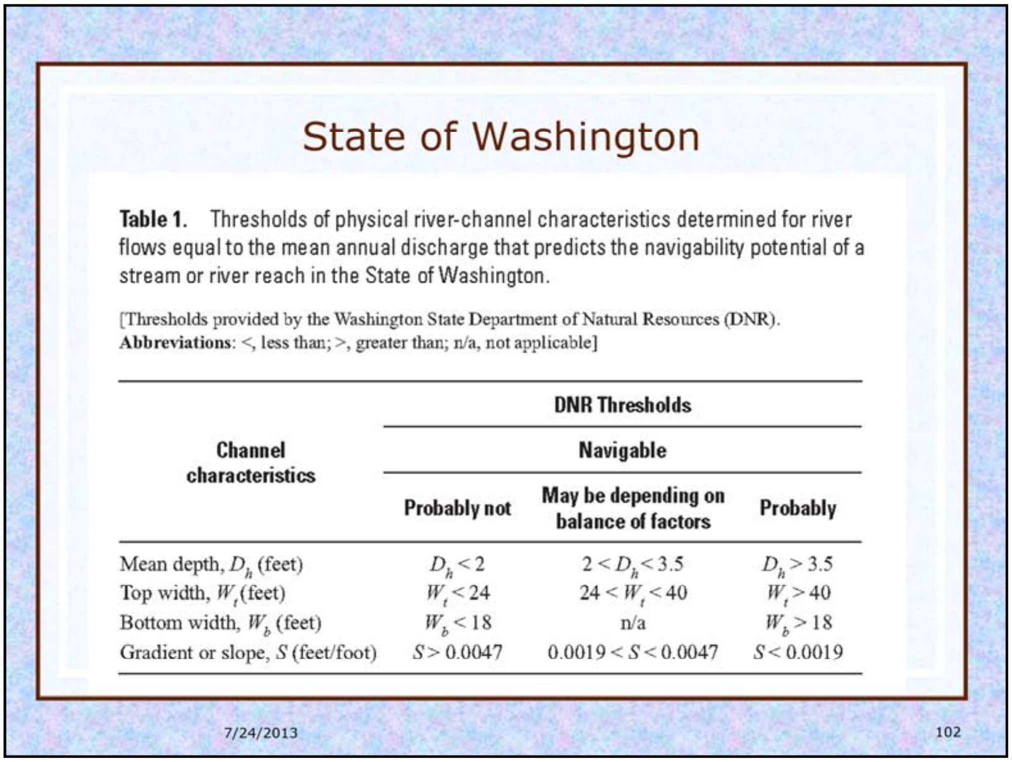


Commercial Canoe

- Carrying weight makes the canoe ride lower
- Pinkerton in 1914 said 19 inches for a freight canoe
- Army Corps says draft should only be 75% of river depth
- Requires depth of 25 plus inches

Source: Pinkerton near the end of Chapter 2

Source: U.S. Army Corps of Engineers 1980 pg 4-2



State of Washington

Table 1. Thresholds of physical river-channel characteristics determined for river flows equal to the mean annual discharge that predicts the navigability potential of a stream or river reach in the State of Washington.

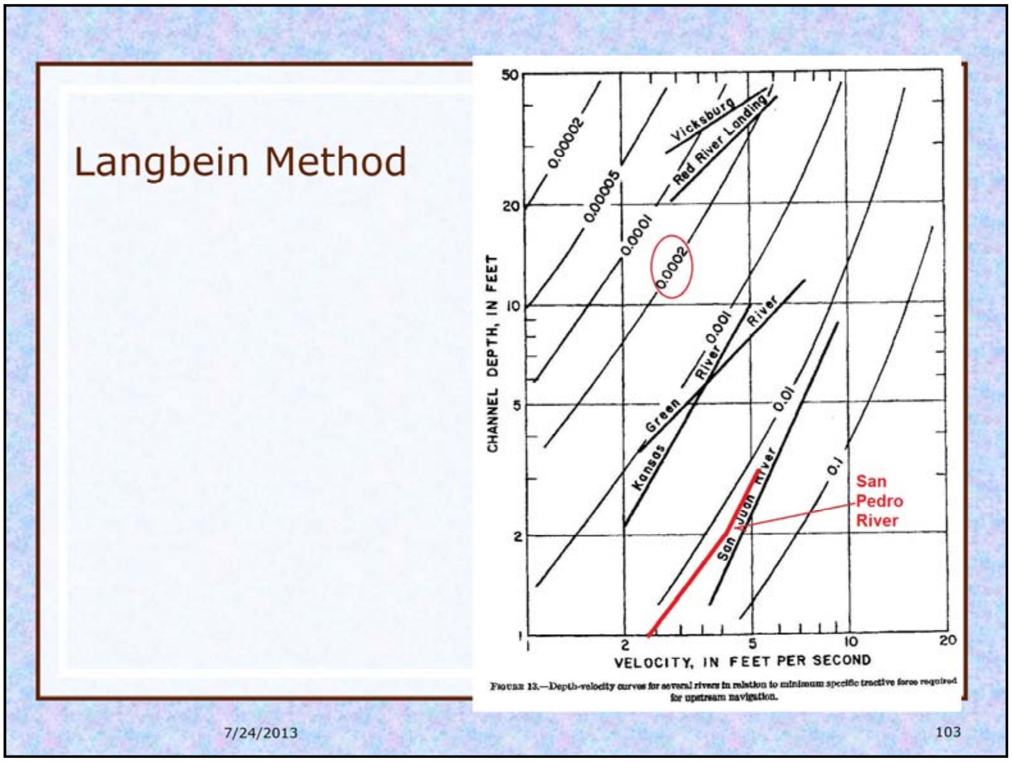
[Thresholds provided by the Washington State Department of Natural Resources (DNR). **Abbreviations**: <, less than; >, greater than; n/a, not applicable]

Channel characteristics	DNR Thresholds		
	Navigable		
	Probably not	May be depending on balance of factors	Probably
Mean depth, D_h (feet)	$D_h < 2$	$2 < D_h < 3.5$	$D_h > 3.5$
Top width, W_t (feet)	$W_t < 24$	$24 < W_t < 40$	$W_t > 40$
Bottom width, W_b (feet)	$W_b < 18$	n/a	$W_b > 18$
Gradient or slope, S (feet/foot)	$S > 0.0047$	$0.0019 < S < 0.0047$	$S < 0.0019$

7/24/2013

102

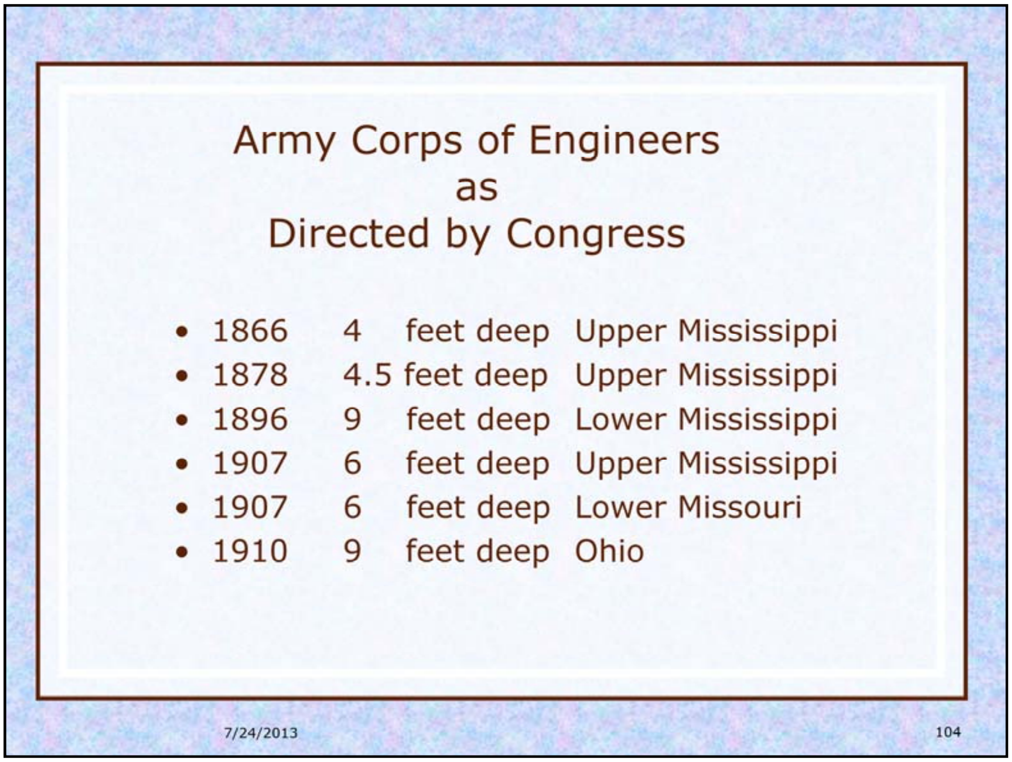
Source: Magirl and Olsen pg 2



Langbein Method

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

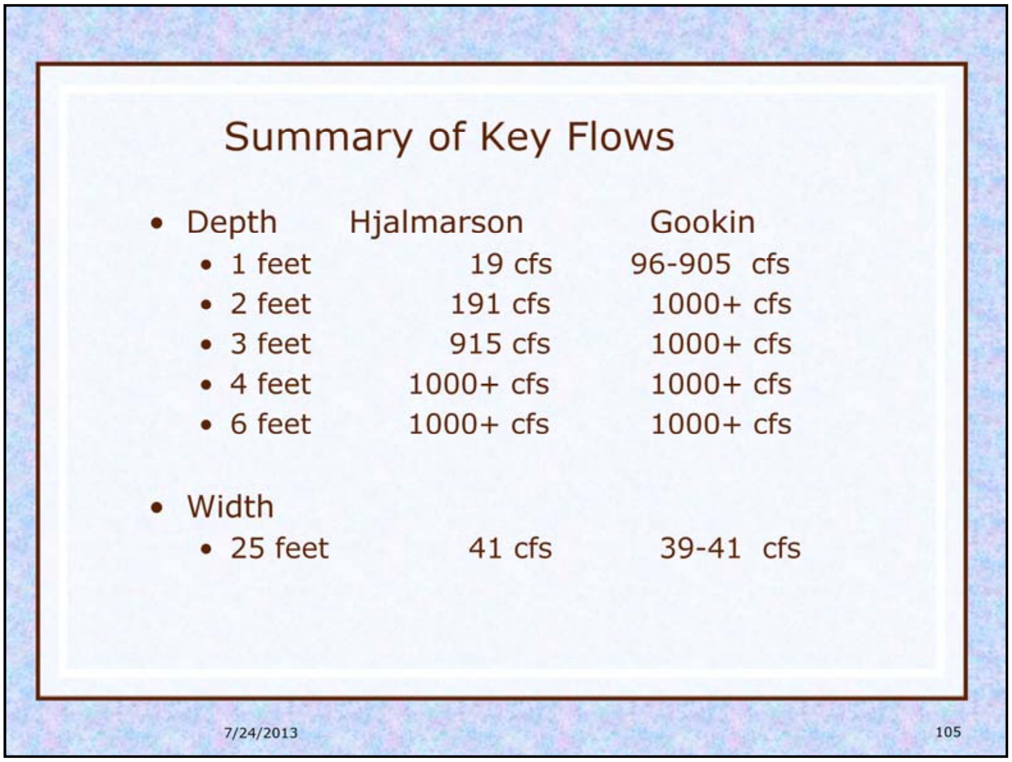
Source: Langbein Figure 13



Army Corps of Engineers
as
Directed by Congress

1866	4	feet deep	Upper Mississippi
1878	4.5	feet deep	Upper Mississippi
1896	9	feet deep	Lower Mississippi
1907	6	feet deep	Upper Mississippi
1907	6	feet deep	Lower Missouri
1910	9	feet deep	Ohio

See Appendix A - Criteria of Navigability



Summary of Key Flows

Depth	Hjalmarson	Gookin
1 feet	19 cfs	96-905 cfs
2 feet	191 cfs	1000+ cfs
3 feet	915 cfs	1000+ cfs
4 feet	1000+ cfs	1000+ cfs
6 feet	1000+ cfs	1000+ cfs
Width		
25 feet	41 cfs	39-41 cfs

For Sand one foot depth requires: 134 cfs

For Riffle one foot depth requires: 96 cfs

For Braided one foot depth requires: 905 cfs

Charleston 6.5 CFS

Appendix A
Supporting Documentation

The Need for Transportation

“The beginning of railroad freight service across southern Arizona on the Southern Pacific Railway's track in 1880 dramatically altered the economic premises of mining in the Gila River watershed. Ever since the Gadsden Purchase, prospectors and investors and speculators in search of mineral wealth had concentrated on very high-grade precious metal ores. When the railroad lowered freight rates to a fraction of those previously paid for wagon transport, mining in the Sonoran Desert region shifted increasingly to exploitation of copper on a massive scale in place of the precious metals. Whereas much of the gold and silver recovered from rich placer and lode deposits had been discovered in pure form--gold in flakes and nuggets, silver in horns and wires -- or could be recovered by milling, copper ores required smelting.”
Dobyns 1981 pg 163

“Mine owners at the new Tombstone camp constructed mills at the edge of the San Pedro River …. In February, a surveyor platted the Charleston townside on the west side opposite Millville and the Tombstone Mill & Mining Company's stamp-mill. Teamster T. S. Harris delivered the first quartz mill, the Toughnut, to Charleston on 28 February. On 6 April Harris left for Gila Bend to load the Corbin Mill and haul it to Charleston. Harris used eight 16 and 18-mule teams to pull his freight wagons.”
Dobyns 1995 pg 43

“The transformation of mining in Arizona Territory can virtually be told in terms of smelter numbers.

1880	2,000,000 pounds
1881	5,000,000 pounds
1882	15,000,000 pounds
1883	24,500,000 pounds”

Dobyns 1981 pg 163

Intermittent Flows

“Historical accounts tend to indicate perennial surface flow in the Rio San Pedro wherever it was crossed. However, Hastings and Turner (1965) found two 1850s references to intermittent flow and an ephemeral reach. Hutton (1859) and Leach (1858)

mentioned an ephemeral nature below Tres Alamos. Lee (1904) described surface flow as continuous, although of small volume during dry seasons."
Hendrickson and Minckley pg 147

"The few American explorers and trappers who ventured into the survey area before 1854 described vast unsettled grasslands, oak-dotted savannas, intermittent sandy-bottomed rivers with powerful seasonal flows" NRCS pg 14

"In the gorge below [Tres Alamos in 1857] and in some of the meadows, the stream approaches more nearly the surface, and often spreads itself on a wide area, producing a dense growth of cottonwood, willows, and underbrush, which forced us to ascend and cross the out-jutting terraces. The flow of water, however, is not continuous. One or two localities were observed where it entirely disappeared, but to rise again a few miles distant, clear and limpid (Parker 1857:25, as cited by Davis 1982:108)."
CH2M Hill pg 3-17

"…a half mile below the bed of the river [in 1857] would be as dry as the road--it sinks & rises again …"
CH2M Hill pg 3-18

"This stream is not continuous all the year [of 1857], but in the months of August and September disappears in several places, rising again, however, clear and limpid,"
Dobyns 1995 pg 27

"Five years later, in the same reach, Parke (1857: 24- 26) noted that: …'The flow of water, however, is not continuous.' "
Hereford and Betancourt pg 136

"A young men [sic] enjoying his adventures on the inter-ethnic frontier wrote to his parents on 1 October 1858 from Tucson that at least some San Pedro River reaches flowed only intermittently. 'We have went [sic] to the river and watered [sic] and it was running fine and a half mile below the bed of the river would be as dry as the road--it sinks and rises again.' "
Dobyns 1995 pg 29

"Intermittent or Interrupted perennial flow for 35 miles below Tres Alamos Wash [1858]."

ADWR Table 3-1

“This steam is not continuous all the year [1858], but in the months of August and September disappears in several places, rising again, however, clear and limpid”
CH2M Hill pg 3-18

“On September 12, 1858, Leach stated:
‘Exceedingly to the surprise of every member of the expedition who had passed over this route in the months of March and April it was discovered after a march of a few miles that the waters of the San Pedro had entirely disappeared from the channel of the stream ...’ ”
CH2M Hill pg 3-18

“The Weekly Arizonian would also record in 1859 which stations, along what is now commonly referred to as the Butterfield Stage route, had water and which did not, for the benefit of travelers. They reported that the San Pedro Station, which was built so close to the river that the waterway later consumed the site, was without water in 1859, long before Tombstone was even discovered and major settlements sprang up along this key, but very limited, water way.”
Rose pg 6

“Settlements along the San Pedro were first established in the 1870s, with the arrival of Mormons at St. David and the discovery of silver near Tombstone (Graham 1976, Fulton 1966). In 1884, the anthropologist Adolph Bandelier visited ruins along the San Pedro and described the arroyos near Tres Alamos and St. David: ‘[At Tres Alamos] the river, now rendered muddy by the washings of the mines worked on its upper course near Contention and Charleston, runs in a cut which is from eight to twelve feet deep... [at St. David] the river runs in a cut with abrupt sides. This cut is 10 to 15 feet deep, and about 25 feet wide (Bandelier 1892: 475-478). ’. This also agrees with McClintock's (1921) account that the first Mormon settlers encountered an entrenched channel of the San Pedro below St. David in 1877. Hastings and Turner (1965) suggest that extensive mesquite thickets existed where the floodplain was entrenched. Mesquite also dominated in the lower reaches where the flow was intermittent.”
Hereford and Betancourt pg 136-7

“The historical record suggests that in the mid-19th century the San Pedro was a continuously perennial stream from its source near Cananea to just beyond the Narrows.

Flow was interrupted (spatially intermittent) in the lower reaches, with the dry discontinuities outdistancing limited surface flow from ground-water outcroppings."
Hereford and Betancourt pg 142

Pre-Entrenchment Soils

"The soils are derived from stratified water-laid deposits somewhat altered by weathering and reworking by surface waters since deposition. They occupy positions adjacent to the San Pedro River, where drainage was rather poorly developed prior to the recent lowering of the channel of the river, and as a consequence the soils contain more or less alkali. The San Pedro fine sandy loam, including a coarse-textured phase, and the San Pedro silt loam were mapped in the area."
Carpenter and Bransford pg 257

"The surface soil of the San Pedro fine sandy loam consists of 6 to 12 inches of a light grayish brown or light-brown fine sandy loam, tinged with pink. The soil is low in organic matter and very loose and porous. The subsoil consists of stratified material, the profile showing two or more strata. The upper layer is of about the same texture as the surface soil, but has a more reddish or pinkish-brown color and varies in thickness from 6 to 14 inches. This is underlain by very dark gray compact clay or silty clay. In places this lower layer is not encountered above 45 inches. Locally the surface soil is rather light textured and approaches a fine sand."
Carpenter and Bransford pg 271

"San Pedro fine sandy loam, coarse-textured phase.-The San Pedro fine sandy loam, coarse-textured phase, consists of 8 to 12 inches of calcareous, reddish-brown or dull-red sandy loam or fine sandy loam carrying considerable coarse sand and some small gravel."
Carpenter and Bransford pg 271

"The surface soil of the San Pedro silt loam consists of 8 to 12 inches of light pinkish brown, calcareous, mellow silt loam. The upper subsoil consists of stratified material ranging in color from light grayish brown to light reddish brown and III texture from a sandy loam to a silty clay loam. …The texture of the surface soil varies somewhat, ranging from very fine sandy loam to light clay loam in areas too small to be shown on the map, though in general the texture of the type is a silt loam."
Carpenter and Bransford pg 272

“Qy2r - Latest Holocene to historical river terrace deposits - Deposits associated with the floodplain that existed prior to the early historical entrenchment of the San Pedro and Babocomari Rivers (Hereford, 1993; Huckleberry, 1996; Wood, 1997). …Qy2r sediments were deposited when the San Pedro and Babocomari Rivers were widespread, shallowly-flowing river systems and are dominated by fine grained floodplain deposits. …These surfaces appear predominantly fine grained at the surface due in part to the input of organic matter and windblown dust deposition but are composed of interfingering coarse sandy to pebbly braided channel and fine sand to silty river floodplain deposits.”
ADWR –App C pg 43

“Specific yield for stream alluvium in the San Pedro Valley derived from model calibration ranges from 13 to 15 percent (Freethey, 1982). Stream alluvium, because of its high hydraulic conductivity and specific yield, permits rapid infiltration of recharge to the underlying aquifer.”
Anderson et. al. 1992 pg B-25

“The alluvial material of the river flood plains is generally coarser grained, less cemented, and, consequently, higher in hydraulic conductivity than the basin fill.”
Freethey pg 7

Post-Entrenchment Soils

“Inset into the basin-fill deposits along the San Pedro River is the recent floodplain alluvium, comprised of unconsolidated, chiefly course-grained sediments that immediately underlie and adjoin, and are in direct hydraulic communication with, the stream.”
Haney pg 311

“The bed material is mainly hard conglomerate overlain by deposits that range from sand to angular and rounded boulders 2 to 3 ft (610 to 920 mm) in diameter. The material surrounding the boulders has a median grain size of 1.2 mm (fig. 14). At the upper end of the reach, conglomerate projections are exposed across the entire channel. The projections are several feet across, and many stand 2 to 3 ft (610 to 920 mm) above the average bed level. Grass and small brush grow along bars at the channel sides.”
Phillips and Ingersoll pg 55

“Qycr - Active river channel deposits - Deposits are dominantly unconsolidated, very poorly sorted sandy to cobbly beds exhibiting bar and swale microtopography but can

range from fine silty beds to coarse gravelly bars in meandering reaches based on position within the channel."
ADWR –App C pg 42

Riffles

"The riffle is a bed feature that may have gravel or larger rock particles. The water depth is relatively shallow, and the slope is steeper than the average slope of the channel. ….. Riffles enter and exit meanders and control the streambed elevation. Pools are located on the outside bends of meanders between riffles. The pool has a flat surface (with little or no slope) and is much deeper than the stream's average depth. At low flows, pools are depositional features and riffles are scour features."
North Carolina Stream Restoration Institute pg 10

"Natural channels characteristically exhibit alternating pools or deep reaches and riffles or shallow reaches, regardless of the type of pattern." Leopold and Wolman pg 39

"Another characteristic of natural streams even in straight reaches is the occurrence of pools and riffles. This has been noted by Pettis (1927), Dittbrenner (1954),). "
Leopold and Wolman pg 53

River Variability

"The planform geometry of a stream is determined by the interaction of numerous variables and one should anticipate to observe a complete range of channel patterns in most river systems (Simons and Julien, 1984)…. Equilibrium planform geometry rarely develops when natural flow and sediment supply variations are considered."
Julien pg 1

"… it cannot be reasonably assumed that single values of the exponents describe the range of conditions found in natural alluvial stream channels. The wide ranges of possible exponent values become apparent when the geometries of unusually wide or narrow channels are considered."
Osterkamp et. al. 1983 pg 1

"Many streams that may not be boatable due to boulders, vegetation, frequent waterfalls, or significant natural hazards may have average annual flow rates or flood peaks that, when combined with hydraulic geometry relationships, indicate that boating could occur."

Stantec Consulting pg 15

“Field training and experience are necessary for effective selection of the active-channel reference levels. Unusually shaped channel cross sections need to be avoided. Relatively straight or stabilized reaches of meandering channels need to be selected where active bank cutting or deposition is not in the process of changing the channel width.”
Hedman and Osterkamp pg. 15

“Stromberg and Tellman (2009) observed, ‘Dryland rivers have some of the most variable flow regimes in the world, as wet periods alternate with dry periods, river channels widen and contract, water levels peak and recede, and vegetation waxes and wanes.’ ”
Noonan pg 6

<u>Prehistoric Entrenchments</u>

“Synchronous arroyo incision in the San Pedro and Santa Cruz valleys,100 and 150km west of the San Bernardino cienega, centered on 4400, 2700, 1800, and 900 cal yr BP suggest periods of high runoff (Waters and Haynes, 2001).”
Minckley and Brunelle pg 428

“Valley degradation within the last 1 My has been due to a combination of slow, regional uplift of the Central Highland Zone in Arizona (Shafiqullah and others, 1980; Menges and Pearthree, 1989) and the San Pedro River's attempt to maintain a graded level or longitudinal profile of equilibrium (Mackin, 1948) as it became connected to the Gila River. During periods of temporary equilibrium the San Pedro River and its tributaries formed erosional strath terraces (Bull, 1991). Since latest Pleistocene and Holocene time, the river has deposited sediments within the axial trench of the basin. (Haynes, 1987; Hereford, 1993; Morrison, 1985). Stratigraphic investigations in the upper San Pedro River Valley by Haynes (1987) indicate that the San Pedro River has repeatedly incised and backfilled its flood plain during the Holocene (approximately 10 ka to present).”
Huckleberry pg 5

“At least six episodes of arroyo formation occurred in prehistoric times. Waters and Haynes (2001) studied stratigraphic records of the Santa Cruz River, tributaries of the San Pedro River, and Whitewater Draw in the Sulfur Springs Valley. Except possibly at the Lehner site, 9 arroyo cutting was absent from about 15,000 to 18,000 14C B.P. During this period, woodlands covered the floors of desert basins, and conditions were

unsuitable for arroyo formation. Arroyo cutting occurred sometime between about 5600 and 8000 14C B.P. on the Santa Cruz River floodplain, approximately 7500 14C B.P. along the San Pedro River, and about 6700 14C B.P. along Whitewater Draw. The frequency of arroyo cutting increased greatly after about 4000 14C B.P.. Five subsequent prehistoric episodes of synchronous channel entrenchment occurred along Curry Draw and other low order streams in the San Pedro River Valley and on the floodplain of the Santa Cruz River. Entrenchments occurred near 4000 14C B.P. in the San Pedro and Santa Cruz valleys, at about 2600 and 2500 14C B.P. in the San Pedro and Santa Cruz valleys respectively, at approximately 1900 and 2000 14C B.P. in the San Pedro and Santa Cruz valleys respectively, near 1000 14C B.P. in the Santa Cruz and San Pedro valleys, and at about 600 and 500 14C B.P. in the San Pedro and Santa Cruz valleys respectively."
Noonan pg 8-9
[14C B.P. means years before 1950 as determined by carbon dating]

"Stratigraphic investigations in the upper San Pedro River Valley by Haynes (1987) indicate that the San Pedro River has repeatedly incised and backfilled its flood plain during the Holocene (approximately 1 ka to present)."
CH2M Hill pg 5-7

"Three of the prehistoric arroyo cutting episodes along the Santa Cruz River and the tributaries of the San Pedro River Valley corresponded with wet periods as documented by pollen, pack rat middens, and geological records at about 4000, 1000, and 500 14C B.P. The poorly documented paleoenvironmental records for about 2000-2500 14C B.P. prevented 14 correlation of arroyo entrenchment with a particular wet period. However, evidence from lakes along the Mogollon Rim showed that desiccated lake basins filled with water between approximately 3000 and 2000 14C B.P., demonstrating that precipitation increased during that time."
Noonan pg 13-14

"All SWD-PSI paleoflood studies conducted thus far in Arizona and adjacent areas (Figure 3) reveal a remarkably consistent record. Certain time intervals during the past few millennia have been characterized by occurrences of extraordinarily large floods, while other intervals have been relatively free of such events. Major episodes of flooding occurred from approximately 1000 to 1200 yr B.P. and during the past century or two. A somewhat less intense phase of flooding occurred between approximately 400 and 600 yr B.P. Time intervals between these flood phases were characterized by fewer, smaller

floods. In addition, there are many indications that channel entrenchment on alluvial streams (arroyo formation) was coincident with flood phases, while aggradation was generally coincident with phases of reduced flooding (Webb, 1985)."
Baker pg 129

Beavers
"Every 5 miles is a beaver dam this is a great Country for them."
CH2M Hill pg 3-18

"A limit to the extent of beaver ponds is set by geomorphological constraints (Johnston and Naiman, 1990) and the territorial behaviour displayed by the individuals and family groups responsible for building and maintaining dams. Boyce (1981) and Baker and Hill (2003) suggested that territorial behaviours resulted in >1 km between colonies. This limit is consistent with the 0.35–0.60 colonies per river kilometer reported for two large cold-desert rivers (Breck et al., 2001)."
Andersen and Shafroth pg 335

"Where beaver populations are undisturbed, localized dam frequencies range from 7.5 per km to as high as 74 per km, with frequencies of around 10 dams per km being more typical in low-gradient streams (Table 1; Warren 1926; Scheffer 1938)."
Pollock et. al. pg 3

"Two studies examining dam occurrence across entire, multiple watersheds found frequencies of 2.5 per km for the 750 km^2 Kabetogama Peninsula in Minnesota and 9.6 dams per km for an 85 km^2 area encompassing two watersheds in Wyoming (Skinner et al. 1984; Johnston and Naiman 1990b)."
Pollock et. al. pg 3

"Reported colony densities of remote or protected populations show a trend of lower densities in subarctic regions and higher densities in more temperate regions, with an overall average of a little less than 0.5 colonies per km (Table 2)."
Pollock et. al. pg 3

"However, we will never be certain whether current estimates of individuals per colony or colony densities are applicable to historic populations. Because colony density is affected by habitat quality, it is not unreasonable to assume that, historically, overall colony densities were much higher, and thus populations much greater, when the entire

vast, productive lowland river bottom habitat throughout North America had not yet been altered by humans and was available for beavers to use."
Pollock et. al. pg 4-5

"Beaver prefer to dam small, low-gradient streams with unconfined valleys, but they can also dam both large and high-gradient streams. Retzer et al. (1956) studied 365 reaches in 61 streams throughout Colorado to determine the physical factors determining beaver pond location. Beaver built dams on 82% of all the low-gradient (1– 3%) streams surveyed."
Pollock et. al. pg 5

Cienegas
"Before the Civil war these same streams wound sluggishly along for much of their course through grass-choked valleys dotted with cienegas and pools."
Dobyns 1995 pg 28

"In the gorge below, and in some of the meadows, the stream approaches more nearly the surface, and often spreads itself on a wide area, producing a dense growth of cotton-wood, willows and underbrush, which forced us to ascend and cross the terraces."
Hjalmarson 1988 attachment to article

"…Hutton (1859) gave a similar description for the reach just below Tres Alamos in 1857: 'The San Pedro … widens out, and from beaver dams and other obstructions overflows a large extent of bottomland, forming marshes, densely timbered with cottonwood and ash.' "
Hereford and Betancourt pg 136

"the valley of the San Pedro 'had a shallow grassy bed and banks covered with luxuriant vegetation.' (Mann 1963:4)."
CH2M Hill pg 3-5

"Analysts of vegetational change in the San Pedro and Santa Cruz River valleys concluded: 'Before the Civil War these same streams wound sluggishly along for much of their course through grass-choked valleys dotted with cienegas and pools',"
Dobyns 1995 pg 28

“Researchers have used of the term ‘cienega’ to describe wetland sediments characterized by ‘dense carpets of tall sacaton grass, forming wet meadows’ (Antevs 1952).”
Ballenger pg 34

The Abundance of Grass 1846 to 1870

“On December 12 [1846], he [Cooke] wrote that the valley floors were, on average, more than a mile wide and covered with grass so tall that it was sometimes difficult to pass through it (Cooke 1974:145).”
CH2M Hill pg 3-14

“Tyler (1881) described the boggy nature of the stream at ‘Bull Run’ (presently Lewis Springs) in 1846: ‘A kind of cane grass grew in this region, from four to six feet high, being very profuse and luxuriant in the bottom near the stream.’ ”
Hendrickson and Minckley 1984 pg 145

“The Mormon Battalion first camped [in 1848] in the valley ‘in a marshy bottom with plenty of grass and water’ (Cooke, 1938). Here and for two days travel downstream conditions remained the same. ”
Hendrickson and Minckley 1984 pg 145

“Cooke (1938) was impressed by the valley [in 1848], and apparently referred to Sporobolis airiodes when he mentioned ‘... bottoms having very high grass and being lumpy’ near Lewis Springs. The next day he wrote ‘the bottom grass is very tall and sometimes difficult to pass through. These bottoms average above a mile and are good land.’ ”
Hendrickson and Minckley 1984 pg 145

“Where Parke descended [in 1854] into the valley eastbound, ‘This bottom is bounded on both sides by an irregular zigzag step, much indented by deep washes, and it is at this point about three miles wide. It is covered with a growth of grass, now dry and crisp.’ ”
Dobyns 1995 pg 25

“The few American explorers and trappers who ventured into the survey area before 1854 described vast unsettled grasslands, oak-dotted savannas, intermittent sandy-bottomed rivers with powerful seasonal flows.”
NRCS pg 14

"James Bell was such an example, bringing a herd of cattle through Arizona on the way to California in the summer of 1854. 'The valley through which the San Pedro passes is a desirable location for ranches. The hills on either side are covered with timber ... and a good quality of grass; some portions of these hills are verry [sic] pretty.' "
Rose pg vi

"Along the 'improved' new route Hutton reported phreatophytes [in 1857]. Along the first twenty miles, descending, the valley is not more than one fourth of a mile in width, bounded on either side by sloping grass-covered terraces from the San Calisto and Santa Catarina mountains, its banks fringed with a growth of cottonwood and ash. Below it opens out, having a varying width between foot hills of from three-fourths of a mile to three miles, with broad rich meadows and well timbered banks, the gradually sloping hill-sides covered with a luxuriant growth of gama and other grasses, and the more elevated slopes densely timbered with mezquit. "
Dobyns 1995 pg 28

"Leach (1858) reported broad Sacaton bottoms 'below Tres Alamos, with Cottonwood, Ash, and Willow lining the river.' "
Hendrickson and Minckley 1984 pg 146

"A Texan westbound from Sulphur Spring in 1867 reached the stream at the Middle Crossing. 'Here we find good grass and water small musquet [sic] for wood the Pedro is small shallow stream sandy with no timber on its banks.' "
Dobyns 1995 pg 32

The Cattle were Disappearing

"Wild herds appeared to dwindle rather quickly, possibly due to hunting by Apaches, military expeditions, and 49ers (Browne, 1869; Bell, 1932)."
Henderson and Minckley 1984 pg 144

"He [James Bell] also noted that the vast herds of cattle reported a few years before had disappeared [1854] (Bell 1932:306)."
CH2M Hill pg 3-18

" [T]here is evidence that large numbers of cattle, horses, sheep, goats, burros, and mules may have been in the region from 1700 to 1840, especially in the 1820S and 1830S, when large Mexican land grants were established …(Cameron 1896; Mattison 1946)."

Bahre pg 114

“Even if there had been large numbers of cattle in the region in the I820s and I830s, there is no evidence of overgrazing.”
Bahre pg 114

The First Historic Entrenchment

“At the Tres Alamos [in the 1850’s] the stream is about fifteen inches deep and twelve feet wide, and flows with a rapid current over a light, sandy bed, about fifteen feet below its banks, which are nearly vertical.”
Hjalmarson 1988 attachment to article

“[T]he cumulative archival evidence suggests that the upper San Pedro River was indeed discontinuously entrenched as early as 1850 (Henderson and MinckIey, 1984:147),”
Huckleberry pg 9

“During the U.S.-Mexico boundary survey of 1851, John Russell Bartlett (1854) also noted continuous streamflow in the upper San Pedro River, but he also noted that the river below St. David (Figure 1) contained steep banks approximately 3 m (9 ft) high (Bartlett, 1854; also in Hastings, 1951, and Hereford and Betancourt, 1993).”
Huckleberry pg 8

“Lt. Col. Graham of the international boundary survey party also described the stream (Graham 1852:35-36, as cited by Davis 1982:64, and Hastings and Turner 1965:293). ‘The San Pedro was pretty high when we arrived here. It is very muddy, with a quick current, resembling very much the Pecos, or Rio Puerco, for this is its proper name—which means dirty or muddy river. The San Pedro runs here through a soft, alluvial soil, and its rapid current has worn a deep bed for it, leaving steep banks on either side.’ ”
CH2M Hill pg 3-16

“John Russell Bartlett (1854) also noted continuous streamflow in the upper San Pedro River, but he also noted that the river below St. David (Figure 1) contained steep banks approximately 3 m (9 ft) high (Bartlett, 1854; also in Hastings, 1951, and Hereford and Betancourt, 1993). Bartlett further noted that incision limited the ability to irrigate adjacent terraces. A few years later, Parke (1857:24) noted that the upper San Pedro River was variably incised from a few cm to as much as 5 m (15 ft).”
Huckleberry pg 8-9

“Also in 1854, Andrew B. Gray surveyed a railroad route for a private company, and crossed the middle reach of the San Pedro River. ‘The San Pedro River, where we struck it, in latitude 31" 34' is a small stream at this stage ,about eight feet wide, and shallow; between steep banks 10 feet high and 25 to 50 feet apart. ... At three points that I have crossed it, it is a living stream with large fish. ... Occasional bunches of mezquite and cotton-wood are seen upon its borders.’ (Gray 1856:76-77, as cited by Davis 1982: 1 07).”
CH2M Hill pg 3-18

“Five years later [in 1857], in the same reach, Parke (1857: 24- 26) noted that: ‘The valley bottom is generally smooth and open, with the streambed curving through it, sometimes a few inches, and at others as much as fifteen feet below the surface of the meadow’ ”
Hereford and Betancourt pg 136

“The San Pedro, at the first point reached in the present road [in 1858], has a width of about twelve (12) feet, and depth of twelve (12) inches, flowing between clay banks ten or twelve feet deep, ”
CH2M Hill pg 3-18

“From the journals of itinerants we know that the river was entrenched at St. David, Tres Alamos, and below the Narrows (Figure 1), with perpendicular banks 3 to 6 m deep as early as the 1850s.”
Hereford and Betancourt pg 134

“A few years later, Parke (1857:24) noted that the upper San Pedro River was variably incised from a few cm to as much as 15 feet. Immediately upstream from The Narrows, Hutton (1859) described the upper San Pedro River as having a width of approximately 12 feet and a depth of 12 inches. Although Hereford (1993) cautions that some of these historical descriptions may be of steep banks on older terraces above the active channel, the cumulative archival evidence suggests that the upper San Pedro River was indeed discontinuously entrenched as early as 1850 (Henderson and Minckley, 1984:147), at least thirty years before the estimate of arroyo initiation made by Kirk Bryan (1926).”
CH2M Hill pg 5-10

“Builders of the Leach Wagon Road encountered incisions just above ‘The Narrows’ but broad, marshy conditions below (Hutton, 1859). Cooke and Reeves (1976) found surveyors' reports (1873 - 81) to indicate incision along some reaches, but lack of it elsewhere. It seems clear that entrenchment was local and discontinuous as early as the 1850s.” Hendrickson and Minckley pg 147

The 1880’s Entrenchment

“Newspaper accounts indicated that large floods occurred on the San Pedro River in 1881, 1886*[2], 1887*, 1890*, 1891*, 1893, 1894, 1896, 1900, 1901*, 1904*, 1905*, and 1926*”
Wood pg 5

“An 1883 photograph of Charleston (Hastings and Turner 1965:36, 162, plate 51a) shows the San Pedro River with a well defined channel trench. In 1883-1884, a flood destroyed the old Butterfield stage station and bridge at Benson (Conkling and Conkling 1947: 150). Bandelier (1892: pt.2, 478), who traveled through the area just before the flooding and arroyo cutting of the 1890's described the San Pedro River a few miles north of the mouth of Dragoon Wash as an entrenched stream within "a cut with abrupt sides ... 10 to 15 feet deep, and about 25 wide.”
CH2M Hill pg 3-20

The 1890 Entrenchment

“A series of large floods in 1890, 1893, 1894, and 1896 resulted in channel cutting and widening along some portions of the lower San Pedro River (Hereford and Betancourt, 1993).”
CH2M Hill pg 5-13

“Dobyns claims that the flood of 1890 caused the ‘death of the San Pedro River’, which removed or drained numerous swampland areas along its course. The 1891 flood may have actually been larger than the 1890 flood, but the newly entrenched channel of the San Pedro conveyed the flood more efficiently (Dobyns, 1978).”
CH2M Hill pg 7-19

Reaches Not Entrenched in 1890

“…residents of the lower San Pedro River whose family records and historical photographs suggested that the lower San Pedro River had a history of channel change

significantly different from that of the upper San Pedro River. In particular, they believed that greater channel changes resulted from the 1926 flood event than from the 1890's flood events.”
Wood pg 1

“Newspaper accounts of the Mammoth/Dudleyville area, and Bayless' account, indicated that the widening of newly-formed arroyos and the extension of headcuts continued after the floods of the 1890's as a result of subsequent flood events. However, several lines of evidence indicated that incision as dramatic, if not more dramatic, resulted from the 1926 flood event. The comparison of the elevations of the pre-1926 Los Angeles Ditch and the 1927 Bayless Ditch, the comparison of the pre- and post-1926 locations of the Bayless Ditch intakes, the newspaper accounts and oral histories - all indicated that the 1926 flood event widened and/or incised any segment of the Redington and Mammoth/Dudleyville reaches that had not yet been notably entrenched”
Wood pg 35-36

“The hypothesis that the down-cutting of the San Pedro River north of The Narrows occurred in two periods (Cooke and Reeves, 1976; Melton, 1965; and Jones, 1968) seems the most likely. The newspaper articles, the analysis of the historical movement of the Bayless Ditch intake, and Bayless' account indicated that, at the very least, several segments of the San Pedro River channel became entrenched as a result of the 1890's flood events (e.g., at the Redington Narrows and near Mammoth and Dudleyville). In contrast, accounts of the Cascabel area, and the analysis of the historical movement of the Bollen Ditch intake, indicated that some channel segments did not become entrenched until the 1926 flood event…."
Wood pg 35

Floods and Entrenchment

“The frequency of large floods on the San Pedro River increased as early as 1890, although Hereford (1993) notes that on the upper San Pedro River it was greatest between 1915 and 1940. This period of increased large frequency during the early part of the 20th century undoubtedly affected channel geometry and position.”
Huckleberry pg 14

“The morphology of the channel is controlled largely by the frequency of channel-forming floods (the control variable). The annual flood series at Charleston (Hirschboeck

this volume) shows a clear pattern of relatively frequent large floods (defined as events in the upper quartile of all flows) during the first part of the 20th century."
Hereford and Betancourt pg 141

"Newspaper accounts, survey records, and other written records describe extensive channel erosion in association with the series of large floods that occurred near the turn of the 19th century."
Hereford and Betancourt pg 141

"Based on Holocene stratigraphy (e.g., Haynes, 1987; Hereford, 1993), entrenchment and widening have occurred in the past and appear to be a natural cycle within the fluvial system. This may simply be a fluvial adjustment to changes in the discharge: sediment load ratio. Human disturbances probably have also affected the magnitude and rate of channel change on the San Pedro River (Bahr, 1991; Dobyns, 1981), but the driving force in these changes are probably not anthropogenic."
CH2M Hill pg 5-16

"Major channel changes along the San Pedro River have occurred primarily as a result of large flood events (Hastings, 1959; Hastings and Turner, 1965; Cooke and Reeves, 1976; Hereford and Betancourt, in press). Newspaper accounts indicated that large floods occurred on the San Pedro River in 1881, 1886*[2], 1887*, 1890*, 1891*, 1893, 1894, 1896, 1900, 1901*, 1904*, 1905*, and 1926* "
Wood pg 5

"The channels of several alluvial streams have become entrenched because a balance was not maintained between factors such as flow, sediment discharge, slope, meander pattern, channel cross-section, and roughness. For example, minor fluctuations in meteorological conditions over a few years can alter the movement, transport, and production of sediment in a basin. During drier years, sediment can accumulate in stream channels, and subsequent wetter years may cause the sediment to be flushed from the basin. Reaches of channel with conditions of both uniform flow and nonuniform flow may appear to be aggrading or degrading. Thus, a reach of channel on an alluvial stream will not necessarily remain stable over a period of a few years."
Hjalmarson 1988 pg 1

Stream Recovery

“Changes in channel shape and planform can occur at a variety of timescales ranging from 1 to 10,000 years. Arid and semiarid streams tend to be more susceptible to rapid changes in channel geometry (Graff; 1988) and require a greater amount of time to reform their original geometry following a disturbance (Wolman and Gerson, 1979).”
Huckleberry pg 7

“Cienega surfaces may remain in a state of equilibrium for long periods of time, as evidenced by long periods of slowly accumulating sediments. The threshold by which the degradation of the surface occurs is not often exceeded, evidenced by the few unconformities in sediments examined from San Bernardino cienega. However, once degradation begins, restoring equilibrium can take significant periods of time (e.g., Fig. 5, 1100–2500 cal yr BP). The regional arroyo history suggests that these unconformities likely represent extraordinary increases in surface flow, which led to scouring of the cienega surface (Waters and Haynes, 2001; Nordt, 2003).”
Minckley and Brunelle pg 429

“Wohl (2000b, p. 167) states …: ‘A flood may cause dramatic changes along some reaches of a channel and have relatively little effect on other reaches. Similarly, a flood that occurs once every hundred years may create erosional and depositional forms that are completely reworked within 10 years along one channel, but that persists for decades along a neighboring channel.’ ”
Schumm pg 127

“Arid and semiarid streams tend to be more susceptible to rapid changes in channel geometry (Graf, 1988) and require a greater amount of time to re-establish their original geometry following a disturbance (Wolman and Gerson, 1979)”
CH2M Hill pg 5-8, 9

“Here, and in other semiarid and arid regions, channel recovery after a flood may take several decades.”
Friedman et. al. pg 2167

“In arid regions and smaller watersheds, flow variability is higher and extreme events can cause channel changes that persist for decades or centuries (Baker 1977)”
Friedman et. al. pg 2168

Statehood Condition

“By 1912, few beaver were found on the river, large fish were all but eliminated, and a deep arroyo had formed over most of the study area (Dobyns, 1978), leaving the San Pedro river channel as a braided stream winding back and forth on a sandy bed located within an entrenched floodplain (USGS, 1901). Furthermore, most investigators believe these channel changes to be, at least in part, caused by natural forces (cf. Cooke and Reeves, 1976; Hastings and Turner, 1965). Therefore, natural stream conditions as of statehood were probably not dissimilar to existing stream conditions.”
CH2M Hill pg 7-5

“The depth of the modem entrenched channel varies 1 to 6 m (5 to 20 ft) throughout the San Pedro River (Kottlowski and others, 1965:Figure 1) and probably does not differ substantially from channel depths in 1912.” Huckleberry pg15

“Channel entrenchment had begun on the San Pedro River several decades before statehood, and most of the San Pedro River was already entrenched by 1912 (Bahr, 1991; Cooke and Reeves, 1976; Haynes, 1987; Hereford, 1993; Hereford and Betancourt, 1993). Exceptions were along short bedrock reaches (e.g., The Narrow) and a reach near Hereford that was only I to 3 feet deep between 1910 and 1914 (Haury and others, 1959).”
CH2M Hill pg 5-15

“Cooke and Reeves (1976) cited Melton (1965) and Jones (1968) when they noted that marked downcutting north of The Narrows appeared to have occurred in two periods: prior to 1895, when a continuous sand-bed was formed; and, 1926-27, when major floods resulted in notable incision. Entrenchment was reported to have happened as late as 1926-27 between The Narrows and Hot Springs Canyon near Cascabel (Melton, 1965, oral communication with a rancher, Charles Gillespie, as cited in Cooke and Reeves, 1976).”
Wood pg 23

“Beginning in the 1880's and continuing into the 1890's were a series of large floods that impacted the geometry of the upper San Pedro River (Hereford and Betancourt, 1993). Large floods occurred in 1886, 1887, 1890, and 1896. The impacts of these floods were variable, but overall they resulted in expanding the entrenched reaches upstream via knick-point retreat (Hastings, 1959; Hereford and Betancourt, 1993) and expanding channel width via bank cutting and collapse (Meyer, 1989). Cadastral survey notes confirm channel widening after 1890 (Cooke and Reeves, 1976; Appendix A).”
Huckleberry pg 10

"Cooke and Reeves (1976) cited Melton (1965) and Jones (1968) when they noted that marked downcutting north of The Narrows appeared to have occurred in two periods: prior to 1895, when a continuous sand-bed was formed; and, 1926-27, when major floods resulted in notable incision. Entrenchment was reported to have happened as late as 1926-27 between The Narrows and Hot Springs Canyon near Cascabel (Melton, 1965, oral communication with a rancher, Charles Gillespie, as cited in Cooke and Reeves, 1976)."
Wood pg 23

"Settlements along the San Pedro were first established in the 1870s, with the arrival of Mormons at St. David and the discovery of silver near Tombstone (Graham 1976, Fulton 1966). In 1884, the anthropologist Adolph Bandelier visited ruins along the San Pedro and described the arroyos near Tres Alamos and St. David: "[At Tres Alamos] the river, now rendered muddy by the washings of the mines worked on its upper course near Contention and Charleston, runs in a cut which is from eight to twelve feet deep... [at St. David] the river runs in a cut with abrupt sides. This cut is 10 to 15 feet deep, and about 25 feet wide (Bandelier 1892: 475-478).". This also agrees with McClintock's (1921) account that the first Mormon settlers encountered an entrenched channel of the San Pedro below St. David in 1877. Hastings and Turner (1965) suggest that extensive mesquite thickets existed where the floodplain was entrenched. Mesquite also dominated in the lower reaches where the flow was intermittent." Hereford and Betancourt pg 136-7

Channel Geometry Method, Braiding and Flooding

"The channel-geometry method will not give good results in stream reaches
having the following conditions:
1. Braided channels. …
5. Channels that have been widened or realigned by an extreme flood"
Omang et. al. pg 12

"Regime equations …may not be appropriate for braided … systems. Many Arizona streams are … braided … systems."
Stantec Consulting pg 15

"Field training and experience are necessary for effective selection of the active-channel reference levels. Unusually shaped channel cross sections need to be avoided. Relatively straight or stabilized reaches of meandering channels need to be selected where active bank cutting or deposition is not in the process of changing the channel width. Braided

reaches need to be avoided, as well as reaches in the channel that indicate the channel has been widened or realigned by an extreme flood … and has not had time to readjust. ”
Hedman and Osterkamp pg 15

“Most natural alluvial stream channels do not have nearly constant discharge, but show variations of at least several orders of magnitude. A channel that is widened by the excessive shear stresses of an erosive flood, therefore, is not adjusted to the conditions of mean discharge following the flood. Generally, the channel requires an extended period of normal flow conditions and shear stresses before accretion and deposition of fine sediment are sufficient to affect channel narrowing and an essentially adjusted geometry. If the sediment available for fluvial transport is principally of sand sizes, the rate of narrowing may be slow owing to a lack of fine cohesive material to form a stable channel section.”
Osterkamp et. al. 1983 pg 14

“…it is not accurate for channels of most sand-bed streams…”
Osterkamp et. al. 1980 pg 191

“[T]he most significant effect on channel morphology appears to be the timing of flood events.”
Osterkamp et. al. 1980 pg 191

Channel Geometry Method-Error

“When Leopold and Maddock published US Geological Survey Professional Paper 252 it was a landmark occasion. …However, some of us neglected to recognize how variable the relations were and how significant was the scatter about the regression lines. This should have warned us that, yes, in a general sense channel width increased downstream as the 0.5 power of discharge, but a prediction of what the width was around the next bend could be in gross error… ”
Schumm pg 1

“For example, using Thomas et. al. (1994) 2-year peak flow regression equation, a 450 acre watershed in Region 13 (Pima County) draining to a 10 ft wide ephemeral stream will indicate at 2-year flow depth of 1.7 ft, which would be boatable by a canoe. Using Hedman & Osterkamp (1982) mean annual discharge equation, the same channel would indicate a mean annual flow rate of 0.001 cfs, which would be non-navigable by any boat type. However, Hedman & Osterkamp's equation for ephemeral streams in the desert

southwest, the stream would need to be 72,000 feet wide to predict a mean annual flow rate of 100 cfs. Compare these numbers to Rillito near Tucson (#09486000): (I) USGS Gage Data: Q2=5, 120 cfs; Qav=14 cfs; Q50%=O.O1 cfs; W=400 ft; (2) Hedman & Osterkamp Qav=O.24 cfs, (3) Thomas et. al. Q2=3,400 cfs."
Stantec Consulting pg 15-16 footnote 2.

"The method, as indicated by standard errors of estimate and other statistical measures, is most accurate when applied to perennial streams with stable banks. Examples are upland streams with coarse material (armor) protecting the bed and banks from erosion, and valley streams with well- vegetated banks formed largely of cohesive silt and clay. Conversely, the use of channel geometry probably is least accurate when applied to streams of flashy or erratic discharge (including ephemeral streams) that have sandy, noncohesive banks, and lack of well-developed growth of riparian vegetation."
Hedman and Osterkamp pg 6

"In general, these types of channel characteristic methodologies are not accurate when applied to most streams in Arizona because the influence of floods (rather than median flow) on channel geomorphology."
Stantec Consulting pg 60

"Hydraulic geometry equations generally are not accurate in semi-arid regions like Arizona because: (1) they assume a relatively constant channel forming discharge, (2) they assume floods are essentially non-erosive, and (3) they are most accurate for cohesive bank: materials with high silt/clay content."
Stantec Consulting pg 15

"A nationwide study of these methodologies concluded: 'Results of the regression analyses indicate that streamflow characteristics can be defined more accurately in the humid Eastern and Southern regions than in the more arid Western and Central regions, that medium flows can be more accurately defined than high flows, and that low flows can be only weakly defined. ' "
Stantec Consulting pg 60

"[T]he use of channel geometry probably is least accurate when applied to streams of flashy or erratic discharge (including ephemeral streams) that have sandy, noncohesive banks, and lack of well-developed growth of riparian vegetation."
Hedman and Osterkamp pg 6

Criteria of Navigability (Highlighting Added**)**

"…one enters the realm of the freight canoe, which may be most anything you wish. For instance, a twenty-foot canoe forty-three or forty-four inches wide and **nineteen inches deep** will weigh nearly two hundred pounds, but will have a capacity of about 2,300 pounds. The selection of such a canoe should depend upon the amount of freight, the nature of the going, and the efficiency of the canoemen."
Pinkerton near the end of Chapter 2

"As early as 1824 the Federal government recognized the need for consistently raising the water level, and by the 1870s they began to put things in motion. In the 1880s the US Congress gave the job of maintaining the country's waterways to the U.S. Army Corps of Engineers."
Engstrom pg 4
[unusual spacing could not be deleted/fixed in Word]

"In 1866, the Federal Government appropriated $400,000 for a **4-foot-deep channel** between Minneapolis and St. Louis. In June 1878, before the 4-foot channel project was complete, Congress authorized the Corps of Engineers to work towards the provision of a 4.5-foot depth. In 1907, Congress, under pressure from river improvement organizations who believed the 4.5-foot depth was inadequate, authorized the Corps to construct a 6-foot-deep channel from the mouth of the Missouri River to Minneapolis."
O'Brien et. al. no pg

"In 1866, states along the Upper Mississippi River convinced Congress to establish a **4-foot deep channel** along the 670-miles between St. Paul and St. Louis. This was upgraded to a **4-½ foot deep channel** in 1878 and to a **6-foot deep** Upper Mississippi River channel by 1907"
Lessiter no pg

"… in 1896 Congress authorized the development and maintenance of a **9-foot channel** 250 feet wide from Cairo, Illinois, to Head of Passes." Robinson pg 260

"Then in 1907, Congress adopted a project depth of 6 feet between the Missouri River just above St. Louis and Minneapolis, to be obtained by dredging and the construction of wing dams to contract the low-water channel."
U. S. Army Corps of Engineers, no date pg 5

“In 1910, Congress mandated a lock and dam system that would guarantee a navigable channel of **9 feet** for the entire length of the Ohio River. By 1929, the mission was completed with 51 locks and dams constructed.”
Engstrom pg 4

“By the dawn of the 20th Century, the wing dams and closing dams, along with periodic dredging, allowed the Corps to maintain a navigation channel **four feet in depth** all the way upstream to Minneapolis. In 1910, the depth of the channel was increased to **6 feet**”
Moore no pg

“In determining the channel size, some of the basic criteria used are the sectional area ratio, draft-depth ratio, and maneuverability requirements. Tests have indicated that the resistance to tow movement in a restricted channel decreases rapidly as the sectional area ratio (ratio of the channel area to the submerged tow area) is increased to a value of 6 or 7 and then decreases less rapidly as the ratio is further increased. Resistance to tow movement and power required to move the tow are increased if the draft is more than about 75 percent of the available depth, particularly if the channel has restricted width, such as a canal or a lock.”
Petersen pg 5-1

“Resistance to tow movement and power required to move the tow are increased if the draft is more than about 75 percent of the available depth,”
U. S. Army Corps of Engineers 1980 pg 4-2

“Section 5 of the Rivers and Harbors Appropriation Act approved 4 March 1915 outlines the basis for channel dimensions as follows:
‘That in the preparation of projects under this and subsequent river and harbor Acts, unless otherwise expressed, the channel depths referred to shall be understood to signify …the mean depth for a continuous period of fifteen days of the lowest water in the navigation season of any year in rivers and nontidal channels,’ ”
U. S. Army Corps of Engineers 1980 pg 4-1

Appendix B
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T. ALLEN J. GOOKIN, P.E., L.S., P.H., S.W.R.S.

SUMMARY

Mr. Gookin has been involved in river movement studies, demographics, power and energy contracts and studies, various phases of engineering design and surveying, economic analyses and hydrologic fields, such as groundwater, surface water and flood control. Mr. Gookin is co-author of the computerized “Call System” adopted by the United States District Court to administer diversions on the Gila River mainstem. Mr. Gookin has also been a lecturer to the Arizona State Bar on “Subflow” in Arizona.

EDUCATION

West High School - Phoenix, Arizona
  Graduated - Magna Cum Laude
Arizona State University - Tempe, Arizona
  B.S. in Engineering - With Distinction

SEMINARS AND OTHER STUDIES

2010	HEC-RAS
2009	Editor - AIH/AHS Conference Proceedings
2009	Co-chair and Presenter – AIH/AHS Annual Conference
2007	Presenter – AIH Annual Conference
2006	Resolving Conflicts of Survey Evidence Seminar
2006	Incoming AIH Vice-President for Institutional Development
2006	AIH Conference
2006	Urban Watershed Mgmt. Seminar
2005	Single-Family Plan Rev. Workshop
2004	Presenter – AIH Annual Conference
2004	Arizona Boundary Law Conference
2004	Pipe Design, Installation, Inspection Seminar
2003	ADS Training Seminar
2003	Land Survey Seminar - COS
2003	Instructor on Subflow Arizona Water Law Conference
1997	Understanding & Protecting Your Water Rights in Arizona Seminar
1994	Cybernet
1987	HEC-1
1985	Engineering Management
1983	Hydrology & Hydraulics
1979	Survey Boundary Control
1977	Modeling of Rivers
1977	Civil Engineering Review Course
1976	Hydraulics and Hydrology Seminar
1976	Fundamentals of Engineering Rev.
1975	Surveyor's Review Course

REGISTRATIONS

CA	27892	Civil Engineer
AZ	12255	Civil Engineer
AZ	15864	Land Surveyor
NV	8169	Civil Engineer
NV	1242	State Water Right Surveyor
A.I.H.	949	Hydrologist

PROFESSIONAL HONORS

NSPE Young Engineer of the Year, Papago Chapter, 1979
Order of the Engineer
Tau Beta Pi Honorary Engineering Fraternity
Who's Who in the West
Who’s Who in America
Who's Who in the World
Who's Who in Finance and Industry
Who's Who of Emerging Leaders in America
Who's Who in Science and Technology
Who's Who in American Colleges & Univ.
Outstanding Engineering Project - ASPE

PROFESSIONAL AFFILIATIONS

Member of:
AZ Board of Technical Registration
  Engineering Enforcement Committee,
  Land Surveying Enforcement Committee,
Past President - Papago Chapter NSPE
American Society of Civil Engineers
Arizona Department of Water Resources
  Subflow Delineation Committee
American Institute of Hydrology (AIH)
  National Vice President, 2007-8
  National Treasurer, 2009 - present
Arizona Hydrological Society (AHS)

PUBLISHED ARTICLES

“Annual Virgin Flows of Central Arizona” (2009)
“Stockpond Seepage in Southern Arizona” (2007)
“Subflow The Child of the Stream” (2007)
“Pumping and Globe Equity No. 59 – The Turner Study” (2006)
“Groundwater Recharge from the Gila River in Safford, Arizona” (2005)

RELEVANT EXPERIENCE - DAM OPERATION

- **SALT RIVER SYSTEM** - Reviewed yields of various operation criteria for utilization in Indian Water Rights Hearings.

- **SALT RIVER FLOODING** - Computed means by which peak flood flows could have been reduced using snow survey data.

- **HOOVER 1983 FLOODING** - Represented Needles in litigation concerning flood releases from Hoover Dam.

- **CAP OPERATIONS** - Computed Colorado River Dam operations under proposed AWC operating criteria.

- **ALAMO DAM** - Provided testimony concerning downstream impacts of water releases on riparian habitats.

- **IDAHO** - Computed and routed maximum probable flood for dam safety analysis.

- **GE #59** – Prepared numerous Reservoir Operation Studies of Coolidge Dam to:
    1. Maximize water yield under provisions of the Gila Decree and
    2. Determine penstock capacities of Coolidge Dam at various “heads”.

- **INDIAN CLAIMS COMMISSION** – Determining sustainable yields of Buttes and Orme Dams under 1883 watershed conditions.

- **GRIC SETTLEMENT** – Prepare reservoir operations under “equal sharing” concepts. Also computed spill probabilities due to reserved storage.

- **HATCH** – Computed and testified to the amount of water that could be developed for municipal use in Tucsyan.

- **ARIZONA (BABBITT) SETTLEMENT** – Worked with representatives of the Arizona Water Commission and the Bureau of Reclamation to identify and prepare preliminary cost estimates of numerous water development scenarios.

- **BUREAU OF INDIAN AFFAIRS** - Prepared computer models to determine the impact and total usable supplies given various states of regulation on both the Salt and Gila Rivers, taking into account the interaction between the surface and groundwater regime.

- **CENTRAL ARIZONA PROJECT** - Prepared computer models to analyze yield situation under various scenarios of reservoir operation.

RELEVANT EXPERIENCE - SURFACE HYDROLOGY

- **LINCOLN RANCH** - Testified regarding water rights values and water exchanges as they relate to Lincoln Ranch on the Bill Williams River.

- **PAYSON** - Prepared study analyzing the ability of Payson to divert from the East Verde River.

- **NORTHERN PUEBLOS TRIBUTARY WATER RIGHTS ASSOCIATION** - Testified on the ability of an irrigation system to divert water and provide an integrated surface groundwater irrigation supply. Also analyzed and laid out an irrigation system and computed cost feasibility thereof.

- **PRESCOTT** - Analyzed flows of Verde River to compute various diversion schemes that would minimize the impact of riparian habitat downstream from the diversion. Responsible for report which analyzed potential for conservation through rate structures. Also worked on analyses of water requirements and savings.

- **GILA RIVER INDIAN COMMUNITY** -Computed the impact of depletions upstream from the Gila River Indian Reservation upon flows of the Gila River.

- **MAHONEY** - Reviewed evidence concerning water measurements.

- **SALT RIVER INDIAN COMMUNITY** - Determined the virgin surface water flow available from the Salt River and the surface virgin water flow available to the Central Arizona area as a whole.
- **SUPERIOR COMPANIES** - Prepared determinations of normal high flows at ungaged locations. Plotted mean high water channel boundaries.
- **TEMPE** - Prepared analysis showing adequacies of existing supplies and supplementation recommendations.

- **ARIZONA (BABBITT) SETTLEMENT** – Worked with representatives of the Arizona Water Commission and the Bureau of Reclamation to identify and prepare preliminary cost estimates of numerous water development scenarios.

- **ARIZONA WATER RIGHTS SETTLEMENT VALIDATION** – Prepared and presented depositional testimony quantifying available water right claims under PIA, Prior Appropriation and existing Court Decrees.

RELEVANT EXPERIENCE - SURFACE HYDROLOGY

- **FIVE CENTRAL ARIZONA INDIAN TRIBES** - Studied the use of irrigation water of the five Central Tribes.

- **IRRIGATION DISTRICTS** - Computed agricultural, municipal and industrial water requirements as well as design of a tentative canal layout for the Queen Creek, San Tan, Harquahala, McMicken and Chandler Heights Citrus Irrigation Districts.

- **GLOBE EQUITY** – Study operation of Gila Decree (Globe Equity #59) and its impact on the Gila River Indian Community. Prepared numerous river operation studies for various settlement options.

- **SAN PEDRO HSR** - Reviewed, provided comments and detailed analysis on the HSR Report. Examined the Jenkins Surface/Groundwater Inter- action Formula.

- **TOHONO O'ODHAM NATION** - Designed gaging stations for surface stream measurements. Examined surface flows for San Simon Wash.

- **UPPER SALT RIVER HSR** - Reviewed and commented on Hydrographic Survey Report.

- **CALL SYSTEM** – Primary creator and co-author of the Globe Equity No. 59 Call System. The Call System is a computerized water rights administrative procedure and tool. The Call System is currently being used by the Gila Water Commissioner to “run the river.”

- **SUBFLOW** – Testified before the Superior Court on the legal/physical characteristics of the Younger Alluvium and Subflow.

- **SUBFLOW II** – Testified before the Special Master on the interpretation of the Arizona Supreme Court Gila IV decision and application of that decision in delineating the Subflow zone.

- **CUFA** – Assisted in negotiations of the Consumptive Use Forbearance Agreement between the Arizona Parties and the State of New Mexico. Prepared analyses of divertible water from the upper Gila subject to restrictions of Arizona v. California, the Colorado River Basin Development Act and Globe Equity No. 59.

RELEVANT EXPERIENCE – HYDRAULICS

- **JOINT PROJECT** - Writing and utilizing computer programs for computation of natural and artificial streams for backwater, inflow and drawdown occurrences, as well as sizing pipelines and flood control channels.

- **SAN CARLOS IRRIGATION DISTRICT** - Designed interconnection between Hohokam main lateral and Pima lateral.

- **PRESCOTT** - Use of computer programs for computing natural and artificial streams for backwater inflow and drawdown occurrences.

- **SCOTTSDALE** - Utilization of computer programs to compute natural and artificial backwater inflow, as well as sizing and flood control channels.

- **WOOLLEY** - Responsible for calculating backwater and drawdown occurrences.

- **COOLIDGE DAM** - Computed penstock capacity curves.

- **DESERT MOUNTAIN** - Computed water hammer times and loads. Designed valving to prevent hammers in the high pressure main.

- **ADAMAN WATER COMPANY** - Supervised design of cast-in-place concrete pipeline to interconnect Beardsley Irrigation System to Adaman Water Company.

- **JAREN** - Prepared Master Plan of pipeline distribution system for Rawhide Water Co. Designed computer program for Pipe Network Solutions.

- **JOHN NORTON SUBDIVISIONS** - Assisted in design of waterlines and sewers for subdivision. The water systems involved loopback to the City system and pipelines, wells and a pressure system.

- **GRIFFIN** - Provided design of well and water production facilities.

- **DYSART** - Provided design of water line fire loops for Dysart High School and cafeteria expansion. Design and inspection of sewer line hookups and off-site lines with lift station to treatment plant. Computed Hardy Cross water system analysis and built necessary connections. Provided design alternatives to water hookups with El Mirage for treatment of nitrates.

- **BRW** - Consultant for the design and sizing of water production and transportation facilities.

- **NADABURG** – Designed water system for service to school including well, storage tank and pumps.

RELEVANT EXPERIENCE - RIVER MOVEMENT STUDIES

- **THOMAS THODE** - Prepared testimony concerning avulsions and accretions near the Yuma Island and the confluence of the Gila and Colorado Rivers.

- **GILA RIVER INDIAN COMMUNITY** - Analyzed the historic meanderings of the Salt and Gila Rivers near their junction and their impact on the Gila River Indian Reservation boundary.

- **NATIONAL INDIAN YOUTH COUNCIL** - Testified to a sub-committee of the U. S. House of Representatives concerning river movements of the Arkansas River.

- **WOOLLEY** - Studied the cause of the migration of the flows from one channel to another on the Salt River during flooding.

- **PALO VERDE VALLEY FARMLAND ASSOCIATION** - Aided in research and testimony preparation in study concerned with accretion and avulsion for various lawsuits.

- **SALT RIVER INDIAN RESERVATION** - Aided in research, analyzed data, and participated in the preparation of a report concerning the thalwag of the Salt River and its movements.

- **PETERSON VS. USA** - Researched, reported and prepared testimony regarding river movements near Bullhead City.

- **SIMONS VS. RIO COLORADO DEVELOPMENT CO.** - Performed on-site inspection, research and prepared report concerning the influence of levees on river channels near Needles.

- **ARIZONA STATE NAVIGABILITY COMMISSION** – Presented testimony concerning changes in the Salt and Gila River channel characteristics.

RELEVANT EXPERIENCE – GROUNDWATER

- **NORTHERN PUEBLOS TRIBUTARY WATER RIGHTS ASSOCATION** - Supervised a portion of the highly technical and complex testing program used in preparing a 3 dimensional leaky artesian computer model.

- **SAFFORD VALLEY** - Analyzed interaction between the Gila River and the groundwater of the Safford Valley.

- **J. ED SMITH WELL** - Co-authored report that was submitted in evidence before the U. S. District Court about the impact of the well upon river flows.

- **PRESCOTT** - Supervised the well test on an exploration hole and wrote a comprehensive report concerning the results of the pump test and aquifer characteristics.

- **NADABURG** – Prepared specifications and field inspections for a well drilled as a part of a water system for the Nadaburg School.

- **FIVE CENTRAL ARIZONA INDIAN TRIBES** - Researched the impact of a well system for use by the Bureau of Indian Affairs.

- **BELLAMAH COMM. DEV. -** Studied groundwater reserves in the East Carefree basin. Determined physical and legal constraints on development potential.

- **GRIFFIN COMPANY** - Designed well and water system for truck stop west of Tolleson.

- **GILA RIVER INDIAN RESERVATION** - Conducted research of groundwater availability and location of wells. Co-authored report concerning the need for non-Project wells. Assisted in the construction of an emergency drought relief system as well as participating in negotiations, preparations of specifications, design of well screens and field /inspections.

- **GE #59 AND HISTORY OF PUMPING** – Provided testimony concerning pumping history and evidence of coverage of pumping by Globe Equity #59 impacts. Received the following accolade from U. S. District Court Judge Coughenour "…let me help them understand how enormously helpful I have found Mr. Gookin's testimony to be and how proud we should be to have somebody of his caliber helping you with this case."

- **ARIZONA GAME AND FISH** - Prepared a hydrologic analysis of the groundwater resource potential and reliability of Pinetop Springs and local wells.

- **MARICOPA ALLIANCE** - Studied the impact of landfills on groundwater in the western Phoenix area.

RELEVANT EXPERIENCE –

GROUNDWATER

- **PAYSON** - Supervised pump test and evaluated reliability of and recharge to a fractured rock groundwater system.

- **FLETCHER FARMS** - Demonstrated an assured water supply on the west side of Phoenix.

- **CHANDLER HEIGHTS CITRUS IRRIGATION DISTRICT** - Responsible for all phases of the preparation of specifications and receipt of bids for the construction of a multi-purpose well.

- **SAFFORD** - Prepared analysis of the interrelationship between surface and groundwater in Safford Valley. Aided and reviewed computer modeling using MODFLOW.

- **SAN PEDRO HSR** - Prepared detailed analysis of the validity of failing to meet assumptions under the Jenkins Formula.

- **TOHONO O'ODHAM** - Computed groundwater recharge from all sources.

- **SUBFLOW** – Testified before the Court on the legal/physical characteristics of the Younger Alluvium and Subflow.

- **SUBFLOW II** – Testified before the Special Master on the interpretation of the Arizona Supreme Court Gila IV Decision and application of that decision in delineating the subflow zone.

- **W&EST, INC**. – Provide historic water use information and historic consumptive use data for use in a groundwater model for Central Arizona Basin area.

- **PAYSON WELL (GAIL TOVEY)** - Assist Gayle Tovey in performing pump test on her property in Payson.

- **ARIZONA (BABBITT) SETTLEMENT** – Worked with representatives of the Arizona Water Commission and the Bureau of Reclamation to identify and prepare preliminary cost estimates of numerous water development scenarios.

RELEVANT EXPERIENCE - SURVEYING AND LEGAL DESCRIPTIONS

I have prepared numerous surveys for houses, commercial developments and schools that are not listed. The following represents the more complex studies performed.

- **DESERT SUN SUBDIVISION** - Assisted in the layout of Desert Sun Subdivision.

- **PALO VERDE VALLEY** - Responsible for examination and comparison on boundary surveys between Arizona and California along the Colorado River.

- **HANCOCK** - Prepared subdivision plat near Bullhead City, Arizona.

- **JOHN NORTON – SUBDIVISIONS** - Assisted in design of waterlines and sewers for subdivision. The water systems involved loopback to the City system and pipelines, wells and a pressure system.

- **FONTES – STARR** – Provided consultation to resolve survey difficulties.

- **VALTECH** - Provided ALTA Survey of Los Arcos Mall in Scottsdale, Arizona.

- **BLUE RIDGE UNIFIED SCHOOL DISTRICT #32** - Responsible for topographic site survey of property lines and existing physical conditions of the site, monument markers, bench marks, legal description, sidewalks, curbs and gutters, utility locations, topographic map and boundary survey drawing, playground area, as-built plans, traffic control signal, maintenance and transportation facility, parking lot.

- **DYSART** - Provided as-built survey of Dysart High School.

- **STATE OF ARIZONA PARKING** - Construction staking for parking lot and storm drainage line.

- **SAN CARLOS IRRIGATION & DRAINAGE DISTRICT** - Provided surveys for intertie of Central Arizona Project Aqueduct into Florence - Casa Grande Canal.

- **SQUATTER SURVEY** – Review survey history and survey site to locate property corners, section corners, encroachments, and to establish location of existing features on site.

- **WATER RIGHT TRANSFER** – Evaluate over 100 applications for the sever and transfer of water rights. Provide affidavits on inadequacy of legal descriptions Testified in U. S. District Court as to the inadequacies of 10 test case applications. Also provided testimony of the history, development and accuracy of the Gila Water Commissioner's Decree map.

RELEVANT EXPERIENCE - EXPERT WITNESS

- **LINCOLN RANCH** - Provided testimony regarding water rights values and water exchanges as they relate to Lincoln Ranch on the Bill Williams River.

- **NORTHERN PUEBLOS TRIB. WATER RIGHTS ASSOC.** - In charge of preparation of canal delivery systems. Presented testimony on P.I.A.

- **NEEDLES** - Prepared and presented expert testimony concerning power contracting with the Department of Energy.

- **HATCH** – Provide testimony concerning the amount of water being generated from an ungaged watershed during pre and post development conditions. Also testified concerning potential water contamination from a neighboring airport.

- **IDAHO** – Computed and routed maximum probable flood for dam safety analysis. Provide depositional testimony.

- **PRESCOTT** - Provided expert testimony concerning the magnitude of flooding on Willow Creek.

- **WINDOW ROCK** - Provided testimony concerning the value of a substandard sewer system.

- **GILA DECREE** - Provided testimony on numerous occasions concerning provisions of the Gila River Decree and its impacts on the allocation of water between different users.

- **FORT MOHAVE** - Provided testimony regarding hydropower contracting from Colorado River Storage Project.

- **ALAMO DAM** - Provided testimony concerning downstream impacts of water releases on riparian habitats.

- **WOOLLEY vs. SALT RIVER PROJECT** – Provided depositional testimony concerning the cause of the floods of 1978, 1979, 1980 and 1983 in the Salt River and their impact on the river channel. Evaluated damages in water elevations and determined scour in the channel during the flood events.

- **JOHN FRANK** – Provide testimony concerning the impact of breeches in levies along the Colorado River on neighboring lands.

- **THODE** - Presented testimony concerning historic river movements in the area where the Gila River joins with the Colorado River.

RELEVANT EXPERIENCE - EXPERT WITNESS

- **PETERSON VS. USA** - Researched, reported and prepared testimony regarding historic river movements near Bullhead City.

- **BOULDER CREEK** - Provide expert witness testimony for Boulder Creek Ranch, Inc. Provide deposition testimony on the value of surface water rights for water from the Agua Fria River and Boulder Creek. Perform water right valuation including the acreage at the headwaters of Lake Pleasant and the leased acreage appurtenant to and surrounding it. Subject property was used as part of a cattle ranching operation with fee lands leased from private parties, grazing lands leased from the State of Arizona, and grazing privileges leased from the BLM.

- **NATIONAL INDIAN YOUTH COUNCIL** - Presented testimony to a subcommittee of the U. S. House of Representatives of historic river movements of the Arkansas River.

- **COYOTE WASH**-Expert assistance regarding Plourd v. IID et al. break. Computed storm frequencies. Determined cause of channel failure and course of flood waters exiting channel breach. Reviewed Coyote Wash depositions. Provided deposition and expert witness testimony in El Centro, California.

- **SUBFLOW** – Testified before the Arizona Superior Court on the legal/physical characteristics of the Younger Alluvium and Subflow.

- **SUBFLOW II** – Testified before the Special Master on the interpretation of the Arizona Supreme Court Gila IV decision and application of that decision in delineating the subflow zone.

- **ARIZONA BILTMORE** – Provided review of studies by the Corps of Engineers concerning ACDC in Reaches 1, 2, 3 and 4. Provided detailed analyses of flows out of Cudia City Wash. Testified to the City of Phoenix.

- **AAMODT** - Evaluated quality of water for growth of crops in conjunction with various soils in the area and provided expert testimony.

- **SALT RIVER SYSTEM** - Reviewed yields of various operation criteria for utilization in Indian Water Rights Hearings.

- **SALT RIVER FLOODING** - Computed means by which peak flood flows could have been reduced using snow survey data.

- **HOOVER 1983 FLOODING** - Represented Needles in litigation concerning flood releases from Hoover Dam.

RELEVANT EXPERIENCE - EXPERT WITNESS

- **CAP OPERATIONS** - Computed Colorado River Dam operations under proposed AWC operating criteria.

- **IDAHO** - Computed and routed maximum probable flood for dam safety analysis.

- **INDIAN CLAIMS COMMISSION** – Determining sustainable yields of Buttes and Orme Dams under 1883 watershed conditions.

- **GRIC SETTLEMENT COURT RATIFICATION** - Provided a PIA Justification for Court approval of the Arizona Water Rights Settlement. Presented depositional testimony.

- **DE MINIMIS** – Provided report and testimony on hydrologic impacts of "de minimis" domestic, stock- watering, and stockpond uses.

- **GOLD CANYON** – Provided expert testimony on failure of flood control system and regulatory impacts of sewage spills.

- **SALTON SEA** – Expert testimony concerning the impact of tropical storms Doreen and Kathleen and irrigation practices of the irrigation district on the Salton Sea elevations.

- **GE #59 AND HISTORY OF PUMPING** – Provided testimony concerning pumping history and impacts. Received the following accolade from U. S. District Court Judge Coughenour "…let me help them understand how enormously helpful I have found Mr. Gookin's testimony to be and how proud we should be to have somebody of his caliber helping you with this case."

- **ALAMO DAM –** Provided expert testimony concerning impacts of water releases on downstream riparian habitats.

- **GE #59 –** Prepared testimony on numerous Decree provisions in comparison of historic operations. Provided design of the Call System computer program adopted by the United States District Court and currently being used by the Gila Water Commissioner to allocate river flows under Globe Equity #59.
  - Worked with the Gila River Indian Community on arranging fish pool exchanges in 1990, 1997, and 1999.
  - Worked with the Gila River Technical Committee to resolve issues concerning fish pool accounting and wells.
  - Prepared numerous Reservoir Operation Studies of Coolidge Dam to:
    Maximize water yield under provisions of the Gila Decree and
    Determine penstock capacities of Coolidge Dam at various "heads".

RELEVANT EXPERIENCE - EXPERT WITNESS

- **HATCH –** Computed and testified to the amount of water that could be developed for municipal use in Tucsyan. Provided expert testimony concerning water contamination potential from a neighboring airport.

- **ARIZONA WATER RIGHTS SETTLEMENT VALIDATION** – Prepared and presented depositional testimony quantifying available water right claims under PIA, Prior Appropriation and existing Court Decrees.

- **WATER RIGHT TRANSFER** – Evaluate over 100 applications for the sever and transfer of water rights. Provide affidavits on inadequacy of legal descriptions Testified in U. S. District Court as to the inadequacies of 10 test case applications. Also provided testimony of the history, development and accuracy of the Gila Water Commissioner's Decree map.

- **DUGAN** – Determine cause of home flooding and provide expert testimony relating to the cause and remedy.

RELEVANT EXPERIENCE - HYDROLOGIC HISTORY

- **HYDROLOGIC HISTORY OF THE GILA RIVER INDIAN RESERVATION** – Author of a report determining irrigation development from 1876 to 1924 and hydrologic impacts of non-Indian irrigation on the Gila and Salt River system and tributaries. Prepare analysis of virgin state conditions in Arizona.

- **CIRCULARITY** – Provided historic research on San Carlos Apache buyout provisions of Globe Equity #59.

- **POOLING REPORT** – Prepare historic analysis of origination and changes in the Pooling provisions of the San Carlos Indian Irrigation Project.

- **236-C** – Prepared analysis of virgin flows and the progression of irrigation depletion of the Gila River.

- **NATIONAL INDIAN YOUTH COUNCIL** – Presented testimony to a subcommittee of the U. S. House of Representatives of historic river movements of the Arkansas River.

- **PALO VERDE VALLEY FARMLAND ASSOCIATION** - Aided in research and testimony preparation in study concerned with historic accretion and avulsion of the Colorado River for various lawsuits.

- **HATCH** – Provided testimony concerning the amount of water being generated from an ungaged watershed during pre and post development conditions.

- **GE #59 AND HISTORY OF PUMPING** – Provided testimony concerning pumping history and impacts. Received the following accolade from U. S. District Court Judge Coughenour "…let me help them understand how enormously helpful I have found Mr. Gookin's testimony to be and how proud we should be to have somebody of his caliber helping you with this case."

- **THODE** – Presented testimony concerning historic river movements in the area where the Gila River joins with the Colorado River.

- **PETERSON VS. USA** - Researched, reported and prepared testimony regarding historic river movements near Bullhead City.
-
- **GILA RIVER INDIAN COMMUNITY** – Analyzed the historic meanderings of the Salt and Gila Rivers near their junction and their impact on the Gila River Indian Reservation boundary.

- **INDIAN CLAIMS COMMISSION** – Determining sustainable yields of Buttes and

Orme Dams under 1883 watershed conditions.

-
- **W&EST, INC.** – Provide historic water use information and historic consumptive use data for use in a groundwater model for central Arizona basin area.

- **FISH POOL** – Study history of San Carlos Reservoir operations and their impact on fish kills.

A Legacy of Change

HISTORIC HUMAN IMPACT ON VEGETATION OF THE ARIZONA BORDERLANDS

Conrad Joseph Bahre

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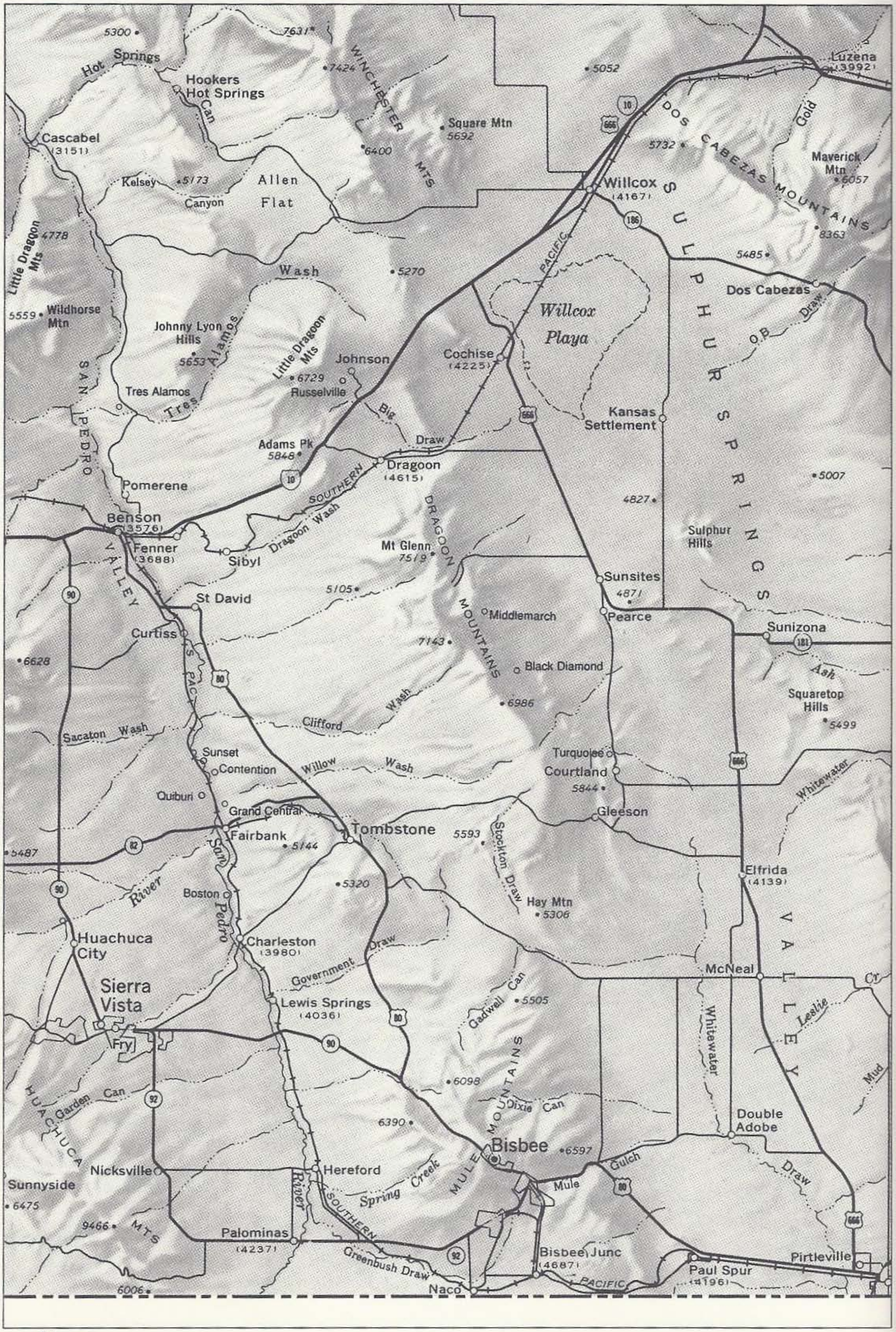5300
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Willcox Playa
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Sunset
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Turquoise
Courtland
Whitewater
Quiburi
5844
Grand Central
Gleeson
Tombstone
5593
Stockton Draw
Fairbank
5144
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5487
River
5320
Elfrida (4139)
90
Boston
San Pedro
Hay Mtn 5306
Huachuca City
Charleston (3980)
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Mud
Garden Can
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HUACHUCA MTS
Dixie Can
Double Adobe
6390
Bisbee
6597
Nicksville
Hereford
Spring Creek
Gulch
Draw
Sunnyside
Mule
80
6475
River
SOUTHERN
666
9466
Palominas (4237)
Greenbush Draw
92
Bisbee Junc (4687)
Pirtleville
Paul Spur (4196)
PACIFIC
6006
Naco

Map 7

Grasslands

Semidesert grasslands and plains grasslands, the dominant cover in the study area, make up 46 percent of the total cover (see Figures 2.5 and 2.6). This figure seems much too high to me, however, and is based on the fact that most ecologists believe that before recent brush increases, the modern grass-shrublands were true grasslands. However, the semidesert grasslands might be better designated semidesert grass-shrublands because they are potentially perennial grass-shrub dominated landscapes located between the desertscrub below and the oak woodlands or plains grasslands above (Wright 1980). Isolated pockets of grassland also occur in Chihuahuan desertscrub. These pockets, referred to as *mogotes*, are dominated by tobosa (*Hilaria mutica*) and sacaton (*Sporobolus wrightii*).

The elevational limits of semidesert grassland are between 3,000 and 5,500 feet. Originally, grasses in this vegetation type were perennial bunchgrasses. Heavy grazing, however, has reduced bunchgrasses and increased low-sod grasses and annuals (Humphrey 1958; Brown

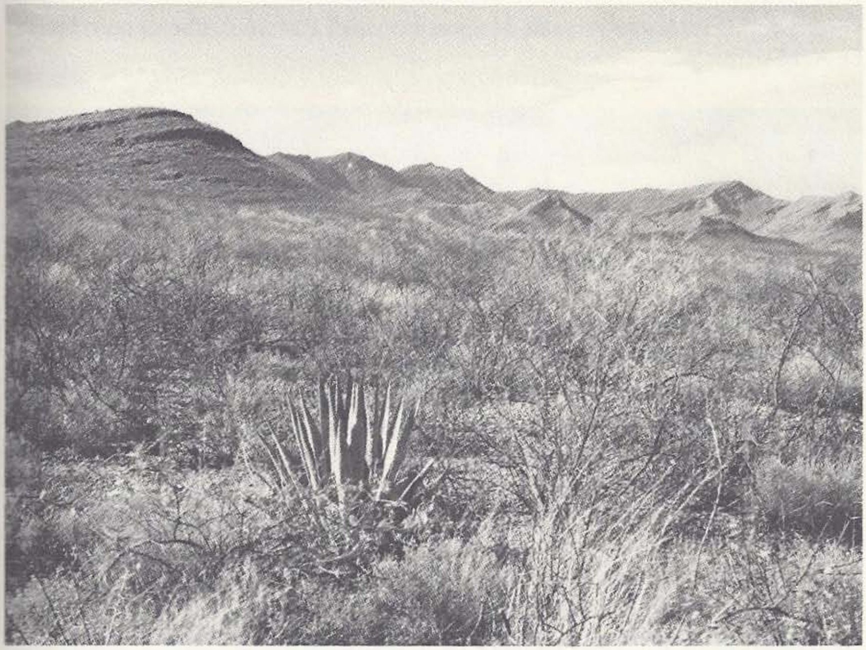

FIGURE 2.4. Chihuahuan desertscrub (tarbush–sandpaper bush–creosote bush community, 4,600 feet, Whetstone Mountains). Photograph by D. A. Martinich.

Arizona having ponderosa pine and mixed-conifer forests: the Chiricahuas, Huachucas, Pinaleños, and Santa Catalinas.

From the time the Southern Pacific Railroad was completed until the early 1920s, a number of other railroads were built to meet the needs of mining and ranching (Myrick 1975). Among the more notable were the El Paso and Southwestern (Arizona and Southeastern); Arizona and New Mexico; Tucson and Nogales; Johnson, Dragoon, and Northern; Mascot and Western; and Arizona Southern.

Completion of the Southern Pacific also sparked a boom in cattle ranching, although Anglo-American ranchers had begun moving large herds of sheep and cattle into southeastern Arizona in the 1870s, especially after severe droughts in California (Haskett 1935; Morrisey 1950; Wagoner 1952). At that time, the grasses of southeastern Arizona were described as lush and abundant (ibid.). By 1885 so much investment capital had poured into southeastern Arizona's ranching industry that cattle numbers on the ranges exceeded all expectations. In 1891 more than 217,000 cattle were reported for Pima and Cochise counties alone—that number, according to some reports, was much too conservative (U.S. Congress, House 1893). Between 1891 and 1893, however, disaster struck: Drought and starvation led to the death of 50 to 70 percent of the cattle in southeastern Arizona (Wagoner 1952). Nevertheless, overstocking and overgrazing were to continue.

Like their Indian and Mexican predecessors, the early Anglo farmers depended on the few perennial streams and rivers for irrigation water. In the 1870s almost all irrigated farming in the region was concentrated along the Santa Cruz and middle Gila rivers, with the exception of some small outliers along Sonoita, Aravaipa, and Babocomari creeks and near the mouth of the San Simon River. In the early 1870s Mormon farmers established farms in the middle and upper Gila Valley between Bryce and Duncan, and in the San Pedro Valley between St. David and Hereford (McClintock 1921). There was some scattered pump irrigation and irrigation from artesian wells in southeastern Arizona after 1880, but until the 1940s most irrigated agriculture depended on surface flow from the perennial streams.

Early Anglo settlers and General Land Office administrators had a major impact on regional fire ecology by (1) initiating fire suppression policies and (2) overstocking and overgrazing the rangelands. Consequently, a major decline in wildfire frequency occurred throughout the region following Anglo settlement. This is documented by fire scars in tree-ring data from southeastern Arizona (Baisan 1988; Swetnam et al. 1989).

Table 3.1. Relationships Between Disturbance and Stream Entrenching in Southeastern Arizona

Valley	Drainage Concentration Featured Associated with Entrenchment	Date of Origin of Feature	Date of Initial Entrenchment
San Simon	a. Irrigation ditch at Solomonville	1883	1883
	b. San Simon wagon road	by 1875	after 1885
	c. Railroad embankment	1884	after 1885
Aravaipa	a. Fort Grant wagon road	by 1875	after 1886
Whitewater	a. Levees	——	after 1884
	b. Cattle trails	——	after 1884
San Pedro	a. Canals, roads	locally before 1851	before 1851 in places
	b. Railroad embankment	——	——
Santa Cruz*	a. Greene's Canal	1910	1914
	b. Sam Hughes's Canal	after 1862	1883 or 1890
	c. San Xavier Canal	by 1851/1883	by 1871/c. 1883

SOURCE: Cooke and Reeves 1976:94.

*Betancourt (1990) notes that Sam Hughes's Canal was completed in 1888 and initial entrenching began in 1889. Also, according to Betancourt, the San Xavier Canal, which was first dug in 1849, was severely eroded by 1850.

their conclusions, they correlate the initiation of arroyo cutting in southeastern Arizona valleys with the occurrence of major bottomland disturbances (see Table 3.1).

Woody plant increases and the degradation of rangelands by cattle attract the most attention from researchers. Range scientists are particularly interested in the causes of woody plant increases and in ways to control the woody species and boost rangeland grazing capacity. Range improvement programs initiated by state or federal agencies have themselves led to extensive vegetation changes. Excellent reviews of the pertinent research on brush increases in the rangelands and range improvement in southeastern Arizona are found in Parker and Martin (1952), Humphrey (1958), Hastings and Turner (1965), and Wright (1980).

The riparian wetlands receive the second largest amount of attention from students of vegetation change. The evidence of changes abounds in the historic record and in repeat photography. Although riparian

Table 4.3. Variability of Annual Precipitation

	Mean Annual Precipitation (in.)	Standard Deviation	Coefficient of Variation	Years of Record
Fort Lowell-Tucson	10.991	3.291	0.299	100
Tombstone	13.378	4.445	0.332	70
Fort Grant	12.724	3.847	0.302	45
Fort Bowie	13.639	3.356	0.246	22
San Simon	8.886	3.162	0.355	60

SOURCE: Cooke and Reeves 1976:76.

Table 4.4. Drought and Wet Periods: Cumulative Precipitation Deficiency or Excess Between June and September at Fort Lowell, near Tucson

Drought	Cumulative Deficiency (inches below mean)	Wet Periods	Cumulative Excess (inches above mean)
1884–86*†	8.834	1866–69	5.72
1891–92	3.016	1871–72	11.47
1894–95*	3.606	1874–76	8.31
1899–1906*	10.794	1878–80	4.26
1912–13	3.866	1889–90	8.62
1915–16	0.966	1896–98	3.26
1932–34*	2.41	1907–11	7.83
1937–39*	3.45	1935–36	2.52
1944–45	1.90	1940–41	2.29
1947–49	8.44	1954–55	4.92
1951–53*	5.08		
1956–57	3.22		
1960–61	2.18		

SOURCE: Cooke and Reeves 1976:77.

*Drought terminated by two or more relatively wet summers.

†Preceded by incomplete data.

Texas (Lehman 1969), California's Central Valley (Burcham 1957), and Chile's Valle Central (Bahre 1979).

HISTORY OF THE LIVESTOCK INDUSTRY

The history of the livestock industry in southeastern Arizona is well chronicled by Cameron (1896), Haskett (1935), Morrisey (1950), and Wagoner (1951, 1952, 1961). Large-scale cattle ranching has been carried on in the area since the 1870s, although cattle and other livestock were introduced into southeastern Arizona two centuries earlier (Bolton 1936:269). While the history of ranching in Arizona is muddled during the Spanish and Mexican occupations, there is evidence that large numbers of cattle, horses, sheep, goats, burros, and mules may have been in the region from 1700 to 1840, especially in the 1820s and 1830s, when large Mexican land grants were established within sixty miles of the present international boundary (Cameron 1896; Mattison 1946). These grants were the San Rafael de la Zanja, María Santísima del Carmén, Luis María Baca, San Bernardino, San Ignacio de la Canoa, San José de Sonoita, San Ignacio del Babocomari, San Juan de las Boquillas y Nogales, and San Rafael del Valle (see Figure 2.10). Supposedly thousands of horses, cattle, mules, and sheep were run on these grants (140,000 cattle on the Babocomari and San Bernardino grants alone) (Bartlett 1854:vol. 1, 396; Haskett 1935:6). Mariana Diaz, a native of Tucson who in 1873 was more than 100 years old, said that "the country around Tucson was covered with horses and cattle in the past and that the trails were so plentiful that it was quite inconvenient to get through the immense herds . . . and that they [cattle] were valuable only for hides and tallow" (*Arizona Weekly Citizen* July 21, 1873). Nevertheless, Apache depredations from 1692 to 1786 and from the late 1820s to 1872 greatly hindered ranching (Cameron 1896; Nentvig 1980).

Considering the general lack of livestock water developments during the early nineteenth century in Arizona (there were no windmills or stock tanks) and the intermittent nature of most streams, it is difficult to believe that the grass and browse in the rangelands adjacent to major sources of perennial water could have supported such high numbers of cattle. Furthermore, large-scale cattle ranching during the 1820s would have been curtailed by Apache depredations that presumably brought ranching operations to a standstill during this period (Haskett 1935). Even if there had been large numbers of cattle in the region in the 1820s and 1830s, there is no evidence of overgrazing. Had the ranges been overgrazed, one might seriously question the premise that overgrazing led to the stream entrenching, fire exclusion, and brush invasion that occurred after 1890. That overgrazing was insignificant in the 1820s and 1830s is also substantiated by the fact that most descriptions of southeastern Arizona from 1850 to 1880 emphasize largely pristine vegetation ideal for cattle (Hastings and Turner 1965:35–50).

Between 1846 (when Lieutenant Colonel Philip St. George Cooke led the Mormon Battalion through southeastern Arizona during the Mexican War) and the Gadsden Purchase in 1853, there were a number of accounts of wild cattle in the region, especially in the San Bernardino and San Pedro valleys (Hastings 1959; Hastings and Turner 1965:34). For example, Cooke, whose battalion was attacked by wild cattle at the junction of Babocomari Creek and the San Pedro River, noted, "There is not on the open prairies of Clay County, Missouri, so many traces of the passage of cattle and horses as we see every day" (1938:79, 143). When John Russell Bartlett, commissioner to the United States-Mexican Boundary Survey, entered southern Arizona with the U.S.-Mexican Boundary Survey in 1851, he described the San Bernardino Valley as desolate and covered with cattle trails. Furthermore, near present-day Douglas, his party used cattle dung for cooking fires because of the lack of firewood in the area. Bartlett also noted a party of thirty to forty Mexicans camped at the confluence of Babocomari Creek and the San Pedro River hunting wild cattle (Bartlett 1854:vol. 1, 398). Apparently, long after the grants were abandoned, Mexicans continued to come to the area to hunt cattle for tallow, hides, hooves, and meat (Wagoner 1952:128). In addition, from 1850 to 1853 large numbers of cattle were driven across southeastern Arizona by immigrants to California but few, if any, of these cattle appear to have been left behind (Cameron 1896; Brady n.d.:39). They must, however, have affected the vegetation along the major trails. Christiansen (1988:95) notes that there may have been 100,000 wild cattle in southeastern Arizona during the 1840s and 1850s, but there is only circumstantial evidence for this figure.

Although large numbers of cattle were driven into southeastern Arizona to meet government and local needs after 1866 (Haskett 1935:19), large-scale cattle ranching did not develop until nearly a decade after the Civil War. In 1872, H. C. Hooker, the most prominent Anglo rancher in southeastern Arizona, had 11,000 cattle in the Sulphur Springs Valley (Haskett 1935:23; Morrisey 1950:152). At that time, small numbers of cattle were also in the Santa Cruz Valley south of Tucson, in parts of the San Pedro Valley, along Babocomari Creek between its junction with the San Pedro River and present-day Sonoita,

The Influence of Climate Change and Climatic Variability on the Hydrologic Regime and Water Resources (Proceedings of the Vancouver Symposium, August 1987). IAHS Publ. no. 168, 1987.

Paleoflood hydrology and hydroclimatic change

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ABSTRACT Important recent advances have been made in the reconstruction and interpretation of ancient floods, particularly in the use of slackwater deposits and paleostage indicators (SWD-PSI). For certain appropriate geomorphic settings, relatively accurate estimates of paleoflood discharges and ages can be made over time scales of centuries and millennia. New statistical tools are available to extract the maximum information content from this unconventional hydrologic data. Preliminary SWD-PSI study results from the southwestern United States indicate that certain time intervals in the last several thousand years have been characterized by occurrences of extraordinary floods, while other intervals have been relatively free of such events. Hydroclimatic change is a likely cause of this nonstationarity.

Introduction

Paleoflood hydrology concerns the study of past or ancient flow events using physical or botanical information, irrespective of any direct human observation. The flow events usually have occurred prior to the possibility of direct measurement by modern hydrologic procedures, although paleoflood hydrologic techniques can be applied to modern floods at ungaged sites (Baker *et al.*, in press). Recent advances in geochronology, flow modeling, and statistical analysis of paleoflood data have greatly increased the ability to extract useful hydrologic information from one variety of paleoflood investigation: slackwater deposit-paleostage indicator (SWD-PSI) studies (Stedinger & Baker, 1987). SWD-PSI investigations can provide reconstructions of discharges and magnitudes for multiple paleofloods with remarkably high accuracy over time scales of centuries and millennia. However, such SWD-PSI studies require special combinations of geological circumstances that must be carefully evaluated in each application.

An outline of SWD-PSI paleoflood hydrology

The methodology of SWD-PSI paleoflood hydrology is discussed by Baker *et al.* (1983) and by Baker (in press). This section will briefly review important aspects of that methodology, emphasizing recent research developments.

Figure 1 Photograph of an accumulation of slackwater deposits downstream of a bedrock spur on the Salt River in central Arizona.

(a) Slackwater deposits consist of sand and silt (sometimes gravel) that accumulate relatively rapidly from suspension during major floods, particularly at localities where flow boundaries result in markedly reduced flow velocities (Figure 1).

(b) Other important paleostage indicators include silt lines, high level scour marks, and flood-modified vegetation.

(c) Sites of slackwater sediment accumulation occur at the following locations: (i) tributary mouths, (ii) abrupt channel expansions, (iii) in the lee of bedrock flow obstructions, (iv) in channel-margin caves and alcoves, (v) at meander bends, and (vi) upstream of abrupt channel expansions.

(d) Regional factors useful in locating river reaches appropriate for SWD-PSI studies include the following: (i) adequate concentrations of sand and silt in transport by floods, (ii) resistant-boundary channels not subject to appreciable aggradation, (iii) depositional sites with high potential for preservation of SWD-PSI features, and (iv) narrow, deep canyons or gorges in resistant geological materials.

(e) Although initially developed and applied in arid and semiarid regions (Baker et al., 1979; Kochel & Baker, 1982; Kochel et al., 1982), SWD-PSI paleoflood hydrology has been extended to the study of humid-region rivers (Kochel & Baker, in press; Patton, in press).

(f) Computer flow models for step-backwater analysis are used to calculate water surface profiles for various discharges in appropriate SWD-PSI study reaches. Paleodischarges are determined by comparing elevations of the various paleostage indicators to the water surface profiles.

(g) Recent research has concentrated on strategies for reducing error in paleodischarge estimation. Important concerns in this regard include: (i) paleoflow cross-sectional stability, (ii) relatively deep paleoflows, and (iii) relatively uniform reaches.

(h) Long-term channel stability is necessary for accurate hydraulic calculations. This can be assured for reaches developed in bedrock, immobile sediment, or other resistant boundary materials.

(i) Narrow-deep channel cross sections are most useful, since increasing flood discharge results in relatively large stage increases (Baker, 1984).

(j) Accuracy of the predicted water-surface profiles can be improved when relatively large flows in a systematic gage record are available to test and calibrate the flow model (Ely & Baker, 1985; Partridge & Baker, 1987).

(k) At ideal SWD-PSI sites thick sequences of multiple sedimentation units record numerous paleofloods (Figure 2). Individual flood units are distinguished by sedimentologic properties such as the following: (i) silt-clay or organic drapes, (ii) buried paleosols, (iii) organic layers, (iv) intercalated tributary alluvium or slope colluvium, (v) abrupt vertical grain size variations, (vi) mudcracks, (vii) color changes, and (viii) induration properties.

(l) Recent advances in geochronology, particularly radiocarbon analysis (Baker et al., 1985), provide excellent opportunities to determine paleoflood ages. As little as 1 to 2 mg of elemental carbon can be analyzed by the new technique of tandem accelerator mass spectrometry (Taylor et al., 1984).

(m) The usual "worst case" end member for SWD-PSI paleoflood information content is a single, vertically-stacked sequence of slackwater deposits (Figure 2). In this case, an informational censoring level (the elevation of each succeeding deposit) increases with time.

(n) Most commonly, SWD-PSI sequences provide much more paleoflood information than in the worst-case scenario. This is achieved by lateral tracing of individual flood deposits to their highest elevations, by correlation of flood deposits among multiple sites, by documenting evidence of limiting high-water levels, and by studying inset stratigraphic relationships.

(o) The information content in SWD-PSI sequences can be structured for flood-frequency analysis through the concept of censoring levels. Flood experience for various time intervals is then analyzed in terms of exceedances or nonexceedances of the censoring levels or threshold discharges (Stedinger & Baker, 1987).

(p) The goal of stratigraphic analysis in SWD-PSI studies is to reconstruct a complete catalog of discharges exceeding censoring levels over specified time periods.

(q) New statistical tools are now available to make optimum use of the information content in appropriately structured paleoflood data (Stedinger & Cohn, 1986; Stedinger & Baker, 1987).

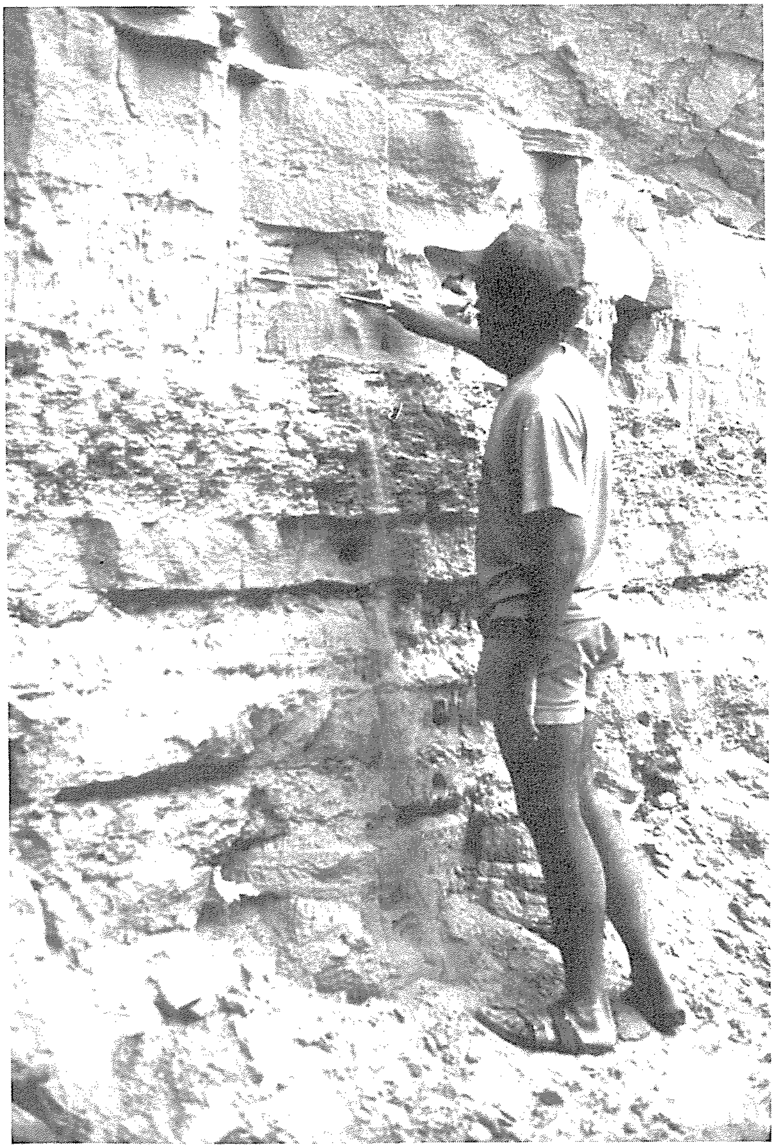

Figure 2 Photograph of The Alcove slackwater sedimentation site (Webb, 1985) on the Escalante River in south-central Utah.

Flood hydroclimatology

Conventional flood-frequency analysis relies on the following assumption: "... the array of flood information is a reliable and representative time sample of random homogeneous events" (U.S. Water Resources Council, 1981, p. 6). Two possible violations of this assumption may be induced by (1) a mixed underlying parent distribution for the flood events, and (2) variation through time in the mean of the underlying probability distribution for flood recurrence (nonstationarity). Both of these situations may derive from climatologic causes (Hirschboeck, in press). Although short-term systematic records are generally ambiguous with regard to such interpretive problems, SWD-PSI paleoflood hydrology provides excellent opportunities to test assumptions. In southern Arizona, for example, annual flow peaks are dominated by floods induced by regional snowmelt, local summer convective storms, and winter frontal storms (Hirschboeck, 1985). More rarely, incursions by tropical storms lead to extraordinary floods that appear as outliers in the systematic flood records. Here the systematic flow record is biased toward one hydroclimatologically induced distribution: that controlling the relatively common, smaller annual floods. Only with the expanded time base provided by paleoflood hydrology can an adequate sample be achieved for the unusually large and rare floods related to another hydroclimatologically induced distribution.

Of course, paleoflood hydrology generally cannot identify the hydroclimatic cause for a given paleoflow event. Nevertheless, the time base of centuries or millennia is ideal for evaluating long-term trends. Knox (1985) documented a pronounced nonstationarity for upper Mississippi Valley floods over the past 9500 years. Early Holocene alluvial fills indicate very low probabilities for large floods between 6000 and 9500 yr B.P. Increased probabilities for large floods are evidenced by boulder gravel in overbank sediments deposited in the following age intervals: (1) 6000 to 4500 yr B.P., (2) 3000 to 1800 yr B.P., and (3) 1000 to 500 yr B.P. (Knox, 1985). Similarly, Patton & Dibble (1982) presented evidence from the Pecos River of western Texas that floods were relatively infrequent during an arid interval between approximately 9000 and 3000 yr B.P., but the extraordinary floods occurring in this interval were unusually large. Between approximately 3000 and 2000 yr B.P. a humid interval resulted in more frequent flooding, but flood magnitudes were moderated. The last 2000 years has been most similar to the early Holocene arid interval.

On a shorter time scale, detailed SWD-PSI studies also have an immense potential for evaluating nonstationarity. For the Columbia River in central Washington, Chatters & Hoover (1986) showed that during the approximate interval 1000 to 1400 A.D. large floods were three to four times more common than at present. Flood frequency characteristics similar to those at present prevailed from approximately 200 to 1000 A.D. and from approximately 1400 A.D. to present. This use of paleoflood hydrology illustrates the fallacy of overly simplistic characterizations of paleoflood records as illustrated by the computer simulations of Hosking & Wallis (1986). Rather than a vague rationalization with which to criticize paleoflood hydrologic studies (Hosking & Wallis, 1986), nonstationarity can be an object of scientific study utilizing the remarkable capability of SWD-PSI studies to generate accurate and complete paleoflood records.

Applications in the southwestern United States

Since 1981 the new procedure of SWD-PSI paleoflood hydrology has been used in a regional study of ancient floods in the southwestern United

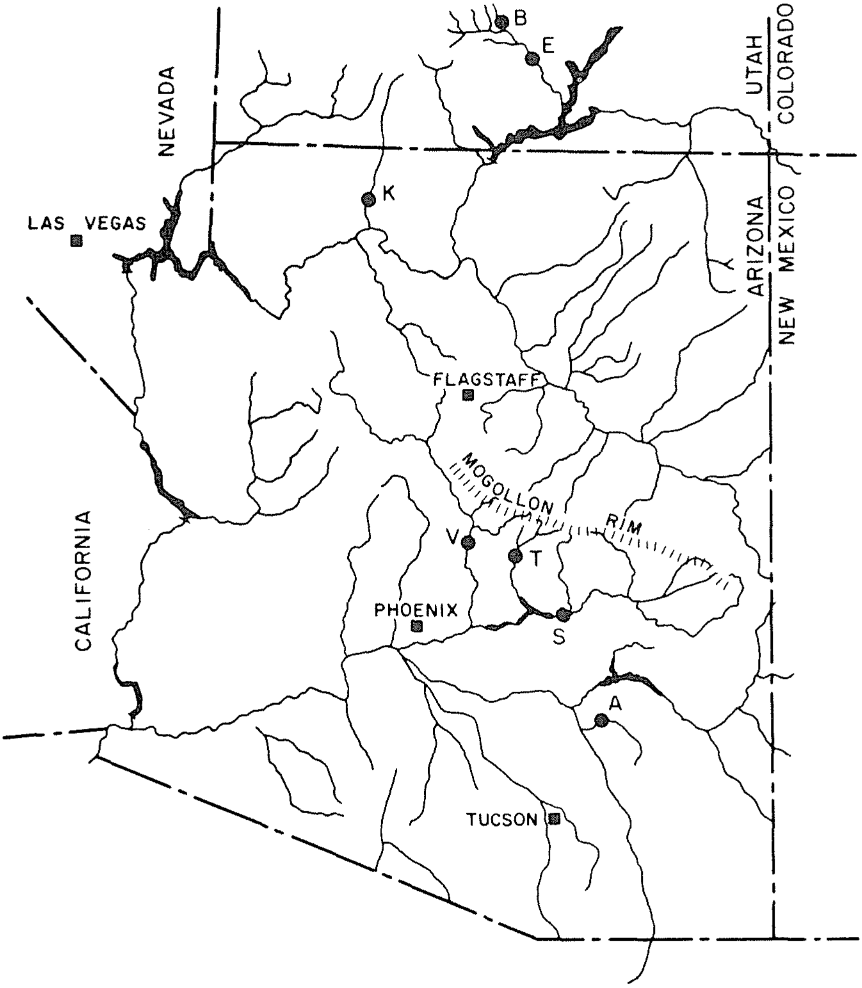

Figure 3 Location of SWD-PSI paleoflood hydrologic investigations in the southwestern United States. Studies were done in south-central Utah on Boulder Creek (B) and the Escalante River (E). In Arizona, studies were done on Kanab Creek (K), Tonto Creek (T), Aravaipa Creek (A), and on the Salt (S) and Verde (V) Rivers.

States (Figure 3). One goal of this regional analysis has been to identify temporal and spatial patterns in extraordinary floods.

The paleoflood record of the Escalante River of south-central Utah (Figure 3) illustrates the trends seen at other study sites. Paleofloods documented by Webb (1985), Webb _et al._ (in press), and O'Connor _et al._ (1986) fall into major time groupings. During the period 2000 to 1300 yr B.P. floods were relatively small. Three major floods occurred between 1200 and 1000 yr B.P., including the largest flood of the record. This period was also one of major arroyo cutting and is well-documented throughout the southwestern U.S. No floods were recorded between 900 and 600 yr B.P., but three floods were recorded between 600 and 400 yr B.P. The next major phase of flooding occurred in the last century, which is the period of most extensive arroyo formation in the region (Webb and Smith, 1986).

The most detailed long-term record of paleofloods in the Southwest occurs just southeast of Phoenix, Arizona (Figure 3). Prehistoric irrigation canals constructed by the Hohokam indians are filled with flood deposits (Masse, 1981). Current research by J.E. Fuller (written communication, 1986) documents that, since 1100 yr B.P., the Hohokam canals recorded a minimum of 25 and a maximum of 30 floods that exceeded 5000 m^3s^{-1}. Of these the largest (>12,000 m^3 s^{-1}) occurred about 1100 yr B.P. during a 250-yr period of pronounced flooding. Large floods again appeared in the last 400 years, including three exceedences of 7000 m^3s^{-1}. The last of these was the 1891 flood with a discharge of between 7000 and 8000 m^3s^{-1} .

Essentially the same timing of paleoflood events is observed on upstream reaches of the Salt River (Partridge & Baker, 1987) and the Verde River (Ely & Baker, 1985). Additional work on these streams and Tonto Creek (Figure 3) by J.E. O'Connor and J.E. Fuller (written communication, 1986) confirms the same sequence. The largest flood occurred approximately 1000 yr B.P. on both the Salt and Verde Rivers. Unusually large floods also occurred during the last century.

Discussion

All SWD-PSI paleoflood studies conducted thus far in Arizona and adjacent areas (Figure 3) reveal a remarkably consistent record. Certain time intervals during the past few millenia have been characterized by occurrences of extraordinarily large floods, while other intervals have been relatively free of such events. Major episodes of flooding occurred from approximately 1000 to 1200 yr B.P. and during the past century or two. A somewhat less intense phase of flooding occurred between approximately 400 and 600 yr B.P. Time intervals between these flood phases were characterized by fewer, smaller floods. In addition, there are many indications that channel entrenchment on alluvial streams (arroyo formation) was coincident with flood phases, while aggradation was generally coincident with phases of reduced flooding (Webb, 1985).

The regional coincidence of flood phases in the southwestern United States suggests a hydroclimatologic cause. A possible mechanism is the variable influence of tropical moisture in the region. Work on evaluating this mechanism is currently in progress.

Considerable potential exists for combining SWD-PSI paleoflood studies with other paleoclimatic indicators. For example, tests of nonstationarity in long-term flood series might be achieved by evaluating other paleohydrologic indicators. Long-term tree-ring series and regime-based paleoflow estimates (RBPE) both can be related to various measures of mean streamflow or mean floods. RBPE studies are accomplished in alluvial channels, which are much more common than the resistant-boundary (non-alluvial) channel conditions required for accurate SWD-PSI studies. Accurately dated mean flow estimates plus chronologies of other paleoclimatic indicators, such as pollen records, plant macrofossils, and isotopic records, can be used to evaluate nonstationarity in paleoflood records and interpret the role of climate change in generating such records. Past climatic change may serve as a guide to the potential for future climatic change. Precise data on the magnitudes of past hydroclimatic change may prove useful in testing models intended to predict future change.

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UNITED STATES
DEPARTMENT OF THE INTERIOR
Oscar L. Chapman, Secretary

BUREAU OF RECLAMATION
Michael W. Straus, Commissioner

REGION 3
E. G. Nielsen, Regional Director

REPORT
ON
WATER SUPPLY
OF THE
LOWER COLORADO RIVER BASIN

PROJECT PLANNING REPORT

NOVEMBER 1952

Sheet 1 of 3

Table 12
LOWER COLORADO RIVER BASIN
Summary of Consumptive Use of Irrigation Water by Crops and Noncropped Areas at Sites of Use

Average annual use in 1,000 acre-feet October 1, 1913-September 30, 1945

Agricultural area and number		Crops	Cities, towns, and farmsteads	Other noncropped areas	Total
ARIZONA					
A-1-LC	Springerville	6.6	0.7	0.7	8.0
A-2-LC	St. Johns	7.6	.7	.7	9.0
A-3-LC	Concho	.2	.2	0	.4
A-4-LC	Silver Creek	6.5	1.0	.8	8.3
A-5-LC	Woodruff	.8	.1	.1	1.0
A-6-LC	Black Creek	.6	.2	.1	.9
A-7-LC	Holbrook	3.4	2.9	.3	6.6
A-8-LC	Hopi, Ganado, and Leupp	1.1	.3	.1	1.5
A-9-LC	Moenkopi	1.1	.3	.1	1.5
A-1-C	Kanab Creek	4.2	.2	.3	4.7
A-2-C	Havasu Creek	.4	0	0	.4
A-3-C	Hualpai Res. & Meriwitica	.2	0	0	.2
A-4-C	Grand Wash	.1	0	0	.1
A-1-V	Short Creek	.1	.1	0	.2
A-2-V	Littlefield	2.3	.2	.2	2.7
A-5-C	Davis Dam to Topock	1.3	0	.1	1.4
A-1-BW	Big Sandy	5.6	.1	.4	6.1
A-2-BW	Santa Maria	3.1	.2	.3	3.6
A-6-C	Colorado River Indian Res.	12.8	.5	.5	13.8
A-7-C	North & South Gila Valleys	19.7	.2	.6	20.5
A-8-C	Yuma Valley	141.9	5.4	5.4	152.7
A-9-C	Yuma Mesa 1/	8.5	.1	.3	8.9
A-1-G	Duncan Valley	7.3	.9	.8	9.0
A-2-G	Alpine	0	0	0	0
A-3-G	San Francisco River	.5	4.8	0	5.3
A-4-G	Eagle Creek	.9	4.9	.1	5.9
A-5-G	Portal	.1	0	0	.1
A-6-G	San Simon Creek	1.5	.3	.1	1.9
A-7-G	Safford Valley	53.1	3.4	4.8	61.3
A-8-G	San Carlos Indian Res.	1.4	.2	.2	1.8
A-9-G	Hereford Valley	.7	0	.1	.8
A-10-G	Middle San Pedro River	8.6	1.0	.7	10.3
A-11-G	Lower San Pedro River	3.0	.4	.2	3.6
A-12-G	Coolidge Dam to Kelvin	1.2	5.6	.1	6.9
A-13-G	San Rafael Ranch	.7	0	.1	.8
A-14-G	Santa Cruz County	5.6	3.7	.5	9.8
A-15-G	Pima County	46.0	8.9	1.9	56.8
A-16-G	Pinal County	173.8	9.1	7.6	190.5
A-17-G	Black River	.1	0	0	.

Table 12 (Continued) Sheet 3 of 3

LOWER COLORADO RIVER BASIN

Summary of Consumptive Use of Irrigation Water

by Crops and Noncropped Areas at Sites of Use

Average annual use in 1,000 acre-feet October 1, 1913-September 30, 19

Agricultural area and number	Crops	Cities, towns, and farmsteads	Other noncropped areas	Total
NEW MEXICO (Continued)				
NM-2-G Virden Valley	4.0	0.3	0.4	4.
NM-3-G San Francisco River	3.3	.8	.4	4.
NEW MEXICO Total	21.8	5.1	2.0	28.
UTAH				
U-1-C Kanab Creek	6.1	.7	.5	7.
U-1-V Virgin River	28.1	4.8	2.5	35.
UTAH Total	34.2	5.5	3.0	42.
MEXICO				
M-1-G San Pedro River	1.3	0	.1	1.
M-2-G Santa Cruz River	6.0	1.6	.6	8.
MEXICO Total	7.3	1.6	.7	9.
LOWER BASIN TOTAL	1,635.7	120.5	74.3	1,830.

1/ Drainage investigations indicate that the practice of irrigation on Yuma Mesa has caused a semiperched ground-water table beneath the irrigated area with an average annual return flow of only 300 acre-feet to the Colorado River system for the 1914-1945 period. Average annual (1914-1945) stream depletion by man on Yuma Mesa would thus be the water pumped to the mesa by the Yuma Mesa and "B" lift pumping plants (1,900 acre-feet plus 7,300 acre-feet) less return flow of 300 acre-feet or 8,900 acre-feet. This depletion has been distributed to crops and noncropped areas in proportion to the respective consumptive use requirements computed for them.

1214.1 89.6 53.1

Sheet 3 of 3

Table 14 (Continued)
LOWER COLORADO RIVER BASIN
Channel Losses and Salvage at Sites of Use
Annual Averages in 1,000 Acre-Feet for 1914-1945 Period and Virgin Flow Conditions

River section	Water surface evaporation			Native vegetation			
	Conditions			Conditions		Salvage	
	Virgin	1914-1945	Salvage	Virgin	1914-1945	Replacement	Growth change
GILA RIVER (Continued)							
Gila River from Calva to Coolidge Dam	10.7	10.7	0	11.1	10.8	0.3	0
San Pedro River in Mexico	-	-	-	a .3	0	.3	-
San Pedro River from Palominas, Ariz. to Charleston, Arizona	.3	.3	0	11.4	10.5	.6	.3
San Pedro R.from Charleston to Mammoth, Arizona	1.1	1.1	0	43.2	44.5	4.6	*5.9
San Pedro R.from Mammoth to mouth	.3	.3	0	13.2	9.4	2.1	1.7
Gila R.from Coolidge Dam to Kelvin	4.6	4.5	.1	9.7	8.0	2.1	* .4
Santa Cruz R.upstream from Nogales gage	-	-	-	a 3.0	0	3.0	-
Santa Cruz R.from Nogales to Rillito	6.6	1.2	5.4	55.4	23.5	23.6	8.3
Salt River above Roosevelt gage	-	-	-	a .7	0	.7	-
Tonto Creek above Roosevelt gage	-	-	-	a .9	0	.9	-
Verde River above Bartlett Dam	-	-	-	a 5.4	0	5.4	-
Verde R.from Bartlett to mouth	4.4	4.0	.4	4.2	3.9	.3	0
Salt River from above Roosevelt Lake to Granite Reef Dam	11.7	12.3	* .6	19.1	19.3	0	* .2
Gila River from Kelvin to Gillespie Dam and downstream from Granite Reef Dam on Salt R.,Rillito on Santa Cruz R.,and Lake Pleasant on Agua Fria R.	44.5	32.9	11.6	401.7	335.1	99.8	*33.2
Gila R.from Gillespie Dam to Dome	51.7	34.1	17.6	367.4	223.8	12.9	130.7
TOTAL	808.6	652.3	156.3	1/ 2,014.5	1,587.4	364.4	62.7

a In headwater sections upstream from points of flow routing.

* Increased losses for 1914-1945 conditions as compared with virgin flow conditions.

1/ Includes 35,000 acre-feet (33,300 replacement of native vegetation and 1,700 decreased losses because of native growth change) in headwater sections upstream from points of flow routing and marked with "a".

Table 22 (Continued)
LOWER COLORADO RIVER BASIN
Analysis of Contributions by States Based on Mean Historic Runoff
For the 1914-1945 Period

Sheet 7 of 11

Unit: 1,000 acre-feet

River section	Item	Arizona	California	Nevada	New Mexico	Utah	Mexico	Undistributed	Total
GILA RIVER FROM CALVA TO GAGE BELOW COOLIDGE DAM, ARIZONA									
San Carlos River near Peridot, Arizona	116	50.5	0	0	0	0	0	0	50.5
Estimated inflow, Calva to Coolidge Dam	117	13.7	0	0	0	0	0	0	13.7
Consumptive use, Calva to Coolidge Dam	118	.4	0	0	0	0	0	0	.4
San Carlos Reservoir evaporation depletion	119	12.2	0	0	0	0	0	0	12.2
Accretion of surface storage in San Carlos Reservoir	120	1.7	0	0	0	0	0	0	1.7
Volumes conveyed, Calva to Coolidge Dam	121	154.4	0	0	198.5	0	0	0	352.9
Channel losses, Calva to Coolidge Dam	122	$ 9.4	0	0	¢12.1	0	0	0	21.5
Gila River below Coolidge Dam, Arizona	123	145.0	0	0	186.4	0	0	0	331.4
SAN PEDRO RIVER FROM GAGE AT PALOMINAS, ARIZONA, TO GAGE AT CHARLESTON, ARIZONA									
San Pedro River at Palominas, Arizona	124	3.9	0	0	0	0	26.1	0	30.0
Estimated inflow, Palominas to Charleston	125	32.6	0	0	0	0	3.6	0	36.2
Consumptive use, Palominas to Charleston	126	.8	0	0	0	0	0	0	.8
Volumes conveyed, Palominas to Charleston	127	35.7	0	0	0	0	29.7	0	65.4
Channel losses, Palominas to Charleston	128	$5.9	0	0	0	0	¢4.9	0	10.8
San Pedro River at Charleston, Arizona	129	29.8	0	0	0	0	24.8	0	54.6
SAN PEDRO RIVER FROM CHARLESTON TO GAGE NEAR MAMMOTH, ARIZONA									
Estimated inflow, Charleston to Mammoth	130	62.3	0	0	0	0	0	0	62.3
Consumptive use, Charleston to Mammoth	131	10.3	0	0	0	0	0	0	10.3
Volumes conveyed, Charleston to Mammoth	132	81.8	0	0	0	0	24.8	0	106.6
Channel losses, Charleston to Mammoth	133	$35.0	0	0	0	0	¢10.6	0	45.6
San Pedro River near Mammoth, Arizona	134	46.8	0	0	0	0	14.2	0	61.0

Item No.

116. Average annual historical flow of the San Carlos River at the gage near Peridot (see Appendix A, Sheet 32 of Table 6); all in Arizona.

117. The estimated inflow to this stream section was computed as the differential needed to balance the measured flow of the Gila River at the gage below Coolidge Dam adjusted for consumptive use by crops and noncropped areas, channel losses, and evaporation depletion and change in storage in San Carlos Reservoir; entire contribution from Arizona.

118. Consumptive use of irrigation water by crops and noncropped areas in this stream section (see A-8-G in Table 12. The total of 1,800 acre-feet for this area was distributed as 500 acre-feet on Gila River upstream from gage at Calva (Item 112), 900 acre-feet on San Carlos River upstream from the gage near Peridot, and 400 acre-feet on San Carlos River downstream from gage near Peridot for this river section item); all in Arizona.

119. Stream depletion by evaporation from San Carlos Reservoir (see Table 8); all in Arizona.

120. Stream depletion by average annual accretion of surface storage in San Carlos Reservoir (see Table 11); all in Arizona.

121. Item 115 plus Items 116 and 117 minus Items 118, 119, and 120.

122. The estimated channel losses of 21,500 acre-feet a year in this section were prorated between New Mexico and Arizona on the basis of the respective volumes conveyed (see Table 14 for total).

123. Item 121 minus Item 122 (see Appendix A, Sheet 33A of Table 6 for total).

124. Average annual historical flow of the San Pedro River at the gage at Palominas, Arizona (see Appendix A, Sheet 34 of Table 6 for total). The flow was prorated between Arizona and Mexico on the basis of their respective drainage areas with consideration for upstream depletions of 1,100 acre-feet a year in Mexico.

125. The total estimated inflow to this stream section was computed as the differential needed to balance the measured flow of the San Pedro River at Charleston adjusted for depletions and channel losses in the section. The total unmeasured inflow was prorated between Arizona and Mexico on the basis of

Notes Accompanying Table 22

Item No.

126. Consumptive use of irrigation water by crops and noncropped areas in this stream section (A-9-G in Table 12); all in Arizona.

127. Item 124 plus Item 125 minus Item 126.

128. Estimated channel losses of 10,800 acre-feet a year were prorated between Arizona and Mexico on the basis of the respective volumes conveyed (see Table 14 for total).

129. Item 127 minus Item 128 (see Appendix A, Sheet 35 of Table 6 for total).

130. The estimated inflow to this stream section was computed as the differential needed to balance the measured flow of the San Pedro River near Mammoth adjusted for depletions and channel losses in the section; all in Arizona.

131. Consumptive use of irrigation water by crops and noncropped areas in this stream section (A-10-G in Table 12); all in Arizona.

132. Item 129 plus Item 130 minus Item 131.

133. Estimated channel losses of 45,600 acre-feet a year in this stream section were prorated between Arizona and Mexico on the basis of the respective volumes conveyed (see Table 14 for total).

134. Item 132 minus Item 133 (see Appendix A, Sheet 36 of Table 6 for total).

135. The estimated inflow to this stream section was computed as the differential needed to balance the measured flow of the Gila River at Kelvin adjusted for depletions and channel losses in the section; all in Arizona.

136. Consumptive use of irrigation water by crops and noncropped areas in this stream section (A-11-G plus A-12-G in Table 12); all in Arizona.

137. Item 123 plus Items 134 and 135 minus Item 136.

Table 23 (Continued) Sheet 10 of 14

LOWER COLORADO RIVER BASIN

Analysis of Contributions by States Based on Mean Virgin Runoff for the 1914-1945 Period, Unit: 1,000 Acre-feet

Item numbers not in parentheses are taken from Table 22, based on historic runoff

River section	Item	Arizona	California	Nevada	New Mexico	Utah	Mexico	Undistributed	Total
SAN PEDRO RIVER FROM HEADWATERS IN MEXICO TO GAGE AT CHARLESTON, ARIZONA									
Consumptive use above Palominas, Arizona	(131)	0	0	0	0	0	1.4	0	1.4
Less replacement of native vegetation	(132)	0	0	0	0	0	.3	0	.3
Net depletions upstream from Palominas	(133)	0	0	0	0	0	1.1	0	1.1
San Pedro River at Palominas, Arizona	124	3.9	0	0	0	0	26.1	0	30.0
Undepleted San Pedro River at Palominas	(134)	3.9	0	0	0	0	27.2	0	31.1
Estimated inflow, Palominas to Charleston	125	32.6	0	0	0	0	3.6	0	36.2
Undepleted volumes conveyed to Charleston	(135)	36.5	0	0	0	0	30.8	0	67.3
Historic channel losses	128	5.9	0	0	0	0	4.9	0	10.8
Virgin channel losses	(136)	$ 6.8	0	0	0	0	¢ 4.9	0	11.7
Replacement of native vegetation	(137)	.6	0	0	0	0	0	0	.6
Decreased losses from native growth change	(138)	.3	0	0	0	0	0	0	.3
Undepleted San Pedro River at Charleston	(139)	29.7	0	0	0	0	25.9	0	55.6
SAN PEDRO RIVER FROM CHARLESTON TO GAGE NEAR MAMMOTH, ARIZONA									
Estimated inflow, Charleston to Mammoth	130	62.3	0	0	0	0	0	0	62.3
Undepleted volumes conveyed to Mammoth	(140)	92.0	0	0	0	0	25.9	0	117.9
Historic channel losses	133	35.0	0	0	0	0	10.6	0	45.6
Virgin channel losses	(141)	$33.7	0	0	0	0	¢10.6	0	44.3
Replacement of native vegetation	(142)	4.6	0	0	0	0	0	0	4.6
Increased losses from native growth change	(143)	5.9	0	0	0	0	0	0	5.9
Undepleted San Pedro River near Mammoth	(144)	58.3	0	0	0	0	15.3	0	73.6

Routing of Mean Virgin Runoff

Notes Accompanying Table 23

<u>Item No.</u>

(129). Uses by native vegetation in cropped and noncropped areas in this stream section under virgin conditions (see Table 14); all in Arizona.

(130). Item (127) minus Item (128).

(131). Consumptive use of irrigation water by crops and noncropped areas in this stream section (M-1-G in Table 12); all in Mexico.

(132). Uses by native vegetation in cropped and noncropped areas in this stream section under virgin conditions (see Table 14, San Pedro River in Mexico); all in Mexico.

(133). Item (131) minus Item (132).

(134). Item (133) plus Item 124.

(135). Item (134) plus Item 125.

(136). Channel losses in this river section were estimated to be 11,700 acre-feet a year under virgin conditions with evaporation from the water surface the same as for historical conditions (see Table 14, Palominas to Charleston for total). Losses apportioned to Mexico were thus considered the same as for historical conditions and the remainder of the virgin channel losses were apportioned to Arizona.

(137). Uses by native vegetation in cropped and noncropped areas between Palominas and Charleston under virgin conditions (see Table 14); all in Arizona.

(138). It was estimated that growth changes attributable to the influence of man decreased the uses by native vegetation between Palominas and Charleston as compared with virgin conditions (see Table 14). As these changes occurred in Arizona, the decreased losses of 300 acre-feet a year were credited to Arizona.

(139). Item (135) minus Item (136).

(140). Item (139) plus Item 130.

Item No.

(141). Channel losses in this river section were estimated to be 44,300 acre-feet a year under virgin conditions with evaporation from the water surface the same as for historical conditions (see Table 14 for total). Losses apportioned to Mexico were thus considered the same as for historical conditions and the remainder of the virgin channel losses were apportioned to Arizona.

(142). Uses by native vegetation in cropped and noncropped areas under virgin conditions in this river section (see Table 14); all in Arizona.

(143). It was estimated that growth changes attributable to the influence of man increased the uses by native vegetation in this river section as compared with virgin conditions (see Table 14). As these changes occurred in Arizona, the increased losses of 5,900 acre-feet a year were charged to Arizona.

(144). Item (140) minus Item (141).

(145). Item (130) plus Items (144) and 135.

(146). Channel losses in this river section were estimated to be 27,800 acre-feet a year under virgin conditions. (See Table 14: San Pedro River from Mammoth to mouth, 13,500 acre-feet plus Gila River from Coolidge Dam to Kelvin, 14,300 acre-feet.) The estimated water surface evaporation from the channel was 100 acre-feet a year less for historical conditions as compared with virgin conditions and the salvage was credited to Arizona on the basis of proportional volumes conveyed. Virgin losses in this stream section apportioned to Mexico and New Mexico were thus considered the same as for historical conditions and the remainder of the virgin channel losses were apportioned to Arizona.

(147). This salvage was discussed under Item (146) (see Table 14, Gila River from Coolidge Dam to Kelvin).

(148). Uses by native vegetation in cropped and noncropped areas in this river section under virgin conditions (see Table 14: San Pedro River from Mammoth to mouth, 2,100 acre-feet plus Gila River from Coolidge Dam to Kelvin, 2,100 acre-feet); all in Arizona.

(149). It was estimated that growth changes attributable to the influence of man decreased the uses by native vegetation in this stream section as compared with virgin conditions. (See Table 14: San Pedro River from Mammoth to mouth, decreased losses of 1,700 acre-feet; Gila River from Coolidge Dam to Kelvin, increased losses of 400 acre-feet; net decreased losses for this river section are thus 1,300 acre-feet.) As these changes occurred in Arizona, the decreased channel losses of 1,300 acre-feet a year were credited to Arizona.

Table 6

LOWER COLORADO RIVER BASIN

Stream Flow in 1000 Acre-feet

SAN PEDRO RIVER AT PALOMINAS, ARIZONA

Location: Lat. 31°22'45", long. 110°06'45", in SE¼ sec. 33, T. 23 S., R. 22 E., at highway bridge, 0.7 mile east of Palominas, 4½ miles downstream from international boundary, and 13 miles southwest of Bisbee.

Drainage Area: 741 square miles.

Water Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Total	Note
1914													90.9	Λ
1915													87.5	|
1916													17.9	
1917													49.4	|
1918													10.8	
1919													49.3	
1920													24.6	
1921													53.7	*
1922													18.3	
1923													22.2	
1924													12.7	|
1925													23.3	
1926													64.8	|
1927													23.5	
1928													7.8	
1929													27.3	V
1930									0.8	10.5	12.0	2.1	*29.9	Λ
1931	0.6	0.5	0.6	0.5	3.0	0.7	0.4	0.2	0.1	1.6	16.4	7.2	31.8	
1932	3.6	0.8	1.7	3.1	1.5	1.2	0.6	0.4	0.2	6.1	6.5	0.4	26.1	|
1933	0.4	0.5	0.7	1.2	0.8	0.4	0.3	0.2	0.2	3.4	2.1	3.7	13.9	
1934													*17.7	1/
1935								0.1	0.1	1.8	10.0	3.7	*19.9	
1936	0.4	1.2	2.0	0.6	0.5	0.3	0.2	0.1	0.8	4.3	4.3	8.9	23.6	|
1937	0.4	0.4	0.5	0.5	0.4	0.4	0.3	0.2	1.1	3.6	25.4	4.3	37.5	
1938	1.5	0.3	0.8	0.4	0.4	0.4	0.2	0.1	0.7	5.2	5.0	3.4	18.4	V
1939	0.3	0.3	1.5	0.5	0.3	0.2	0.2	0.1	0	5.6	17.3	2.8	29.1	2/
1940	0.3	0.3	0.4	0.4	0.6	0.3	0.2	0.1	0.6	2.9	23.5	1.6	31.2	3/
1941	0.5	0.5	0.7	4.4	1.4	0.9	0.7	0.3	0.1				*22.7	4/
1942													11.4	*
1943													28.6	*
1944													11.8	*
1945													21.1	*
14-45 Mean	1.0	0.7	2.1	1.3	0.8	0.6	0.3	0.2	0.9	6.0	11.6	4.5	30.0	*

* Estimated.
1/ Geological Survey Water-Supply Paper 1049 except (*).
2/ Geological Survey Water-Supply Paper 879.
3/ Geological Survey Water-Supply Paper 899.
4/ Geological Survey Water-Supply Paper 929 except (*).

Table 6

LOWER COLORADO RIVER BASIN

Stream Flow in 1000 Acre-feet

SAN PEDRO RIVER AT CHARLESTON, ARIZONA

Location: Lat. 31°37'40", long. 110°10'30", in NE¼NE¼ sec. 11, T. 21 S., R. 21 E., in Spanish land grant of San Juan de las Boquillas y Nogales, at highway bridge ¼ mile south of Charleston, and 8½ miles upstream from Babocomari River. Prior to Dec. 1, 1942, at site 1½ miles downstream.

Drainage Area: 1,216 sq. mi.; 1,250 sq. mi. prior to Dec. 1, 1942.

Water Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Total	Note
1914	0.2	3.5	0.5	0.9	0.6	0.5	0.4	0.3	0.3	8.7	126.2	6.4	148.5	
1915	2.9	2.0	75.6	17.1	12.1	9.8	3.0	1.5	1.2	12.3	5.4	6.4	149.3	
1916	0.8	1.2	1.1	5.3	1.2	0.7	0.4	0.4	0.2	8.5	11.1	3.4	34.3	
1917	4.0	0.3	0.7	1.6	0.9	2.2	1.8	2.3	2.2	34.4	33.9	5.9	90.2	
1918	0.5	0.7	0.7	0.9	0.5	0.6	0.3	0.1	3.2	7.1	5.3	0.4	20.3	
1919	1.0	0.6	1.4	1.0	0.7	0.5	0.2	0.2	0.1	43.2	30.9	13.8	93.6	
1920	3.6	7.6	4.4	8.0	2.9	2.4	1.1	0.5	2.0	0.9	5.7	2.6	41.7	
1921	0.3	0.7	0.7	1.0	0.7	0.9	0.3	0.2	0.4	53.9	40.2	2.4	101.7	
1922	0.7	0.7	0.9	0.9	0.6	0.6	0.3	0.2	0.6	12.6	10.7	7.8	36.6	
1923	0.3	0.5	1.3	1.0	0.4	0.7	0.4	0.2	0.2	14.9	18.3	4.1	42.3	
1924	0.6	1.7	6.3	3.7	0.7	1.4	0.4	0.2	0.2	5.0	4.3	0.6	25.1	
1925	0.3	0.4	0.4	0.6	0.5	0.6	0.6	0.4	9.9	11.2	10.0	2.0	36.9	1/
1926	0.6	1.3	1.0	1.2	0.9	0.9	0.9	0.4	0.1	1.6	1.6	112.3	122.8	
1927	10.2	2.3	1.9	1.6	1.2	1.2	1.2	0.8	0.6	7.9	12.4	2.8	44.1	
1928	1.1	1.2	1.3	1.3	1.3	1.1	0.9	0.8	0.4	2.2	4.3	1.1	17.0	
1929	7.6	1.4	1.2	1.2	1.1	1.0	0.9	0.6	0.4	24.1	10.0	4.5	54.0	
1930	1.9	1.0	1.2	1.6	1.3	1.5	0.9	0.7	1.3	21.1	17.0	4.0	53.5	
1931	1.1	1.2	1.8	1.4	4.6	1.1	0.5	0.5	0.5	4.7	32.6	14.9	64.9	
1932	6.5	1.5	3.6	6.3	1.6	2.2	1.2	0.8	0.6	10.0	10.9	0.7	45.9	
1933	0.9	1.4	1.2	1.7	1.6	1.2	0.7	0.9	0.6	7.9	3.2	6.8	28.1	
1934	2.5	0.9	1.2	1.2	0.9	0.9	0.7	0.4	0.2	6.0	17.0	1.4	33.3	
1935	0.7	0.9	1.4	2.2	1.7	1.5	0.8	0.6	0.3	2.0	25.0	6.9	44.0	
1936	0.9	2.3	3.2	1.5	1.4	1.1	0.9	0.5	1.1	6.4	10.7	14.7	44.7	
1937	1.4	1.2	1.3	1.6	1.1	1.2	0.8	0.7	1.4	5.1	33.7	6.4	55.9	
1938	2.2	0.8	1.4	1.2	1.0	1.0	0.7	0.6	1.0	8.3	10.0	6.4	34.6	
1939	0.8	0.9	2.4	1.1	0.9	0.9	0.6	0.4	0.2	7.7	27.4	6.5	49.8	
1940	1.3	1.0	1.1	1.1	1.8	1.0	0.6	0.5	1.0	8.2	37.9	3.0	58.5	
1941	1.4	1.2	1.6	5.9	2.9	1.5	1.4	0.9	0.5	5.0	13.6	4.8	40.7	
1942	1.6	0.7	1.8	1.3	1.1	1.1	0.8	0.5	0.2	3.3	5.1	6.1	23.6	2/
1943	0.6	0.7	1.0	1.1	0.9	0.8	0.5	0.9	5.3	7.6	26.4	2.0	47.8	
1944	1.3	0.8	1.0	1.1	0.9	1.4	0.7	0.6	0.3	5.4	7.6	3.2	24.3	
1945	0.9	0.9	1.1	1.2	0.9	1.1	0.9	0.5	0.2	3.4	26.0	0.6	37.7	
14-45 Mean	1.9	1.4	3.9	2.5	1.6	1.4	0.8	0.6	1.1	11.3	19.8	8.3	54.6	

Subsequent Records

1946	1.2	0.7	0.9	1.2	1.0	1.0	0.7	0.4	0.3	5.4	17.6	3.1	33.5	2/
1947	0.6	0.7	1.0	1.1	0.9	0.9	0.6	0.5	0.3	1.9	22.3	1.5	32.3	2/
1948	0.4	0.6	0.8	0.8	1.1	0.9	0.6	0.4	0.2	6.8	13.2	7.4	33.2	2/

1/ Geological Survey Water-Supply Paper 1049.

2/ Geological Survey annual Water-Supply Papers.

Table 6

LOWER COLORADO RIVER BASIN

Stream Flow in 1000 Acre-feet

SAN PEDRO RIVER NEAR MAMMOTH, ARIZONA

Location: Lat. 32°44', long. 110°39', in NE¼ sec. 18, T. 8 S., R. 17 E., at bridge on Mammoth-Winkelman highway 1¼ miles north of Mammoth.

Drainage Area: 3,607 square miles.

Water Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Total	Note
1914													134.4	↑
1915													157.9	
1916													34.1	
1917													58.7	
1918													26.5	
1919													148.6	
1920													63.3	
1921													149.6	*
1922													34.9	
1923													91.1	
1924													16.5	
1925													23.7	
1926													86.5	
1927													47.5	
1928													34.3	
1929													61.2	↓
1930													92.1	
1931								0	0.7	2.3	57.3	18.2	*89.7	↑
1932	12.2	4.2	6.6	7.2	8.8	3.3	0.5	0	0	11.9	11.2	0	65.9	
1933	0	0	0.4	1.0	0.8	0.1	0	0	0	6.1	2.1	4.5	15.0	
1934	2.6	0.1	0.2	0.1	0	0	0	0	0	2.9	18.0	0.9	24.8	1/
1935	0	0	0.3	1.7	1.9	1.2	0	0	0	0.1	29.2	10.6	45.0	
1936	0.2	1.8	3.2	0.9	2.9	0	0	0	0.3	4.1	14.9	9.7	38.0	
1937	0	0.2	0.5	1.0	4.5	0.1	0	0	0	1.2	42.3	13.2	63.0	↓
1938	0.5	0	0.3	0	0	1.2	0	0	0.4	7.0	14.5	7.1	31.0	
1939	0	0	0.6	0	0.1	0	1.0	0	0	7.5	39.0	7.4	55.6	2/
1940	1.6	0	0	0	0.7	0	0	0	0.6	6.1	51.9	2.5	63.4	3/
1941	0.4	0.3	11.4	8.5	6.9	6.9	0.9	0.2	0				*73.3	4/
1942													19.0	*
1943													39.2	*
1944													32.2	*
1945													35.8	*
14-45 Mean	1.8	0.6	3.2	2.8	2.3	1.0	0.2	0	0.3	10.8	29.8	8.2	61.0	*

* Estimated.

1/ Geological Survey Water-Supply Paper 1049 except (*).

2/ Geological Survey Water-Supply Paper 879.

3/ Geological Survey Water-Supply Paper 899.

4/ Geological Survey Water-Supply Paper 929 except (*).

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A Technique for Determining Depths for T-Year Discharges in Rigid-Boundary Channels

Geological Survey, Menlo Park, Calif Water Resources Div

Dec 77

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16. Abstracts

A simplified technique for determining T-year flood-boundary altitudes for natural channels having channel controls is presented in this report. Channel-control conditions usually exist during T-year discharges in natural rigid-boundary channels; therefore the simplified technique probably would be applicable for flood-inundation studies for many rigid-boundary channels. The technique requires that T-year discharge for a reach of interest be known or readily available; also a channel-shape factor, a width at a reference depth, channel-bottom slope (or water-surface slope) and the Manning's roughness factor, *n*, must be estimated or determined at representative cross sections. The standard error of estimate or the flood-boundary altitudes determined according to the simplified technique is not known; however, it is probably about 25 to 30 percent. In comparison, the standard error of estimate for the flood-boundary altitudes determined according to guidelines given in the report Flood Insurance Study, Guidelines and Specifications by U.S. Department of Housing and Urban Development is about 23 percent.

17. Key Words and Document Analysis. 17a. Descriptors

*Floods, *Hydraulics, Natural streams, Discharge, Roughness (hydraulic), Flood profiles, Flood frequency, Flood plain zoning

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100-year discharge, FIA flood studies, Simplified flood-mapping technique

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A TECHNIQUE FOR DETERMINING DEPTHS FOR T-YEAR DISCHARGES IN RIGID-BOUNDARY CHANNELS

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CONVERSION FACTORS

For readers who may prefer to use metric units rather than English units, the conversion factors for the terms used in this report are listed below:

Multiply English unit	*By*	*To obtain metric unit*
ft (feet)	0.3048	m (meters)
ft^2 (square feet)	.0929	m^2 (square meters)
ft^3/s (cubic feet per second	.02832	m^3/s (cubic meters per second)
mi (miles)	1.609	km (kilometers)

A TECHNIQUE FOR DETERMINING DEPTHS FOR T-YEAR DISCHARGES IN RIGID-BOUNDARY CHANNELS

By Durl E. Burkham

ABSTRACT

A simplified technique is presented for determining depths for *T*-year discharges (the discharge that will occur, on an average, once in *T*-years--10 years, 50 years, 100 years) for natural channels (channels not significantly affected by manmade structures) having channel-control conditions and rigid boundaries (channels having a low probability of change that would significantly affect the hydraulic characteristics of a *T*-year discharge). Channel-control conditions usually exist during *T*-year discharges in natural rigid-boundary channels and, therefore, the simplified technique probably would be applicable for flood-inundation studies for many natural rigid-boundary channels. The technique requires that the *T*-year discharge for a reach of interest be known or readily available; also, a channel-shape factor, a width at a reference altitude, a channel-bottom slope (or a water-surface slope), and the Manning's roughness factor, n, must be estimated or determined at representative sections having channel-control conditions. The standard error of estimate for depths determined according to the simplified technique is not known; however, it is probably 25-30 percent. In comparison, the standard error of estimate for the depths determined according to the step-backwater procedure and to guidelines and specifications for flood-insurance studies of the Federal Insurance Administration is about 23 percent.

INTRODUCTION

Public Law 93-235, Flood Disaster Protection Act of 1973, requires the U.S. Geological Survey and other selected Federal agencies to assist the Federal Insurance Administration (FIA) of the U.S. Department of Housing and Urban Development (HUD) in identifying flood-prone areas. Present study guidelines (U.S. Department of Housing and Urban Development, 1976) for mapping flood-prone areas require detailed and time-consuming analyses, which only a few Federal agencies and a limited number of private engineering firms have the competence to perform. An acceptable simplified approach that would have a broad application for mapping flood plains and for making floodway analyses could alleviate manpower stresses.

Several simplified methods for determining flood-boundary altitudes have been developed by the U.S. Geological Survey. However, these simplified methods are not directly applicable for nonnatural channels--channels affected by bridges, lined canals, dams, reservoirs; for sheet flow; for movable-boundary channels--channels that have a high probability of temporal change that would significantly affect the hydraulic characteristics of a *T*-year discharge; and for floodway analyses.

This report is a result of studies concerned with the development of a simplified technique that would be applicable to mapping of flood plains along natural and nonnatural channels. The discussions that are presented in the present report, however, are pertinent only to the development of equations for *T*-year depths in rigid-boundary channels having channel-control characteristics during a *T*-year discharge and to the application of the equations to a selected study reach. Unless otherwise stated, a *T*-year depth for a site of interest is the water-surface altitude for a *T*-year discharge minus the channel-bottom altitude (point of zero flow, altitude at which water ceases to move in the channel). A *T*-year discharge for a site or reach of interest is the discharge that will occur, on an average once in *T*-years--10 years, 50 years, 100 years.

The term "control" (or control of flow) means the establishment of definite flow conditions in the channel or, more specifically, a definite relation between discharge and depth of flow. True controls in an open channel are of two types, channel and section. A true channel control exists when the physical characteristics of a reach of a uniform channel downstream from a site of interest determines the relation between discharge and depth at the site. A true section control exists when the physical characteristics of a single cross section of a stream control the relation between discharge and depth. True controls may exist in a natural channel. Typically, however, for a site in a natural rigid-boundary channel a relatively short length of channel having the characteristics of a section control exists for relatively low flows and a relatively long length of channel having the characteristics of a channel control is effective for relatively high discharges. The section-control condition for low flows in a natural channel may be the result of a single riffle or the result of a restricted width for a single short length of channel. The channel-control condition for high flows may be the result of a long reach of a fairly uniform channel; however, it ordinarily results from the composite effects of restricted width at several relatively short lengths of channel. This report deals primarily with relatively high discharges; therefore, the remaining discussions in this report, unless otherwise stated, pertain primarily to relatively high discharges in natural rigid-boundary channels having channel-control conditions.

APPROACH TO SOLUTION

Introduction

The approach used to determine *T*-year depths in a reach of interest is based on the premise that:

1. A *T*-year discharge is known or is readily obtainable.
2. Depth for a *T*-year discharge usually does not vary greatly in a relatively long reach of a natural rigid-boundary channel; the water-surface profile approximately parallels the channel-bottom profile and the average depth can adequately represent (errors introduced are not prohibitive) depth in the reach.
3. Depth of flow is a function of discharge and the physical characteristics--channel size, shape, slope, and roughness--of lengths of channel in the reach that are partial or true controls.
4. Depth of flow in a length of channel having the characteristics of a partial control can be adequately determined using a small amount of field data.
5. The average of computed depths for a few representative partial controls can be used to represent average depth in the reach.

Six basic steps are required in determining depths for *T*-year discharges in a reach of interest:

1. Determine a *T*-year discharge.
2. Develop a channel-bottom profile.
3. Determine the locations of partial (or true) controls in the reach.
4. Compute depths for *T*-year discharges by equations for representative cross sections for a few of these partial controls; to do this a small amount of field data must be obtained.
5. Average the depths determined in step 4.
6. Develop a water-surface profile by graphically adding the average depth, obtained in step 5, to the channel-bottom profile developed in step 2.

The development of an inundation map would involve an additional step (step 7), the transfer of altitudes from the water-surface profile to a topographic map.

A brief description of steps 1, 2, and 3 follows in this section. A detailed discussion concerned with the development of equations to be used to compute depths at representative cross sections in lengths of channel that have the characteristics of controls (step 4) is presented in the section "Depths for *T*-year discharges in channels having channel-control conditions." Step 5 is self-explanatory. Descriptions of steps 6 and 7 are presented by an example in the section "Application of method."

T-Year Discharge

A *T*-year discharge determination for a reach of interest is based on a flood-frequency analysis. If a long-term record of discharge is available for a site, the flood-frequency analysis consists of the development of a flood-frequency curve from which the *T*-year discharge is obtained directly (U.S. Water Resources Council, 1976). For a typical case, however, records are not available and flood-frequency information must be transferred from gaged sites to ungaged sites.

Flood information based on long-term records for a gaged site can be transferred to a site of interest on the same gaged stream by one of several schemes. Generally, however, T-year discharges at sites near gaging stations on the same stream are computed by the following equation:

$$Q_{T_{(u)}} = \left(\frac{A_u}{A_g}\right)^X Q_{T_{(g)}} \tag{1}$$

where

$Q_{T_{(u)}}$ = T-year discharge at an ungaged site on a gaged stream;

$Q_{T_{(g)}}$ = T-year discharge at a gaged site;

A_u = drainage area for the ungaged site;

A_g = drainage area at a gaged site; and

X = exponent.

The value of X to be used for a hydrologic region must be evaluated or estimated. Generally, X will range from 0.5 to 0.8.

The transfer of T-year information from gaged sites to ungaged sites on other streams is usually done by regression of the T-year floods on the physical and climatic characteristics of drainage basins. A characteristic regression equation has the following form:

$$Q_T = aA^b P^c S^d \tag{2}$$

where

Q_T = T-year discharge;

A = size of drainage area;

P = precipitation index;

S = slope of the principal channel; and

a, b, c, d = regression constants.

The U.S. Geological Survey, in 1970, made state-by-state studies to define regression equations for T-year discharges for ungaged streams. The details for the equations obtained by the regression study are shown in open-file reports available at the 47 district offices of the U.S. Geological Survey (Benson and Carter, 1973).

Channel-Bottom Profile

The altitudes and distances needed to develop a channel-bottom profile for a reach of interest may be scaled from a topographic map, which shows altitude contours, or they can be determined by field surveys. When altitudes and distances are taken from a topographic map, the accuracy of the contours must be considered. The standard error of ground altitudes taken from topographic maps is about one-fourth the contour interval. Generally, field surveys are made if topographic maps having a contour interval smaller than about 5 ft are not available. In field surveys, point altitudes can be determined very accurately; however, for practical purposes, thalweg altitudes are not usually determined closer than about ±0.5 ft.

Controls

The criteria for locating sites at which depths for a given flow rate can be computed by equations are, in general, the same as those for slope-area measurements (Dalrymple and Benson, 1967). A reconnaissance-level survey of the study reach is necessary for the selection of sites. Experience, good judgment, and a thorough knowledge of the hydraulic principles of open-channel flow are essential for the proper selection of the sites. The channel-bottom profile developed in step 3, contour maps, and aerial photographs are useful aids.

DEPTHS FOR T-YEAR DISCHARGES IN CHANNELS HAVING CHANNEL-CONTROL CONDITIONS

Introduction

The relation between discharge and depth for relatively high flows (T-year events) in channels having channel-control conditions usually can be adequately represented as a straight line on logarithmic graph paper; this is one method to extend rating curves when high-discharge measurements are not available. The general equation for the discharge-depth relation is

$$d = CQ^f \qquad (3)$$

or

$$\log d = \log C + f \log Q \qquad (4)$$

in which

d = depth of water;

C = a coefficient; equals effective depth when Q equals 1;

f = slope of the discharge-depth relation; and

Q = discharge.

Both the coefficient and the exponent for the logarithmic straight-line equation are functions of the physical characteristics of the controls of flow. Theoretical considerations, experience, judgment, and a minimal amount of field data are the basis for estimating values for the coefficient, *C*, and exponent, *f*, in the discharge-depth relation.

Development of Equation

The thesis of this report is that, providing the *T*-year discharge is known, Manning's discharge equation can be used to make reasonably accurate estimates of *C* and *f* for channel-control conditions without obtaining detailed field information. Manning's discharge equation for English units is

$$Q = \frac{1.49}{n} AR^{2/3} S^{1/2} \tag{5}$$

in which

n = a 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 for conditions of channel control to compute flow rates; however, detailed data pertinent to channel boundary characteristics must be measured in the field.

Several assumptions and simplifications must be made before Manning's equation can be used to estimate *C* and *f*. For a *T*-year discharge it is assumed that R can be adequately represented by the mean cross-sectional depth, $\overline{d}$, 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, $\overline{d}$, multiplied by the top width, W.

Width in a rigid-boundary channel is a function of depth. For a wide range of flood depths in typical rigid-boundary channels, a depth-width relation can be represented as a straight line on logarithmic graph paper. As used in this study, the general equation for logarithmic straight-line relation is

$$W = a_1(d)^x \tag{6}$$

or

$$\log W = \log a_1 + x \log d \tag{7}$$

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

Considering the assumptions and simplifications presented in the preceding paragraphs, Manning's discharge equation can be represented by

$$Q = a_1 \frac{1.49}{n} \left(\bar{d}\right)^{5/3} (d)^x S_o{}^{1/2} \tag{8}$$

A further simplification is made; $\bar{d}$ is represented by the formula "$\bar{d} = a_2 d$." The parameter a_2 also is a function of channel shape; it is 1 for a rectangular shape, 1/2 for a triangular shape, and 2/3 for a parabolic shape. The depth, d, now can be represented by

$$d = \left(\frac{n}{a_1(a_2)^{5/3}(1.49)(S_o)^{1/2}}\right)^{3/(5+3x)} (Q)^{3/(5+3x)} \tag{9}$$

Equation 9 is directly comparable to equation 3 and, therefore,

$$C = \left(\frac{n}{a_1(a_2)^{5/3}(1.49)(S_o)^{1/2}}\right)^f \tag{10}$$

and

$$f = \left(\frac{3}{(5+3x)}\right) \tag{11}$$

Equations 9, 10, and 11 are approximately correct for stage-discharge relations for high discharges in uniform channels. They are assumed to be adequate in approximating depths for high discharges at partial-control sites (restricted sections) in natural channels having channel-control conditions. The value x would range from 0 to 1 and, therefore, f would range from 0.60 to 0.38 for rigid-boundary channels. The typical natural channel is approximately parabolic in shape, for which f would be 0.46. The writer determined that the average value of f was 0.42 for the high-discharge segment of 539 stage-discharge relations for selected sites in Iowa, Maryland, Minnesota, New York, North Carolina, Ohio, and Wisconsin; the standard deviation for the 539 sites was 0.12.

Testing of Equation

Data from a report by Barnes (1967) were used to test the algebraic form of equation 9. For the Barnes data, Q, d, n, and S_w were known or were readily obtainable for sites in 50 stream channels in the United States. In the test analyses a parabolic cross-sectional shape was assumed for each site, and therefore a_2 is 2/3, x is 1/2, and f is 0.46.

Equation 6 was used to compute values for a_1; this required a reference depth, d_r, and a reference width, W_r. For a cross section of interest, a reference altitude was assumed, d_r was determined, and the corresponding value for W_r was scaled from the appropriate graph in Barnes' report. The assumed reference altitude was based on a judgment that the formula $\frac{W}{(d)^x} = a_1 = \frac{W_r}{(d_r)^x}$ was adequately satisfied.

The procedures for estimating a_1 using equation 6 and for estimating d using equation 9 are presented by use of a sample computation. The data from Barnes (1967) for reach 3-4 in the stream channel at the gaging station "South Fork Clearwater River near Grangeville, Idaho" are used for this purpose. Section 4 represents a restricted section in the reach. The peak discharge for the flood of May 28, 1948, at this site is 12,600 ft ^{3}/s (Barnes, 1967, p. 158-159); n is 0.05; measured depth, d_m, is 12 ft; and the slope of the water surface, S_w, is 0.0080 (2.85 divided by 357). Values of n and S_w for cross-section 4 were needed for the computation; however, these values were not available. The use of 0.05 and 0.0080, which are for the reach 3-4, probably introduces errors in the computation. Above an altitude of 20 ft (fig. 1), equation 6 probably adequately represents width because there is no abrupt increase in width with an increase in depth. The reference depth, d_r, therefore, is taken to be 7.0 ft and was determined by subtracting the channel-bottom altitude 13.0 ft from 20.0 ft. The width, W_r, is 124 ft at 20.0 ft altitude (fig. 1). When these values for depth and width are entered in equation 6, the computed a_1, which represents the apparent width at 1.0 depth, is 46.9 ft. When the 46.9 ft for a_1 and the other pertinent numerical values described in this paragraph are entered in equation 9, the computed depth is 11.3 ft, which is 0.7 ft less than the measured depth.

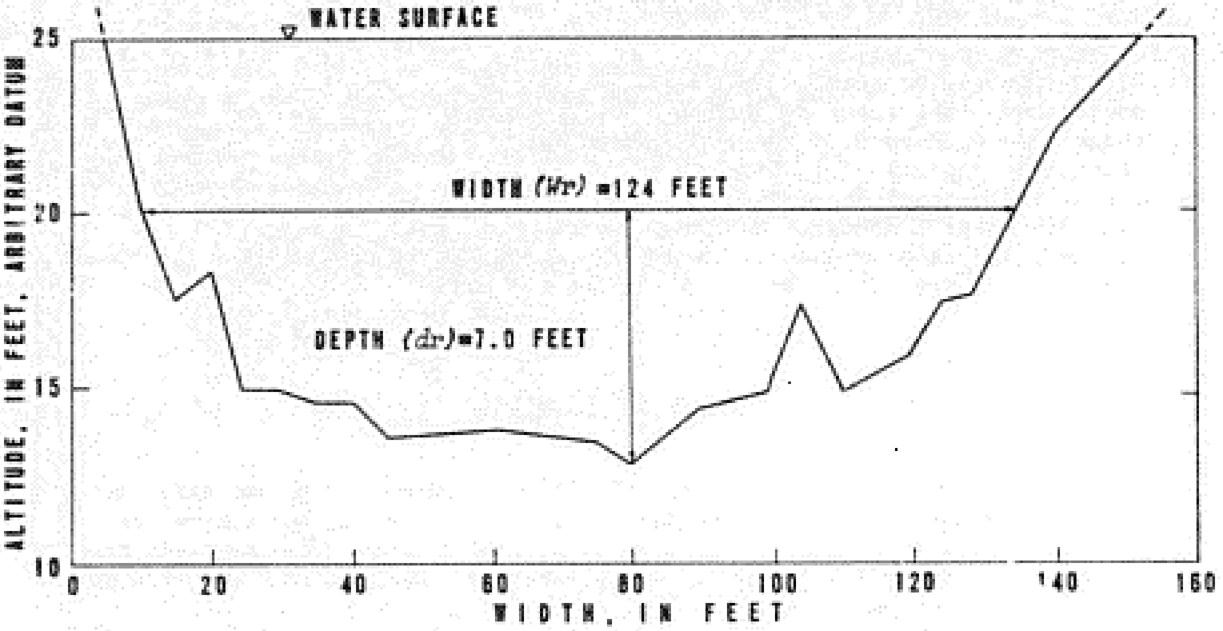

FIGURE 1.—Cross section, South Fork Clearwater River near Grangeville, Idaho. (Modified from Barnes, 1967, p. 159, cross section 4.)

The computed depths, flood characteristics, and cross-sectional properties for the Barnes data are presented in table 1. Except for the site "Columbia River at Vernita, Wash." (not shown in table), flood depths were computed for all sites. An apparent discrepancy exists for the Columbia River data; for cross-section 3 (Barnes, 1967, p. 11), the mean depth is shown to be approximately equal to the maximum depth. For the site "Beaver Kill at Cooks Falls, N.Y.," an apparent discrepancy exists for cross-section 7 (Barnes, 1967, p. 59); the vertical axis for altitude is not calibrated correctly. Data for cross-section 6 were used in the computation for Beaver Kill.

The standard error of estimate for computed depths for the Barnes data is about 10 percent; apparently there is little, if any, overall bias in computed depths (fig. 2). The standard error of estimate for computed flood depths for most sites in natural channels, however, probably would be larger than 10 percent. The Manning's n is unknown for most sites in natural channels and estimate of n would have to be made for these sites in order to use equation 9. Errors would be introduced with these estimates.

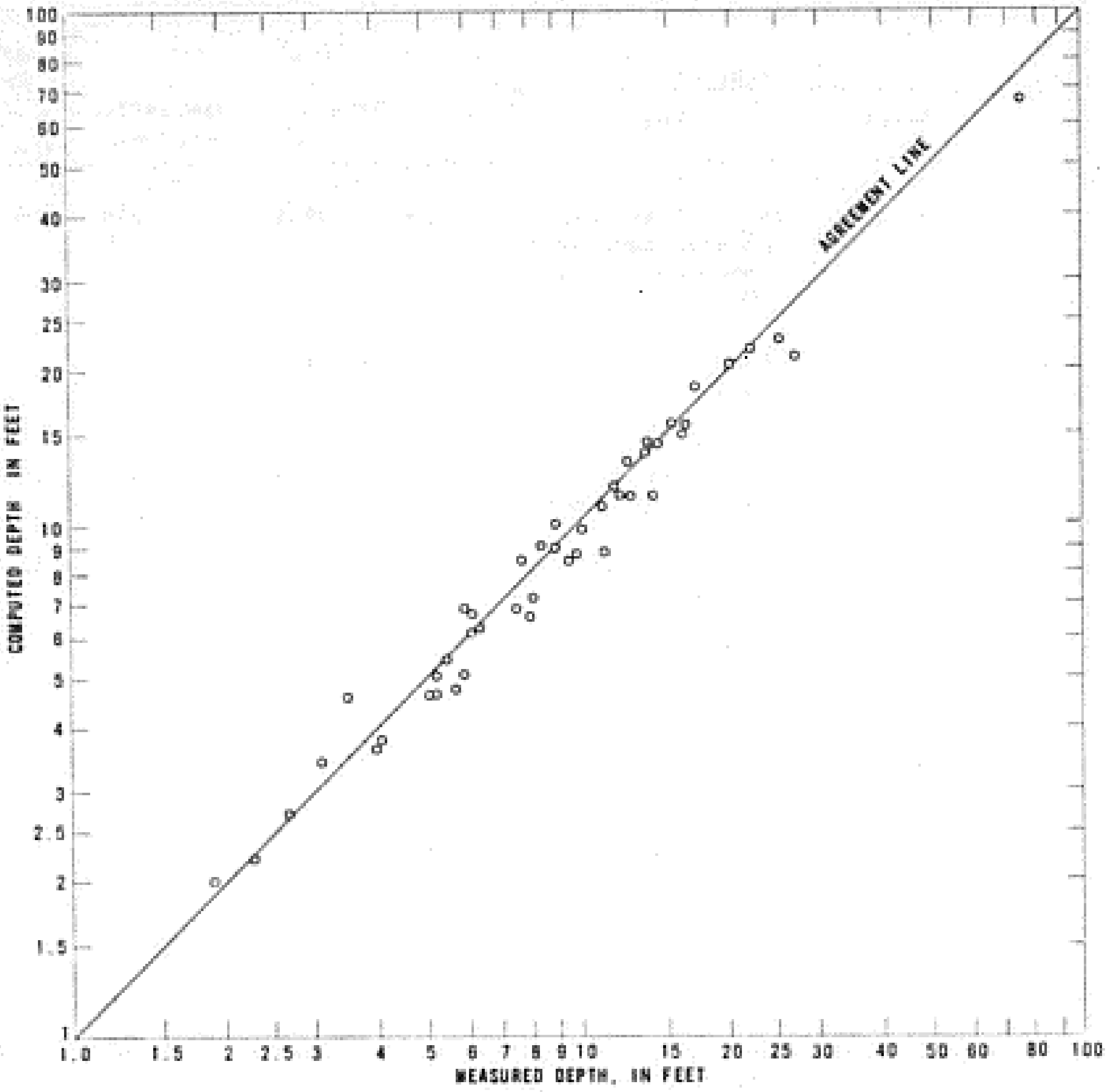

FIGURE 2.—Computed depth compared with measured depth.

Table 1.--*Flood characteristics, cross-sectional properties, and*

Station		Flood characteristics		
Number	Name	Date	Discharge (ft^3/s)	Measured depth d_m (feet)
3-1215.	Indian Fork below Atwood Dam, near New Cumberland, Ohio	May 11, 1948	768	6.3
8-1235.	Champlin Creek near Colorado City, Tex.	May 17, 1949	2,390	5.7
12-3545.	Clark Fork at St. Regis, Mont.	May 24, 1948	68,900	20.0
12-3405.	Clark Fork above Missoula, Mont.	May 23, 1948	31,500	13.5
14-1057.	Columbia River at The Dalles. Oreg.	May 31, 1948	1,000,000	75.0
1-3625.	Esopus Creek at Coldbrook, N.Y.	Mar. 22, 1948	13,900	7.2
6-8030.	Salt Creek at Roca, Nebr.	May 2, 1954	1,860	13.5
12-3385.	Blackfoot River near Ovando, Mont.	May 22, 1948	8,200	7.5
12-4120.	Coeur d'Alene River near Pritchard, Idaho	May 21, 1948	11,300	10.0
8-2900.	Rio Chama near Chamita, N. Mex.	Mar. 24, 1950	1,060	5.2
9-5020.	Salt River below Stewart Mountain Dam, Ariz.	Mar. 24, 1950	1,280	2.7

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computed depths for stream-channel sites described by Barnes (1967)

	Cross-sectional properties							
Station Number	Manning's roughness coefficient, n	Water-surface slope, S_w	Reference depth, d_r (feet)	Reference width, W_r (feet)	Coefficient			Computed depth (feet)
					a_2	a_1	C	
3	0.026	0.00025	1.5	40	0.67	33.2	0.28	6.1
4	.027	.00480	1.0	42	.67	42.0	.13	4.7
3	.028	.00073	5.0	300	.67	134	.12	20.2
4	.030	.00061	2.5	260	.67	168	.12	13.8
4	.030	.00029	25.0	1,250	.67	250	.12	66.4
2	.030	.00340	3.0	220	.67	130	.09	7.2
3	.030	.00037	2.0	19	.67	13.4	.42	13.6
2	.031	.00230	2.0	160	.67	110	.11	6.7
4	.032	.00300	4.5	130	.67	62.2	.13	9.6
2	.032	.00120	1.7	60	.67	46.0	.19	4.6
7	.032	.00340	1.0	110	.67	110	.10	2.7

Table 1.--*Flood characteristics, cross-sectional properties, and*

Station		Flood characteristics		
Number	Name	Date	Discharge (ft^3/s)	Measured depth d_m (feet)
1-4205.	Beaver Kill at Cooks Falls, N.Y.	Mar. 22, 1948	15,500	9.0
13-3390.	Clearwater River at Kamiah, Idaho	May 29, 1948	99,000	25.0
2-3890.	Etowah River near Dawsonville, Ga.	Jan. 22, 1959	2,260	14.0
12-3425.	West Fork Bitterroot River near Conner, Mont.	May 29, 1948	3,880	5.9
12-4845.	Yakima River at Umtanum, Wash.	May 29, 1948	27,000	14.0
5-Misc.	Middle Fork Vermilion River near Danville, Ill.	May 1, 1956	1,620	3.2
12-4570.	Wenatchee River at Plain, Wash.	May 29, 1948	22,700	12.5
12-3065.	Moyie River at Eastport, Idaho	May 24, 1948	8,030	8.5
12-4225.	Spokane River at Spokane, Wash.	May 31, 1948	39,600	22.0
2-2135.	Tobesofkee Creek near Macon, Ga.	Mar. 7, 1958	2,540	12.5
8-1185.	Bull Creek near Ira, Tex.	June 1, 1948	3,220	9.8

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computed depths for stream-channel sites described by Barnes (1967)--Continued

	Cross-sectional properties							
Station Number	Manning's roughness coefficient, n	Water-surface slope, S_w	Reference depth, d_r (feet)	Reference width, W_r (feet)	Coefficient			Computed depth (feet)
					a_2	a_1	C	
6	0.033	0.00230	3.0	210	0.67	121	0.10	8.9
3	.033	.00120	11.0	460	.67	139	.11	22.6
11	.041	.00084	5.0	50	.67	22.4	.32	11.1
3	.036	.00460	1.0	82	.67	82.0	.11	5.0
3	.036	.00280	5.0	180	.67	78.0	.13	14.1
3	.037	.00330	1.0	96	.67	96.0	.11	3.4
3	.037	.00230	5.0	200	.67	39.4	.13	12.9
4	.038	.00470	5	115	.67	51.4	.14	8.9
4	.038	.00130	10	230	.67	72.7	.16	21.1
17	.043	.00077	3.5	60	.67	39.5	.22	11.1
2	.041	.00120	2.0	65	.67	46.0	.21	8.7

Table 1.--*Flood characteristics, cross-sectional properties, and*

Station		Flood characteristics		
Number	Name	Date	Discharge (ft^3/s)	Measured depth d_m (feet)
12-3557.	Middle Fork Flathead River near Essex, Mont.	May 22, 1948	14,500	11.0
2-2175.	Middle Oconee River near Athens, Ga.	May 31, 1959	6,110	16.0
6-3940.	Beaver Creek near Newcastle, Wyo.	May 30, 1953	1,600	13.0
13-3200.	Catherine Creek near Union, Oreg.	May 27, 1948	1,740	5.2
12-4565.	Chiwawa River near Plain, Wash.	May 29, 1948	5,880	8.0
1-3625.	Esopus Creek at Coldbrook, N.Y.	Mar. 22, 1948	13,900	11.0
13-3190.	Grande Ronde River at La Grande, Oreg.	May 22, 1948	4,620	7.6
2-2210.	Murder Creek near Monticello, Ga.	Feb. 7, 1958	840	8.0
10-1550.	Provo River near Hailstone, Utah	June 13, 1952	1,200	4.1
3-3015.	Rolling Fork near Boston, Ky.	Mar. 11, 1949	6,090	27.0
2-1885.	South Beaverdam Creek near Dewy Rose, Ga.	Nov. 26, 1957	820	6.1

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computed depths for stream-channel sites described by Barnes (1967)--Continued

	Cross-sectional properties							
Station Number	Manning's roughness coefficient, n	Water-surface slope, S_w	Reference depth, d_r (feet)	Reference width, W_r (feet)	Coefficient a_2	Coefficient a_1	Coefficient C	Computed depth (feet)
5	0.041	0.00250	2.5	127	0.67	80.3	0.14	11.1
5	.042	.00055	5.0	100	.67	58.5	.20	15.3
2	.043	.00124	2.0	18	.67	12.7	.39	11.5
3	.043	.00620	1.0	37	.67	37.0	.16	5.0
4	.043	.00680	2.5	105	.67	66.4	.12	6.5
2	.043	.00450	4.0	139	.67	70.0	.13	10.6
3	.043	.00240	3.0	88	.67	50.8	.17	8.4
8	.045	.00260	3.5	23	.67	12.3	.34	7.5
9	.045	.00970	1.0	40	.67	40	.14	3.8
6	.046	.00038	5.0	60	.67	26.8	.37	20.4
5	.052	.00094	2.0	43	.67	30.4	.30	6.6

Table 1.--*Flood characteristics, cross-sectional properties, and*

Station		Flood characteristics		
Number	Name	Date	Discharge (ft^3/s)	Measured depth d_m (feet)
2-1005.	Deep River at Ramseur, N.C.	Dec. 28, 1958	8,300	16.0
6-7195.	Clear Creek near Golden, Colo.	May 26, 1958	1,380	5.1
2-3310.	Chattahoochee River near Leaf, Ga.	Feb. 7, 1959	5,100	9.0
13-3380.	South Fork Clearwater River near Grangeville, Idaho	May 29, 1948	12,600	12
11-4510.	Cache Creek near Lower Lake, Calif.	Jan. 24, 1951	3,840	11.2
4-2750.	East Branch Ausable River at Au Sable Forks, N.Y.	Mar. 31, 1951	7,790	9.5
1-1805.	Middle Branch Westfield River at Cross Heights, Mass.	Mar. 22, 1948	3,400	3.5
12-4620.	Mission Creek near Cashmere, Wash.	May 19, 1955	123	2.3
2-935.	Haw River near Benaja, N.C.	Dec. 29, 1958	1,000	6.0
12-1135.	North Fork Cedar River near Lester, Wash.	Dec. 15, 1959	996	4.0
3-4485.	Hominy Creek at Candler, N.C.	June 16, 1949	6,460	15.2

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computed depths for stream-channel sites described by Barnes (1967)—Continued

Station Number	Manning's roughness coefficient, n	Cross-sectional properties						Computed depth (feet)
		Water-surface slope, S_w	Reference depth, d_r (feet)	Reference width, W_r (feet)	Coefficient			
					a_2	a_1	C	
7	0.049	0.00091	5.0	112	0.67	50.0	0.23	14.6
15	.050	.01410	2.0	40	.67	28.3	.16	4.6
5	.051	.00104	2.5	115	.67	73.0	.19	9.9
4	.051	.00800	7.0	124	.67	46.9	.15	11.3
3	.053	.0500	8.8	33	.67	11.1	.19	8.5
2	.055	.00560	3.0	125	.67	72.2	.14	8.4
2	.056	.00870	1.0	93	.67	93.0	.11	4.6
3	.057	.01500	1.0	13	.67	13.2	.24	2.2
7	.059	.00130	5.0	75	.67	33.0	.28	6.8
4	.059	.0230	1.0	30	.67	30.0	.15	3.6
3	.060	.00176	4.0	62	.67	31.0	.23	15.6

Table 1.--*Flood characteristics, cross-sectional properties, and*

Station		Flood characteristics		
Number	Name	Date	Discharge (ft^3/s)	Measured depth d_m (feet)
12-3455.	Rock Creek Canal near Darby, Mont.	Sept. 23, 1948	138	1.9
11-2645.	Merced River at Happy Isles Bridge, near Yosemite, Calif.	June 17, 1950	1,950	6.4
3-3020.	Pond Creek near Louisville, Ky.	Feb. 14, 1950	1,480	17.0
12-3215.	Boundary Creek near Porthill, Idaho	May 28, 1948	2,530	6.2
12-3450.	Rock Creek near Darby, Mont.	May 27, 1948	1,500	5.5

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computed depths for stream-channel sites described by Barnes (1967)--Continued

Cross-sectional properties								
Station Number	Manning's roughness coefficient, n	Water-surface slope, S_w	Reference depth, d_r (feet)	Reference width, W_r (feet)	Coefficient a_2	Coefficient a_1	Coefficient C	Computed depth (feet)
7	0.060	0.0170	1.0	19	0.67	19.0	0.20	2.0
4	.065	.00861	2.0	46	.67	32.0	.19	6.2
7	.070	.00048	5.0	25	.67	11.0	.62	17.8
4	.073	.01530	1.0	32	.67	32.0	.18	6.6
3	.075	.0520	4	33	.67	16.5	.19	5.4

The accuracy of an estimated roughness coefficient, *n*, is unknown. Because the only bases for selecting a roughness coefficient are judgment, experience and a set of guidelines, and because its value during flow in a natural channel depends on a number of time-variant and space-variant factors, the accuracy may not be good. Some of the factors in a reach that probably exert the greatest influence on the roughness coefficient are: (1) Flow-boundary roughness, (2) size and shape of stream channel and flood plain, (3) stream-channel irregularity and alinement, (4) vegetation, (5) obstructions, (6) flow depth and rate, (7) filling and scouring, (8) size and concentration of sediment in the flow, and (9) bed form. Conditions encountered in natural channels are outside the range of "judgment and experience" at times.

Data were not available or readily obtainable so that the standard error of estimate for estimated roughness coefficient could be determined directly. Data for the 50 sites described by Barnes (1967), however, were used to obtain a number that was used to represent the standard error of estimate for estimated roughness coefficient *n*. The number obtained is assumed to be only a rough approximation of the standard error because the procedure used to obtain the number did not have rigid controls to insure against biasing the results. For each of the sites, the photographs, description of the channel, the plan sketch, and the graph of the cross section were used by six hydrologists as a basis for selecting *n* values independently. In estimating *n* values, the experience of the six ranged from a veteran to a beginner. The report by Barnes (1967) was not available to the six hydrologists while they were estimating *n* values.

The *n* values estimated by the six hydrologists ranged from 54 to 203 percent, and averaged 100 percent, of the verified values. The square root of the mean variance for the 300 individual percentages was 18.7. The variance of estimates of *n* reported by Riggs (1976) at 20 of the 50 sites was also computed; these selections were made in the field before the *n* verifications reported by Barnes (1967) were made. The estimated *n* values taken from the report by Riggs (1976) ranged from 76 to 155 percent, and averaged 103 percent, of the verified values. The square root of the mean variance for the 56 individual percentages from Riggs' report was 18.

The 18.7 percent (square root of the mean variance) probably is significantly larger than the standard error of estimate that would have been obtained if a better controlled experiment had been run. For example, it is agreed by most hydrologists that pictures are a very poor substitute for actually viewing a reach in the field, and a beginner would generally have someone with which to discuss field-selected values. Furthermore, the experiment totally disregards the review process set up to review the *n* values selected.

The 18.7 percent was used to represent the standard error of estimate even though the value probably is larger than the true standard error. The 18.7 percent, however, is not applicable directly to the current problem; the standard error in percentage of depth that results because of errors in the n value is needed for this study. By ignoring the interrelation between n and the other variables on the right side of equation 9, the standard error in log d resulting from errors in log n can be represented as

$$(\log d)_{\text{ERROR}} = f\ (\log n)_{\text{ERROR}} \tag{12}$$

Equation 12 says that the standard error in depth, d, in log units resulting because of errors in n is f times the standard error in n in log units. The log-unit equivalent of 18.7 percent is 0.081; 0.46 was used to represent f even though it probably is larger than the true value for a typical natural stream (see page 9). The resulting standard error in d, in log units, is 0.037, which represents an error of 8 percent.

The standard error of estimate for computed depths for the sites described by Barnes (1967) probably would be insignificantly less than 13 percent (of the depth) if the n value were estimated. The 13 percent was determined using the formula "standard error = $\left[(10)^2+(8)^2\right]^{\frac{1}{2}}$" in which 10 represents the standard error (in percent of depth) for computed depths when n values are known and 8 represents a standard error (in percent of depth) for estimated n values. The errors, represented by the 8 and 10 percentages, are assumed to be independent. The 13 percent is considered a reasonable approximation of the true standard error of estimate for equation 9 but only when the equation is used to estimate T-year depths at sections having partial-control characteristics.

APPLICATION OF METHOD

A 9.67-mi reach of Little Sugar Creek in North Carolina was selected to demonstrate the simplified technique for determining 100-year depths. The North Carolina reach is one of three suggested by E. J. Kennedy (oral commun., 1976) for a demonstration study. A report describing the results of a HUD type-15 study for the reach is being prepared (W. H. Eddins, written commun., 1976); therefore, data for the demonstration study were readily available.

Ordinarily, data needed to determine T-year depths by the simplified method would be obtained during a field survey. These data are: an average value of n; assumed values for x and a_2 based on channel shape; measured width for an assumed depth; and channel or water-surface slopes. For the demonstration study, however, data extracted from those obtained for the HUD type-15 study were used (U.S. Department of Housing and Urban Development, 1976).

The data for the study reach furnished by W. H. Eddins (written commun., 1976) consisted of topographic maps; physiographic properties listed on computer printouts; 10-, 50-, 100-year discharges; a stream-channel profile; and water-surface profiles for 10-, 50-, and 100-year floods. The topographic maps, which are at a scale of 1:4,800 for subreach A and 1:2,400 for subreach B, show the locations of 113 cross sections, altitude contours at 4-ft intervals for subreach A, and altitude contours at 2-ft intervals for subreach B. Subreach A extends from the South Carolina State boundary to about 0.6 mi north of the northern boundary of Pineville City (fig. 3). Subreach B extends from about 0.6 mi north of Pineville City to the bridge at Park Road in Charlotte, N. C.

The computer printouts showed data pertinent to step-backwater computations (Bailey and Ray, 1966) which are required for detailed flood-inundation studies according to the U.S. Department of Housing and Urban Development (1976) guidelines. These data included ground altitudes and distances along the 113 cross sections; n values for subsections of the cross sections; distances between cross sections; and cross-sectional properties--area, conveyance, alpha, width, wetted perimeter, distances for the left and right edges of water for different water-surface altitudes for each of the cross sections.

Equations 3, 6, 9, 10, and 11 were used to determine 100-year depths at 11 selected cross sections in subreach A (fig. 3). The 11 cross sections were selected because they were representative of "restrictive" widths in the total reach and, therefore, probably represent partial controls. The average of the 11 depths was used to represent the average depth for the 9.67-mi reach. For the analysis, parabolic cross-sectional shape was assumed and, therefore, 2/3 was used to represent a_2 in equation 9, 1/2 was used to represent x in equations 6 and 9, and 0.46 was used to represent f in equations 3, 10, and 11.

Data extracted from those furnished by Eddins for the 11 cross sections were roughness coefficients, reference widths needed to compute a_1, and channel slope, S_0. A roughness coefficient for a cross section was obtained by averaging the n values given for the subsections of a section. A value of a_1 for a cross section was determined according to the following steps:

1. A reference depth of 14 ft was obtained by using 0.2 for C and 10,900 ft^3/s for discharge in equation 3. The average of C values shown in table 1 is 0.2, and the 10,900 ft^3/s is the 100-year discharge for the study reach (W. H. Eddins, written commun., 1976).

2. The reference depth was added to the channel-bottom altitude to give a reference altitude.

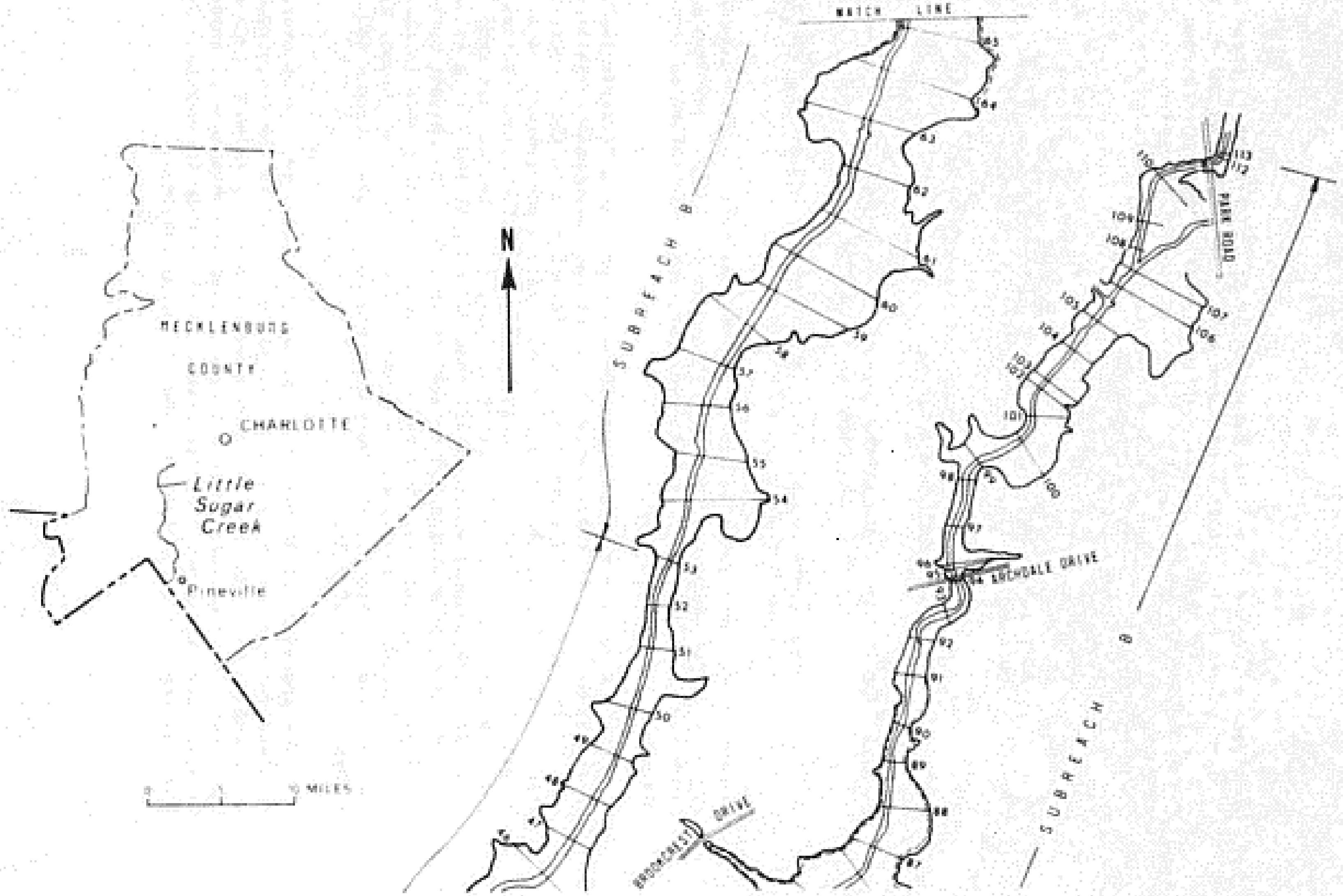
3. The channel width at the reference altitude was determined directly from data shown on the computer printouts.

4. The reference depth, the reference width, and x equal to 1/2 were used in equation 6 to compute a_1.

The reference depth normally would have been selected on the basis of cross-sectional shape. In order to eliminate the task of developing cross-section profiles for the 11 sections, the 14-ft reference depth was used.

The method used to determine 100-year depths at a "restrictive" width in the study reach is illustrated by use of the computations for cross section 14 (fig. 3). The roughness coefficient used in the computation was represented by 0.065, the average of the n values for subsections A (0.075), B (0.045), and C (0.075), respectively (fig. 4). The channel-bottom altitude for cross section 14 is 527.6 ft; therefore, the reference altitude is 541.6 ft. The channel width at altitude 541.6 ft is 180 ft. A value for a_1, determined by dividing 180 by $\sqrt{14}$, is 48.1 ft. The channel-bottom slope, 0.00138, for the site was obtained by dividing the difference in channel-bottom altitude at cross sections 3 and 4 by the length of channel between the two cross sections. The 100-year depth for cross-section 4 was determined to be 18.2 ft.

The procedure of determining a value of n for a section by averaging the n values for subsections probably introduces errors in the computation. According to H. F. Matthai (written commun., 1977), a value to represent n for a section determined by weighting n values by conveyance of subsections or by subsection areas would be preferable to an arithmetic average. Weighted averages were not determined for the following reasons: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SUBREACH B
PARK ROAD
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BROOKCREST DRIVE
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MECKLENBURG
COUNTY
CHARLOTTE
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Sugar
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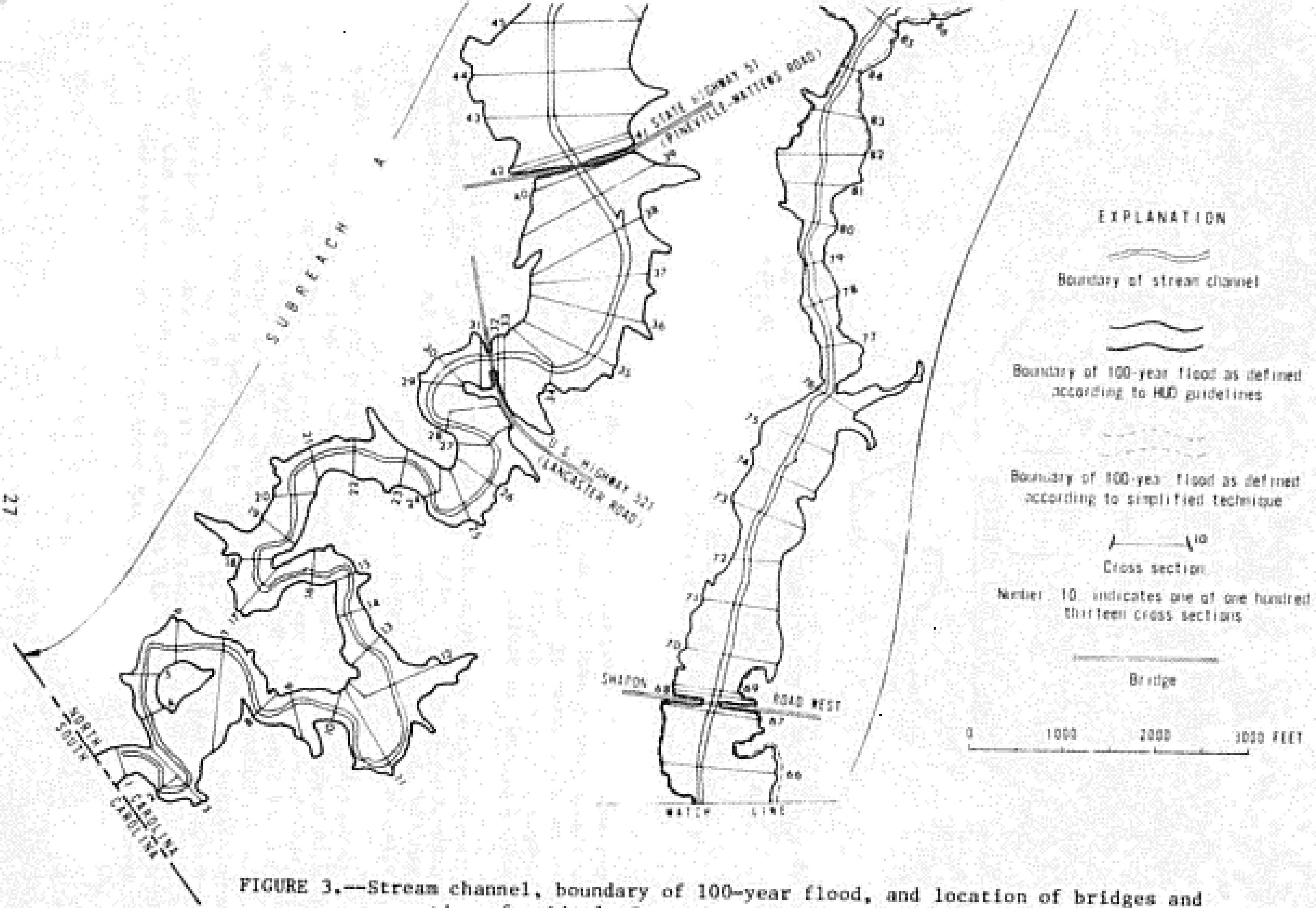

FIGURE 3.--Stream channel, boundary of 100-year flood, and location of bridges and cross sections for Little Sugar Creek, southwestern North Carolina.

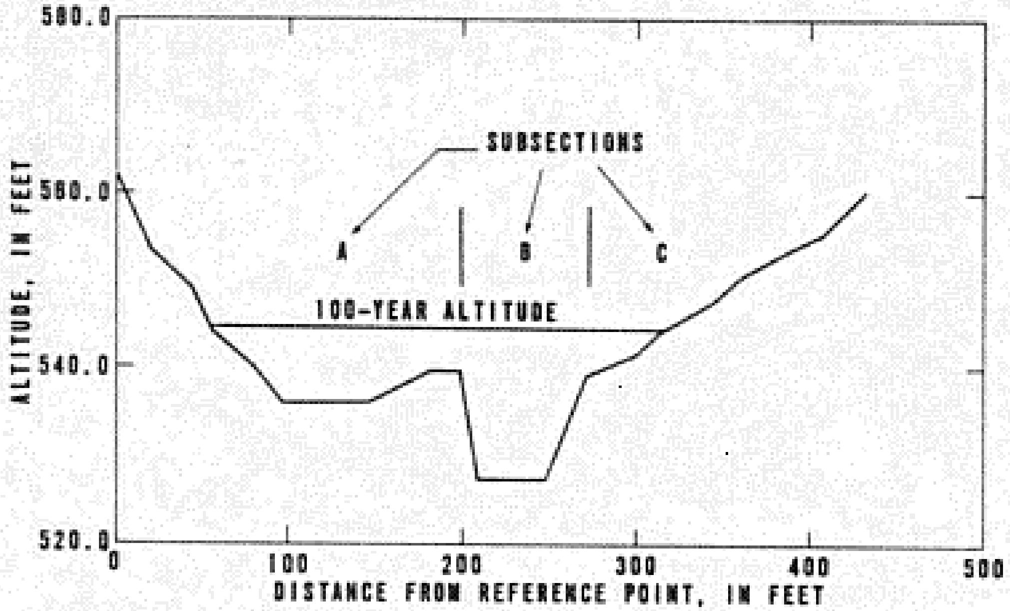

FIGURE 4.—Cross section 14 (fig. 3), Little Sugar Creek, southwestern North Carolina.

1. Errors in depth (in percent) resulting from errors in n values would be significantly smaller than those in the n values (in percent). For example, assuming that equation 9 is applicable and that f equals 0.46, a 20-percent standard error for n would result in an error of about 9 percent in depth.

2. For the procedure to remain simplified, it would not be practical to mathematically weight n values by conveyance or area. This does not mean that n values for subsections cannot be weighted intuitively when estimating an average value for a section.

The cross-sectional properties and computed depths for the 11 cross sections are presented in table 2. In table 2, computed 100-year depths determined according to the step-backwater procedure (Bailey and Ray, 1966) and HUD guidelines (U.S. Department of Housing and Urban Development, 1976) were extracted from data furnished by W. H. Eddins (written commun., 1976). The 11 depths computed according to the HUD guidelines ranged from 14.3 ft to 18.1 ft and averaged 16.3 ft; the standard deviation was 1.2 ft. The 11 depths determined by using equation 9 ranged from 11.6 ft to 21.4 ft and averaged 16.5 ft; the standard deviation was 2.8 ft. Depths determined for the 113 cross sections according to the HUD guidelines ranged from 13.9 ft to 19.4 ft and averaged 16.8 ft; the standard deviation for the depths is 1.1 ft.

Table 2.--*Cross-sectional properties and computed depths for controls in subreach A (fig. 3)*

Cross-section number	Cross-sectional properties					Computed 100-year depth	
	Roughness coefficient	Channel-bottom altitude (ft)	Reference		Channel slope	According to HUD guidelines (ft)	Equation 9 (ft)
			Altitude (ft)	Width (ft)			
1	0.065	519.6	533.6	242	0.00136	18.1	15.9
8	.065	524.3	538.3	263	.00175	17.8	14.4
10	.065	525.5	539.5	245	.00058	17.4	19.3
14	.065	527.6	541.6	180	.00138	17.0	18.2
15	.065	528.2	542.2	188	.00062	17.0	21.4
21	.053	533.2	547.2	342	.00106	15.4	12.9
22	.053	533.8	547.8	389	.00019	15.5	17.9
23	.053	533.9	547.9	343	.00021	15.8	18.5
51	.050	541.0	555.0	407	.0010	14.3	11.6
52	.060	541.5	555.5	249	.00115	14.5	15.4
53	.060	542.1	556.1	267	.00115	16.1	14.9
					Average----	16.3	16.4

The differences between corresponding depths shown in table 2 apparently are about the magitude that should be expected on an average. The square root of the mean variance (Σ[(depth determined according to HUD guidelines) minus (depth determined according to simplified procedure)]^2 divided by the number of sets of data) for the 11 sets of data is 2.4 ft. Assuming that 8 percent (of the depth) is the standard error of estimate, SE_D, for the step-backwater procedure and 13 percent (p. 23) is the standard error of estimate, SE_S, for the simplified procedure, the expected value (on an average) for the square root of the mean variance, SE_{D-S}, is 2.5 ft. The 2.5 ft was obtained using the formula

$$SE_{D-S} = \left(\bar{d}\sqrt{(SE_D)^2+(SE_S)^2}\right)\Big/100 = 16.3\ \text{ft}\sqrt{(8)^2+(13)^2}\Big/100$$

in which $\bar{d}$ is the average depth and $(SE_D)^2$ and $(SE_S)^2$ are variances.

The 9.67-mi study reach along Sugar Creek apparently satisfies premise 2 (p. 3). The 1.1-ft standard deviation for depths for the 100-year discharge at the 113 cross sections probably is representative of true changes in depth along the reach; however, the value is relatively small. For the given discharge the standard error for depths, computed according to the step-backwater procedure, would be larger than the 1.1 ft on an average; 8 percent of 16.8 ft (average of the 113 depths) is 1.3 ft.

A graphical representation of the 100-year depths is given in figure 5. Except for the standard error of estimate, the remaining values shown on figure 5 are self-explanatory. The standard error of estimate for the computed 100-year depths determined according to the step-backwater procedure and the HUD guidelines should be considered only as a rough approximation of the true standard error of estimate. The standard error is represented by the equation

$$(SE)_{\text{tot}} = \sqrt{(SE_q)^2 + (SE_d)^2} \tag{13}$$

in which

$(SE)_{\text{tot}}$ = total standard error of estimate for the 100-year depth;

SE_q = standard error for the 100-year discharge; and

SE_d = standard error for depths determined according to the step-backwater procedure and HUD guidelines.

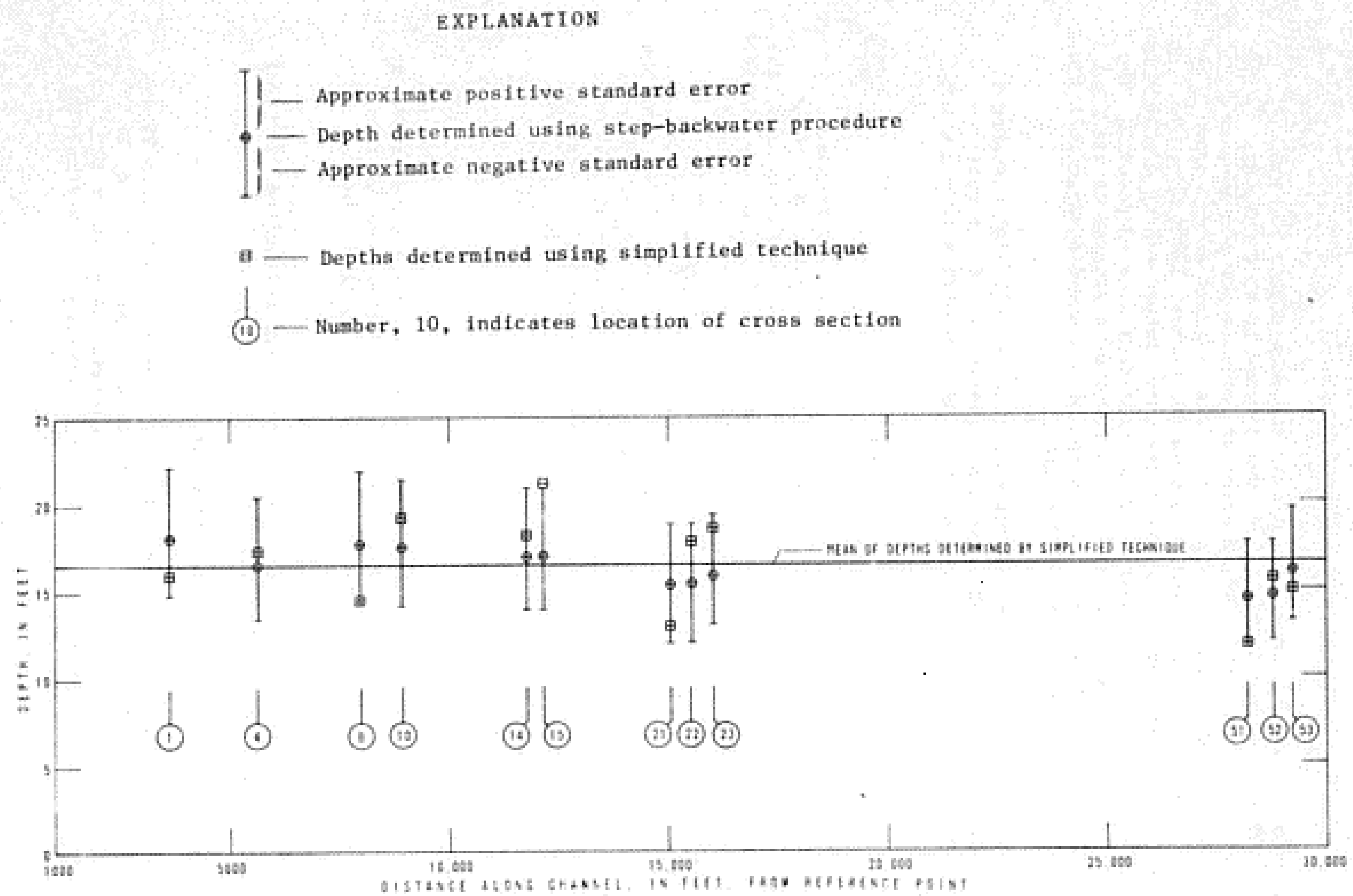

FIGURE 5.--Graph showing depths for the 100-year discharge computed according to the simplified technique and mean of these depths; and depths for the 100-year discharge determined according to the step-backwater procedure and to HUD guidelines and standard error graphically added to these depths for Little Sugar Creek, southwestern North Carolina.

To use equation 13, SE_Q and SE_d must have the same units; for this study percentage of 100-year depth is used. SE_d was assumed to be 8 percent. For streams in North Carolina, the standard error of estimate for the 50-year discharge determined by a regression equation apparently is 43 percent of the discharge--average of +51.8 and -34.2 percentages--(Benson and Carter, 1973, fig. 9). The standard error of estimate for the 100-year discharge determined by a regression equation is assumed to be only insignificantly different from 43 percent. The method used to convert the standard error in percent of discharge to standard error in percent of depth makes use of the slope of a stage-discharge relation for a typical natural channel in North Carolina.

The relation between depth and discharge for relatively high discharges, as previously discussed, can be represented by equation 4. For a relation of this form, the standard error in log d resulting from errors in log Q can be represented as

$$(\log d)_{\mathrm{ERROR}} = f\ (\log Q)_{\mathrm{ERROR}} \tag{14}$$

which says that the standard error in d, in log units, resulting because of errors in Q is f times the standard error in Q, in log units. The value of f for natural channels has a wide range. For streams in North Carolina, the average value of f for 118 gaging station-sites apparently is 0.45; the standard deviation for the 118 values of f is 0.15. When a value of 0.45 for f and 0.182 (log unit equivalent of 43-percent error) for $(\log Q)_{\mathrm{ERROR}}$ is used in equation 14, the resulting standard error in d, in log units, is 0.082, which represents an error of 19 percent. A rough approximation of the standard error for 100-year depths in North Carolina, determined according to the step-backwater procedure and HUD guidelines, is 20.6 percent of the depth (average of +23.0 percent and -18.2 percent). The standard errors shown in figure 5 are based on the +23.0 and -18.2 percentages and computed depths.

Information presented in figure 6 includes:

1. Channel-bottom profile;

2. Water-surface profile for the 100-year discharge determined according to the step-backwater procedure and HUD guidelines; the standard error of estimate which is graphically added to this 100-year profile;

3. Water-surface profile for the 100-year discharge determined according to the simplified technique; and

4. Locations of bridges and cross sections.

Except for the standard error of estimate for the 100-year depth (item 2) and item 3, this information is derived directly from data furnished by W. H. Eddins (written commun., 1976). The standard error of estimate is based on the +23.1 and -18.2 percentages and the mean depth of 16.8 ft previously described.

The 100-year water-surface profile for the simplified technique was developed by graphically adding 16.5 ft to the channel-bottom profile. Except for the distance between cross-sections 53 and 64, the stream-channel profile presented by Eddins was used to represent the channel-bottom profile. According to the definition for channel bottom (p. 2), the stream-channel profile from about cross-section 53 to cross-section 64 cannot be a channel-bottom profile. A smooth "sketched in" curve is used to represent the channel-bottom profile for the distance between the two sections.

The 100-year profile for the simplified technique probably is not significantly different from that determined according to the step-backwater procedure and HUD guidelines except perhaps for the relatively short distance from about cross-section 64 to cross-section 69 and from cross-section 80 to cross-section 92.

The effects of bridges, if any, were not considered in the development of the 100-year profile according to the simplified technique. Bridges, however, usually affect the water-surface profile for a 100-year discharge. Determining the effects of bridges on Sugar Creek was beyond the scope of this study.

To delineate the inundated areas, altitudes taken from a water-surface profile can be transferred to maps on the basis of contours on topographic maps or on the basis of field surveys. The steps, when the latter procedure is used, are: (1) The horizontal and vertical extent of the 100-year flood is determined by field survey for selected sites on the flood plain; these sites are flagged so they can be spotted on aerial photographs; (2) aerial photographs are obtained and the boundary of the 100-year flow is outlined on the photographs; and (3), the boundary of the 100-year flood then is transferred to topographic maps or, if such maps are not available, to a mosaic compilation of the photographs.

The boundary of the 100-year flood obtained according to the simplified technique apparently is not significantly different from that obtained according to the step-backwater procedure and HUD guidelines except perhaps for the distances from about cross-section 64 to cross-section 69 and from about cross-section 80 to cross-section 92 (fig. 6). The boundary for the 100-year flood for the study reach on Little Sugar Creek (fig. 6) was based on water-surface profiles for the 100-year discharge and topographic maps showing contours at 2- or 4-ft intervals.

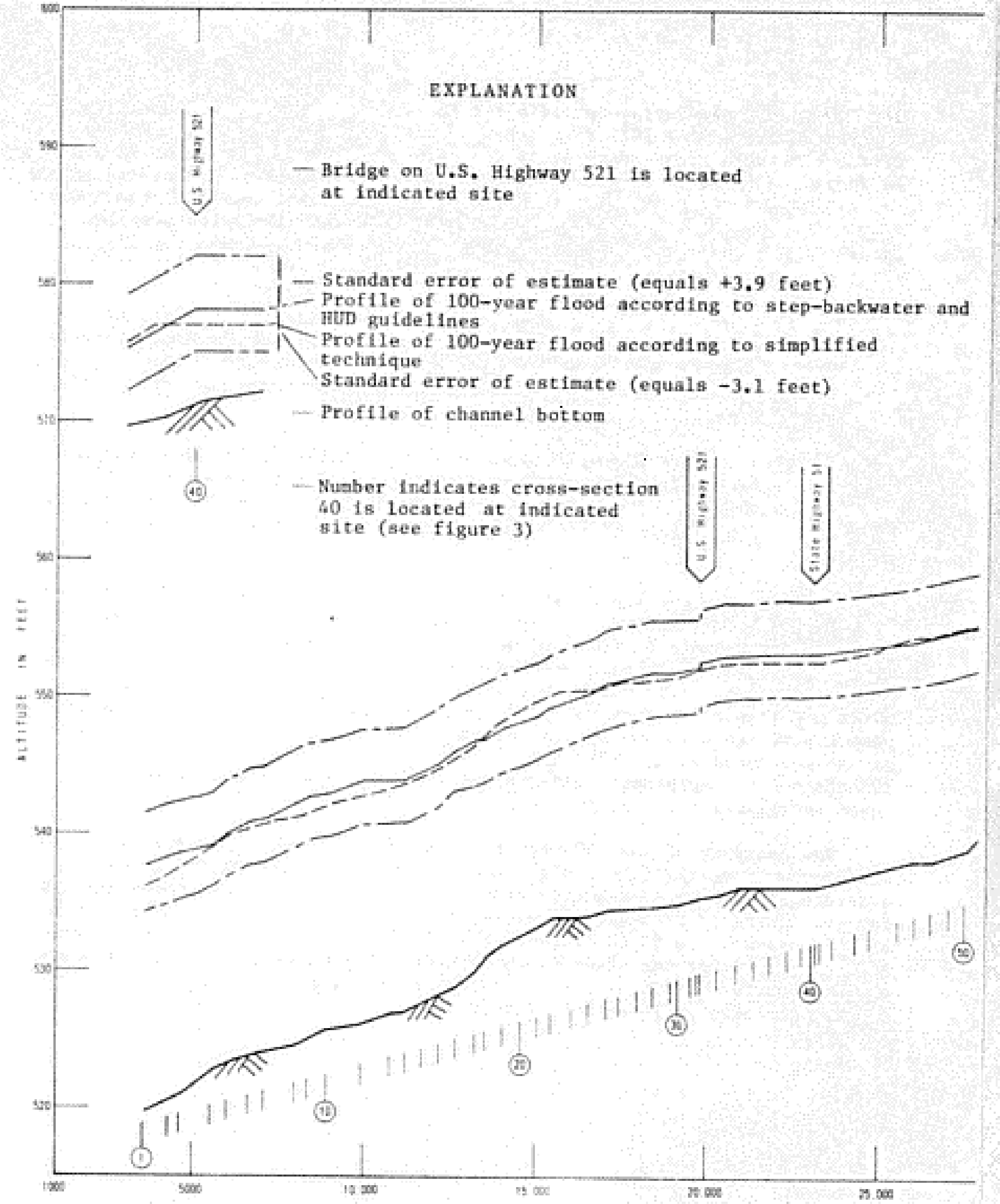

FIGURE 6.--Channel-bottom profile; water-surface profile for the 100-year discharge, step-backwater procedure and HUD guidelines; water-surface profile for the 100-year and cross sections for Little Sugar Creek, southwestern North Caroline (fig. 3).

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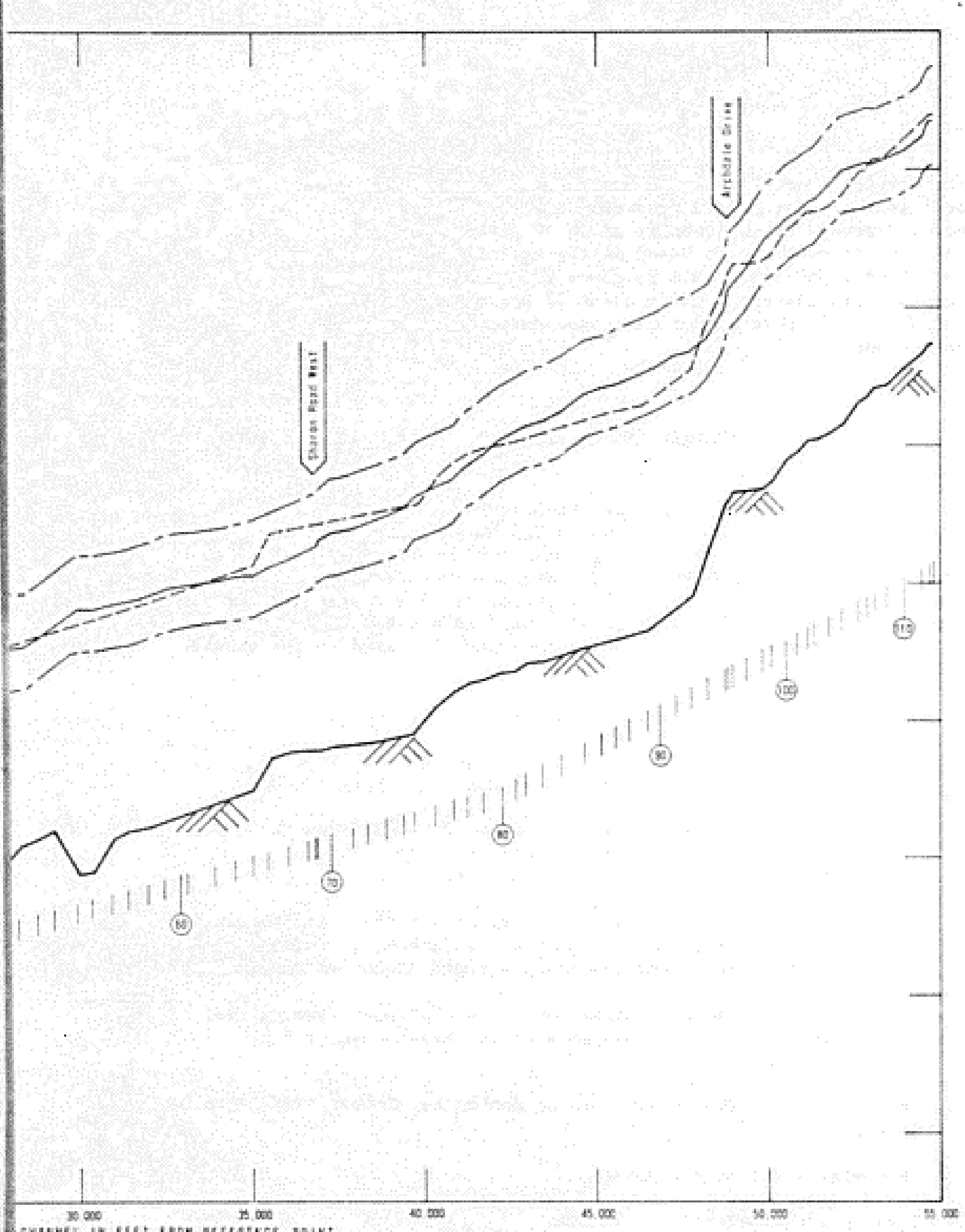

with the standard error of estimate graphically added, determined according to the discharge determined according to the simplified technique; and locations of bridges

OVERALL ACCURACY

The overall average standard error of estimate for 100-year flood-boundary altitudes determined according to the simplified technique is not known; however, it is probably 25 to 30 percent of the depth. The 25 to 30 percent estimate is based on the criterion that the accuracy of the simplified technique should be about the same as the accuracy of the physiographic procedure, which is about 27 percent. The 25 to 30 percent is comparable to 23 percent for altitudes determined according to the detailed method.

SUMMARY AND CONCLUSIONS

The report describes a simplified technique for determining depths for *T*-year discharges in natural channels (channels not significantly affected by manmade structures) having channel-control conditions and rigid boundaries (channels having a low probability of change that would significantly affect the hydraulic characteristics of a *T*-year discharge). Channel-control conditions usually exist during relatively high discharges in natural rigid-boundary channels. The technique is based on the premise that:

1. A *T*-year discharge is known or is readily obtainable.
2. Depth for a *T*-year discharge does not vary greatly in a relatively long reach of a natural rigid-boundary channel.
3. Depth of flow is primarily a function of discharge and the physical characteristics of lengths of channel in the reach that are partial or true controls.
4. Depth of flow in the length of channel having the characteristics of a partial control can be adequately (errors introduced are not prohibitive) determined using a small amount of field data.
5. The average of computed depths for a few representative partial controls in a reach can be used to represent average depth for the reach.

Six basic steps are required in determining depths for *T*-year discharges in a reach of interest:

1. Determine a *T*-year discharge.
2. Develop a channel-bottom profile.
3. Determine the locations of partial (or true) controls in the reach.

4. Compute depths for *T*-year discharges by equations for representative cross sections for a few of these partial controls; to do this a small amount of field data must be obtained.

5. Average the depths determined in step 4.

6. Develop a water-surface profile by graphically adding the average depth obtained in step 5 to the channel-bottom profile developed in step 2.

The development of a map of the areas inundated would involve an additional step (step 7)--the transfer of altitudes from the water-surface profile to a topographic map.

The simplified technique for determining depths for 100-year discharges was demonstrated using data for a 9.67-mi reach of Little Sugar Creek in North Carolina. Data for the demonstration study were readily available from a report describing the results of a HUD-15 study for the reach.

Conclusions reached as a result of this study are:

1. The simplified technique for determining depths for *T*-year discharges and the corresponding water-surface profiles and flood boundaries probably could be used for HUD flood-inundation studies for many natural rigid-boundary channels. The use of the simplified technique instead of the step-backwater procedure (Bailey and Ray, 1966) and HUD guidelines (U.S. Department of Housing and Urban Development, 1976) would sacrifice some accuracy to alleviate manpower stresses.

2. The standard error of estimate for the flood-boundary altitudes is not known; however, it probably would be 25 to 30 percent of the depth, which is only slightly larger than the 23 percent for the flood-boundary altitudes determined according to the step-backwater procedure and HUD guidelines.

3. Experience, good judgment, and a thorough knowledge of the hydraulic principals of open-channel flow that are required for HUD type-15 studies would also be essential in order to obtain adequate results when the simplified technique is used.

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FROM FIRE TO FLOOD:

Historic Human Destruction of Sonoran Desert Riverine Oases

by

Henry F. Dobyns

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of them constantly, keeping the third in reserve, to process 100 tons of ore daily using English coke costing $65 per ton delivered at the furnaces.

The Tacoma Copper Company owned mines located some two and a half miles northwest of Globe, and leased a 60-ton-per-day capacity smelter situated on Pinal Creek (Hamilton 1884:212, 216). The Buffalo Company exploited mines north of the Old Dominion properties. It erected a water-jacket smelter with a 30-ton daily capacity on Pinal Creek. The Long Island Copper Company also put up a smelter below Globe. In 1884, these two companies had suspended operations because of the high cost of transporting their product (Hamilton 1884:217). All of these smelting operations withdrew water from the creek, prejudicing the downstream irrigated agricultural enterprises. They also undoubtedly polluted the creek flow to the detriment of downstream users.

All of these silver and copper mines promptly generated severe depauperation of timber in their immediate vicinities. Freight costs were extremely high away from the Colorado River and its steamboats from 1856 to 1880, and away from the Southern Pacific Railway after 1880. Mine operators tried to limit as much as possible their shipments of milled lumber, especially for shaft timbering and for fuelwood. They hired woodcutters and boys with donkeys to haul locally-cut wood to stack in cords in woodyards at the mines, many of which used steam-powered hoists in their shafts, and at the mills and especially the smelters. Accompanying photographs provide a perception of the scale of such wood cutting and consumption.

THE 1880s

The beginning of railroad freight service across southern Arizona on the Southern Pacific Railway's track in 1880 dramatically altered the economic premises of mining in the Gila River watershed. Ever since the Gadsden Purchase, prospectors and investors and speculators in search of mineral wealth had concentrated on very high-grade precious metal ores. When the railroad lowered freight rates to a fraction of those previously paid for wagon transport, mining in the Sonoran Desert region shifted increasingly to exploitation of copper on a massive scale in place of the precious metals.

Whereas much of the gold and silver recovered from rich placer and lode deposits had been discovered in pure form--gold in flakes and nuggets, silver in horns and wires--or could be recovered by milling, copper ores required smelting. The transformation of mining in Arizona Territory can virtually be told in terms of smelter numbers. In 1874, one Mexican-style smelter turned out from one to four tons per day. By 1884, twenty furnaces with a capacity of over 1000 tons were operating. This increase had allowed an expansion of spectacular proportions in territorial copper production (Hamilton 1884:152):

1880	2,000,000 pounds
1881	5,000,000 pounds
1882	15,000,000 pounds
1883	24,500,000 pounds

Every new copper smelter required tremendous quantities of fuelwood to provide the heat needed to melt the metal from its ores, and immediately threw a crippling burden upon the forest resources in its immediate vicinity.

THE SAN PEDRO RIVER:

RECORDS OF CONDITIONS AND CHANGES

by

Henry F. Dobyns

1995

Kearny's expedition, called by him a trout without scales."[65] Graham described the San Pedro River as "pretty high when we arrived here. It is very muddy, with a quick current, resembling very much the Pecos, or *Rio Puerco*." Beaver were reported earlier and later on the San Pedro River, so their presence in 1851 must be inferred. If the stream was muddy as Graham described it, then it must have been so seriously eroding somewhere in the headwaters that beaver ponds could not precipitate out the sediment in their still waters. Such sediment fertilized the fields of the Gila River Pimas.

Proto-Colonization. During the summer growing season of 1851, the Mexican garrison at Tucson again sent a detachment to Tres Alamos to raise crops. A squad of soldiers provided protection against Apache raiders. In 1886, a Tucson native who had served as a scout for the 1851 gardeners stated that: "The valley was at that time very marshy (pantano) along the rivr. There were a great many beaver dams . . . There were Indian trails but no wagon road."[66]

Judging from later descriptions of the Río San Pedro, it became a stable, mature stream under beaver management. It curved and meandered over its flood plain so that it flowed approximately twice as far as a straight line between any two points along its

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[65] James D. Graham, *Report of the Secretary of War, Communicating, In Compliance with a Resolution of the Senate, the Report of Lieutenant Colonel Graham on the Subject of the Boundary Line Between the United States and Mexico.* Senate Ex. Doc. No. 121, 32d Congress, 1st Session, 1852, p. 35.

[66] Jay J. Wagoner, *Early Arizona: Prehistory to Civil War.* Tucson: University of Arizona Press, 1975, p. 230; Francisco Romero 14 June 1886 affidavit, Hayden file, Arizona Historical Society, Tucson.

course. This condition was described in court testimony taken in 1889. "There is a little difference if you follow the course of the river, in following the crooks and bends. . . It is a very crooked river. It is one of the crookedest rivers I ever saw, . . . It would be twice as far to go by the courses of the river."[67] We infer that the Río San Pedro had reached that maturity with meanders doubling its length by mid-nineteenth century and quite likely even earlier.

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[67] Peter Moore, testimony, pp. 929-30, in Hill vs. Herrick, Cochise County Court, 1889.

SAN PEDRO RIVER MANAGEMENT UNDER UNITED STATES SOVEREIGNTY

In 1853, James Gadsden negotiated the United States' purchase of Mexican territory south of the Gila River to the present international boundary. The U. S. Senate ratified the treaty in June of 1854, so theoretically the Gadsden Purchase became part of the United States. In geopolitical reality, U. S. Dragoons did not enter the later Arizona portion of the Purchase until November of 1856. Meanwhile, one of the federal railroad route surveying parties traversed the Purchase and reported something about the Río San Pedro.

1854

Lt. Jno. G. Parke in 1854 rapidly surveyed one version of the national southern wagon road between California and the eastern states in terms of its feasibility as a railroad route. Parke surveyed the wagon road from Tucson southeast to Ciénega Creek in the pass between the Rincón and Whetstone Mountains, and across the San Pedro River though the Dragoon Mountains and across Playa de los Pimas to Apache Pass between the Dos Cabezas and Chiricahua Mountains.

Where Parke descended into the valley eastbound, "This bottom is bounded on both sides by an irregular zigzag step, much indented by deep washes, and it is at this point about three miles wide. It is covered with a growth of grass, now dry and crisp." As for the river: "The stream is about eighteen inches deep and twelve feet wide, and flows with a rapid current, at about twelve feet below the surface of its banks, which are nearly vertical, and of a treacherous miry soil, rendering it extremely difficult to approach the water, now muddy and forbidding" on 25 February during the winter rainy season. Park did not report phreatophytes. "The banks are devoid of timber, or any sign indicating the course or even the existence of a stream to an observer but a short distance removed."[1] In his remarks about railroad feasibility, Parke significantly underestimated the bridge span that would be required to avoid accelerating stream erosion. "The river can be bridged by a single short span, the waterway being about twenty-five feet wide."[2] A man who had traveled the southern road in 1850, warned in 1857 that the San Pedro River at times flooded. "At this river a substantial bridge, capable of resisting floods, would have to be constructed. This must be done at some point where the bluff banks, above high water marks, can be had."[3]

1855

United States Boundary Commissioner William H. Emory described the San Pedro River Valley in general and positive terms.

> Throughout the whole course of the San Pedro there are beautiful valleys susceptible of irrigation, and capable of producing large crops of

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[1] Jno. G. Parke, *Report of Explorations for that Portion of a Railway Route, Near the Thirty-Second Parallel of Latitude, Lying Between Dona Ana, on the Rio Grande, and Pimas Villages, on the Gila.* House Doc. 129, 1855, p. 10.

[2] Parke, *Report*, p. 20.

[3] A. Anderson, to the Hon. Thos. L. Rusk, U. S. Senator, Washington City, March 10, 1857. Records of the Office of the Secretary of Interior Relating to Wagon Roads 1857-1881. Letters received relating to the El Paso-Fort Yuma Wagon Road 1857-1861. Record Group 48, Microcopy 95, Roll 3, United States National Archives.

> 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.[4]

1857

In mid-decade, Congress appropriated funds for improving numerous western wagon roads, including the southern route. The General Superintendent appointed to supervise the field crews differentiated the volume of the San Pedro River from that of the Colorado River. "The Mimbres and San Pedro are small streams and are readily forded at all seasons; the Colorado is crossed by ferry."[5]

The crew that "improved" the wagon road between El Paso and Fort Yuma attempted to divert traffic northward parallel to the San Pedro River for 51 miles.

> "The San Pedro, at the first point reached in the present road, has a width of about twelve (12) feet, and depth of twelve (12) inches, flowing between clay banks ten or twelve feet deep, but below it widens out, and from beaver dams and other obstructions overflows a large extent of

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[4] William H. Emory, *Report on the United States and Mexican Boundary Survey, Made Under the Direction of the Secretary of the Interior.* Senate Ex. Doc. No. 108, 34th Congress, 1st Session. Washington: A. O. P. Nicholson, Printer, 1857, p. 94.

[5] Albert H. Campbell, Report upon the Pacific Wagon Roads, Constructed Under the direction of the Hon. Jacob Thompson, Secretary of the Interior, in 1857-'58--59. Pp. 3-12 in *Report of the Secretary of the Interior, Communicating Reports upon the Pacific Wagon Roads constructed under the direction of that Department.* Senate Ex. Doc. No. 36, 35th Congress, 2d Session. [Ye Galleon Press, 1969 reprint], p. 11.

> bottom land, forming marshes densely timbered with cottonwood and ash, thus forcing the road over and around the sides of the impinging spurs."

Engineer Hutton made one very important observation concerning San Pedro River flow in spite of beaver pond and marsh modulation. "This stream is not continuous all the year, but in the months of August and September disappears in several places, rising again, however, clear and limpid."

Along the "improved" new route Hutton reported phreatophytes.

> Along the first twenty miles, descending, the valley is not more than one-fourth of a mile in width, bounded on either side by sloping grass-covered terraces from the San Calisto and Santa Catarina mountains, its banks fringed with a growth of cottonwood and ash. Below it opens out, having a varying width between foot hills of from three-fourths of a mile to three miles, with broad rich meadows and well timbered banks, the gradually sloping hill-sides covered with a luxuriant growth of gama and other grasses, and the more elevated slopes densely timbered with mezquit.[6]

Analysts of vegetational change in the San Pedro and Santa Cruz River valleys concluded: "Before the Civil War these same streams wound sluggishly along for much of their course through grass-choked valleys dotted with cienegas and pools."[7]

1858

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[6] Hutton, "Report," p. 87.

[7] James R. Hastings and Raymond M. Turner, *The Changing Mile: An Ecological Study of Vegetation Change With Time in the Lower Mile of an Arid and Semiarid Region*. Tucson: University of Arizona Press, 1965, p. 35.

A young men enjoying his adventures on the inter-ethnic frontier wrote to his parents on 1 October 1858 from Tucson that at least some San Pedro River reaches flowed only intermittently. "We have went to the river and wattered and it was running fine and a half mile below the bed of the river would be as dry as the road--it sinks and rises again." On the other hand, the letter began its description of the San Pedro River by emphasizing its fish and beaver. "The San pedro river as they Call it--is a stream one foot deep six feet wide and runs a mile and half an hour and in ten minutes fishing we Could Catch as many fish as we Could use and about every 5 miles is a beaver dam this is a great Country for them."[8]

Colonization

1858

The Butterfield Overland Mail Company established a relay station at what became known as the Middle Crossing of the Río San Pedro. The company also constructed a bridge across the stream to facilitate stage coach travel.[9] That bridge would have kept narrow wagon wheels from cutting into the soft river bed and fostering erosion. Drivers of other vehicles would have used the bridge as a matter of convenience. On the other hand, the wheel-rutted road over the slopes east and west of the crossing cut small water erosion channels that had not previously existed.[10]

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[8] James H. Tevis, *Arizona in the '50's.* Albuquerque: University of New Mexico Press, 1954, p. 55 (facsimile of Tevis' 1 Oct. 1858 letter).

[9] Roscoe P. and Margaret B. Conkling, *The Butterfield Overland Mail 1857-1869.* Glendale: Arthur H. Clark Co., 1947, I:93.

[10] Ronald U. Cooke and Richard W. Reeves, *Arroyos and Environmental Change in the American South-west.* Oxford: Clarendon Press, 1976, p. 16, chart the multiple human

floodplain. Lack of mention of this flood by Tres Alamos colonists suggests that Arivaipa Creek flooded, rather than the main stream.

1867

Long after newcomers began to colonize the San Pedro River Valley, transcontinental travelers continued crossing the stream. A Texan westbound from Sulphur Spring in 1867 reached the stream at the Middle Crossing. "Here we find good grass and water small musquet for wood the Pedro is small shallow stream sandy banks with no timber on its banks." The traveler moved camp the evening of 12 August. Then "it rained very hard and next morning where our old camp was the ground was covered a foot deep with water so we just moved in time the river was overflowed."[16] A summer monsoon storm generated, in other words, only a foot deep rise in the stream spread out over its normal flood plain.

Canal. Tres Alamos colonist Juan Lopez opened a second irrigation canal on the west side of the river hearing some three miles upstream from the first canal. It took him three months, January, February, and March.[17]

1868

In view of modern knowledge concerning malaria transmission, the incidence of that disease among newcomers to the San Pedro River valley provides indirect evidence of the prevalence of marshes where mosquito vectors flourished. Camp Grant initially was located at the confluence of Arivaipa Creek with the San Pedro River. The garrison

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[16] Hofstater, Texas to California. Diary of an Overland Journey from the Trinity River Texas to California, 1867. The Newberry Library, Chicago (Ayer Collection).

[17] Juan Lopez, testimony, Grijalba vs. Dunbar, p. 26; Emilio Carrillo, testimony, p. 5.

1879

Mine owners at the new Tombstone camp constructed mills at the edge of the San Pedro River in new settlements named Charleston on the west bank and Contention downstream, and the Boston Mill. In February, a surveyor platted the Charleston townside on the west side opposite Millville and the Tombstone Mill & Mining Company's stamp-mill. Teamster T. S. Harris delivered the first quartz mill, the Toughnut, to Charleston on 28 February. On 6 April Harris left for Gila Bend to load the Corbin Mill and haul it to Charleston. Harris used eight 16 and 18-mule teams to pull his freight wagons. The wheels of the heavily laden wagons those teams pulled would have cut into the river bed at the Middle Crossing where Harris crossed from the east to the west bank.[38] By May, Charleston had gained 300 to 400 inhabitants, whose constant crossing and re-crossing the stream undoubtedly scarred its channel, too.

The Grand Central Mining Co. located its mill on the east bank of the river approximately a mile and a third downstream from the Babacomari Creek-San Pedro River confluence. So it was some four and a half miles below the Boston Mill, and two miles above the Contention mill built in the fall of 1879. Contention Mill employees enlarged its (Mason) ditch that fall. "The water run pretty fast in the ditch."

Ethnic Chinese truck gardeners grew vegetables at Charleston, irrigating their plots by diverting San Pedro River water. Charles A. Noyes and his brother and a Dane named Christianson "took out" a ditch a short distance downstream from the Babacomari Creek confluence. Their ditch was too wide to step across. The Noyes brothers spent part of their time in Charleston and part on their "ranch" In June and July they cut hay composed of mixed alfalfa and barley, selling it to teamsters such as T. S. Harris. The

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[38] T. S. Harris, testimony, pp. 697, 699, 712, 717, in Hill vs. Herrick, 1889.

> The Gila has been pretty high for some time in consequence of the melting snow in the mountains on the upper Gila. It is now fordable from the fact that Messrs. Finch & Bates have finished their ditch, and robbed the turbulent Gila of the waters of the San Pedro that helped to swell its angry bosom.[51]

In June of that year, "C. F." described a buggy journey from Florence up the Gila and San Pedro rivers. From Riverside, the travelers reached in a few afternoon hours the Cunningham Ranch on the San Pedro. "We passed several fine ranches, and saw numbers of fat cattle and horses. This region is unexcelled for its splendid grazing and agricultural lands." Farther south, Finch noted that colonists had taken the roof timbers from old Camp Grant. "We crossed the Arrivaipa, and drove up to the door of Mr. Wm. Hunton's country residence . . . he is raising wild currants." Finch and Pete Broscha continued upstream to the Whitlock ranch and the Webb ranch 40 miles upstream, where they recovered the stolen horse that was the object of their trip. "The valley for twenty miles will average perhaps one mile wide, dotted here and there with cattle and horses."[52] If Finch mentioned all of the colonists along the lower San Pedro River, settlement was sparse and involved little or no agriculture.

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[51] C. E. Finch, "San Pedro News," *Arizona Enterprise* (Florence, A. T.) April 15, 1882, p. 2, c. 2.

[52] C[harles] F[inch], "Up the Gila and San Pedro," *Arizona Weekly Enterprise* June 24, 1882, p. 3.

THE SAN PEDRO RIVER'S MODERN EROSION HISTORY

By 1889, San Pedro River Valley beavers were clearly losing their struggle to maintain the ancient hydraulic regime along the stream. For 32 years, participants in machine-age Western Civilization had colonized the valley and consciously and unwittingly made it increasingly vulnerable to wind and water erosion. All of the industrial age insults to Sonoran Desert lands that scholars have identified as starting arroyo cutting operated along the Río San Pedro, plus a few that have not previously been considered. In 1890, very intense summer monsoon precipitation produced floods that within a week converted mature, meandering stream into a down-cutting, laterally expanding one constantly shifting its non-flood channel and increasingly flowing beneath its sandy or gravelly bed.

Channel Entrenchment Drops Surface Flow to Subflow Beneath a Gravel River Bed

1890

Two summer monsoon floods washed away much of Fairbank and so deeply entrenched the San Pedro River channel as to change fundamentally the stream environment. Tombstone reportedly received 2.3 inches of rain during the first storm. The raging San Pedro River "washed out the N. M. & A. track and much of the S. P."[1] The "freshet . . . dug down the channel of the San Pedro river an average of ten feet." As a

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[1] *Tombstone Epitaph* July 24, 1892, p. 3.

result, a newspaper correspondent wrote in early 1891 that "There has been less sickness in the valley this year than at any time previous. Much of the former illness consisted of malarial ailments, and their cause has been removed in the draining out of many of the low places by the floods." Marsh and pond draining and channel entrenchment significantly desiccated the stream, making it more ephemeral along more of its reaches than it had been. A single storm thus "appears to have delivered the *coup de grace* to the San Pedro River"[2] as it had existed until that event.

The next storm late in July washed away bridges along the San Pedro River "and considerable damage was done at Fairbank." From the perspective of Tombstone's urban newspaper editor, however, "the general good to the cattle and farming interests will more than compensate for the loss sustained."[3] Within a few days, however, the newspaper began to describe "THE GREAT FLOOD." Rain fell on Tombstone from about 4:00 to 5:30 p.m. on 31 July, a Monday.

> Old-timers say that more water fell in that time than ever before in their recollection. . . All the gulches were filled with raging torrents and no one ventured across the streets while the storm was at its height. All bridges between here and Fairbank were washed away and those living in the track of the waters suffered the loss of their gardens and fruit trees, in several instances three and four feet of sand being left on their cultivated land. Wells were filled up, reservoirs broken and much other damage done.

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[2] Dobyns, *From Fire to Flood*, p. 186; Lynn R. Bailey, *"We'll All Wear Silk Hats": The Erie and Chiricahua Cattle Companies and the Rise of Corporate Ranching in the Sulphur Spring Valley of Arizona, 1883-1909.* Tucson: Westernlore Press, 1994, p. 127.

[3] *Tombstone Epitaph* Aug. 1, 1890, p. 2.

> Fairbank was flooded to a depth of several feet and nearly all the houses partly filled with sand and mud. Considerable damage was done to property but no loss of life is reported. The San Pedro river was higher than ever before known, in many places flooding the valley several feet.

The Río San Pedro necessarily eroded upstream from Fairbank in order to deposit two feed of sand over the railroad track at that track-side settlement. That the river aggraded at Fairbank bears emphasis.

One factor in the main stream flood was Walnut Gulch draining the Tombstone area. "The water in Walnut gulch, about a mile and a half north of this city, could be heard roaring quite plainly and several persons who went over reported that the flood was all of thirty feet deep."

The flood forced the Grand Central Mill on the river to shut down for a few days, but it was not damaged. The Sterling Silver Mill halted for only an hour.

On Tuesday, the first of August, another storm "let go on the Huachuca and Mule mountains, which was more severe than the one the evening previous. . . No damage of any consequence is reported except at Fairbank, where the flood washed down and completely wrecked the International Hotel." One may therefore infer that the San Pedro River continued at flood stage. Wagon ruts on all human travel routes accelerated erosion during the runoff. "All the roads throughout the county visited by the storm are washed out and nearly impassible." On the road between Ochoaville and Lewis' Springs, all the fences "washed away and likewise many trees."[4]

On the night of 7-8 August, another "heavy storm struck Tombstone." It came from the south. "The first fall of rain lasted about three-quarters of an hour and was

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[4] *Tombstone Epitaph,* Aug. 5, 1890, p. 3; Cole, Data of Floods, SUMMARY, p. 1.

accompanied by a heavy wind . . . After letting up about half an hour the clouds let go again and another flood came near giving everybody a free ride to Fairbank." Once again, the San Pedro River's major Tombstone area tributary roared. "The roar of waters in Walnut gulch, about a mile north of town, could be heard very plainly early this morning [8 August] and means another flood for Fairbank." Fed by Walnut Gulch and an unknown number of other tributaries, the main stream again flooded. "The San Pedro river is continually rising and has gained about two feet in the last twenty-four hours."

Even the telegraph wires were down from Fairbank to Benson. The physical alteration of the natural drainages involved in railroad construction also fostered erosion. "The railroad companies are working very assiduiously to keep their roads open but it must be rather discouraging to start out in the morning and find all the work done the day before heading for the Gulf of California."[5] As news from outlying areas reached Tombstone, the destructive impact of the 7-8 August storm became clearer.

> The storm Thursday night proved to be the most severe ever known in this part of Arizona. Reports from outside districts show the rainfall to have been enormous, and in many places the hail was terrific, destroying fruit, melons, vines and plants wherever it fell. Nearly every gulch of any size shows a water mark of from eight to twenty-five feet, and in many places bedrock that has not been exposed since the year one is now uncovered. Adobe walls and buildings melted down like sand and left only a mass of mud and debris . . . much stock was drowned, in one place on the San Pedro river several horses and cattle that were corraled being swept entirely away.

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[5] *Tombstone Epitaph*, Aug. 8, 1890, p. 3.

> . . .
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> The San Pedro has ceased to be a river and is a moving sea of raging and foaming waters, carrying everything within its reach--fences, corrals, trees, orchards, gardens, and in many cases stables and farming implements. No such flood was ever known before . . .

The riverside village of Fairbank suffered greatly. The postmaster there wrote the Tombstone postmaster that he had no mail for him. "Too many wrecks here for anybody to think of anything else. Guindani's store has fallen down and his dwelling house is injured. Salcido's house has fallen. Parades' house badly damaged and many other casualties of less importance. Roof of Grand Central mill partly blown off and one house washed away." According to a later report, every house was "more or less damaged, in many instances the entire household effects being destroyed, including wearing apparel. The repairs done on the railroad are all washed away and several miles of new damage done. The telegraph wires are prostrated, in one place over a mile or wire and poles being completely gone."[6]

In other words, the San Pedro River entrenched itself vertically and widened its channel laterally instead of aggrading as it had during the earlier flood runoff. "Howard Herring has been down to look at the place where the railroad was and where the river now is, and says that words are inadequate to describe the wholesale changes made in the valley by the flood."[7]

Erosion rendered impossible direct travel along the river between Tombstone and Mammoth. A Mammoth resident who made the trip was

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[6] *Tombstone Epitaph*, Aug. 9, 1890, p. 3.

[7] *Tombstone Epitaph*, Aug. 10, 1890, p. 3.

> compelled to travel about 160 miles on account of washouts, although that camp is only about ninety miles from this city. All bridges are gone and he came by way of Tucson and circled down toward Harshaw, finally landing at Fairbank. He was unable to cross there and had to go to Contention, and at that place the crossing was very dangerous, owing to the rapid rise of the river.[8]

1891

A major storm system caused flooding in many Arizona streams again in late February of 1891. "Pioneer farmers and miners and freighters, as well as wagon-road builders and trappers, had irreversibly altered conditions."[9] Dr. David Pool, living 18 miles below Tres Alamos, reported the flood's impact on the San Pedro River Valley.

> The flood did some damage to his portion of the valley--washed out crops and fences but took no houses or live stock. This was mostly due to the freshet of last August, which dug down the channel of the San Pedro river an average of ten feet. From this cause the water of the present flood, greater in volume, did less damage.
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> . . .
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> The loss to crops has been inconsiderable, perhaps one fourth altogether being damaged, which will be replaced by corn in a few weeks.[10]

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[8] *Tombstone Epitaph*, Aug. 14, 1890, p. 3.

[9] Dobyns, *From Fire to Flood*, p. 194.

[10] *Arizona Enterprise* (Florence) March 21, 1891, p. 1, col. 6.

Farther downstream at Dudleyville near the Gila River, the flood caused "considerable damage to farms along the San Pedro . . . nearly all the ditches destroyed and much land covered with sand. The river was four feet higher than was ever known."[11] The San Pedro River flowed above its previous high water mark at least as far upstream as Mammoth.[12] The river deposited along the downstream reach sand eroded away upstream.

Evidently a second spring storm system dropped sufficient precipitation on the San Pedro River watershed to flood its downstream reach late in March or early in April. On 4 April, the Florence newspaper reported erosion of vulnerable roadway.

> The road between Riverside and Mammoth was badly washed by the recent floods and is almost impassable particularly above Dudleyville and no regular mail is now carried over that route. Therefore all mail for Mammoth should be sent by way of Tucson, from which point a daily stage is run.[13]

1891-1892

A woman whose family both farmed and raised cattle 22 miles north of Benson remembered an 1891-1892 drought as crucial to environmental deterioration. "If we had started conservation fifty years ago it would have done some good, but cattlemen overstocked the land, the cattle trails turned into washes and the drought of 1891-92 finished everything." Consequently, "Almost all of these old places have been

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[11] Dobyns, *From Fire to Flood*, p. 194, following *Arizona Silver Belt*, March 7, 1891, p. 3.

[12] *Arizona Daily Star*, February 28, 1891, p. 4.

[13] *Arizona Enterprise*, Florence, April 4, 1891, p. 3, c. 1.

wasted away by erosion. The water has cut a deep channel through the valley. It was so different when we first went there" in 1878.[14]

The 1890-91 winter precipitation carpeted the range with grass, so graziers were optimistic. The 1891 summer monsoon did not begin until 21 July, and thunder showers fell in their usual erratic pattern. By September, residents perceived that a drought gripped the Southwestern United States. The San Pedro River Valley range was "absolutely bare." Cattle survived on mescal and bear grass at lower elevations and juniper, oak, mountain mahogany and berries if they retreated into the mountains. Between 1 May and November, the Babocomari Cattle Co. shipped out all of its cattle.[15]

1892-93

The United States resurveyed its boundary with Mexico in the final decade of the nineteenth century, rebuilding monuments. Mammologist Edward A. Mearns reported beaver on both the upper San Pedro River and its Babocómari Creek tributary. In fact, his type locality for Sonoran beaver was the upper San Pedro River near boundary monument No. 98, although on the Sonoran side of the line.[16] The headwaters evidently still flowed the year around.

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[14] Etz, Reminiscences, pp. 2-3.

[15] Bailey, *"We'll All Wear Silk Hats,"* pp. 128, 130, 134. Misdating the catastrophic drought to 1893, Cooke and Reeves (*Arroyos and Environmental Change*, p. 47) claimed that between 40 and 60 per cent of cattle died. Bailey (p. 136) concluded that 25 per cent of Cochise County cattle died.

[16] Edgar Alexander Mearns, *Mammals of the Mexican Boundary of the United States*. U. S. National Museum Bulletin 56, Part 1. Washington: Government Printing Office, 1907, pp. 350, 359.

Chapter 3. Historic Geomorphology of the San Pedro River: Archival and Physical Evidence

Richard Hereford and Julio L. Betancourt

1. Introduction

The need to explain and manage arroyos, or water-carved gullies, in the western United States has been a dominant theme in American geomorphology since the turn of the 20th century. To date no single explanation satisfies widespread and almost synchronous arroyo formation around the turn-of-the-century. Is this dramatic episode of erosion unique, or has it repeated itself both in kind and in magnitude during past millennia? Surprisingly, attempts to explain arroyos far outnumber efforts to characterize their initiation and subsequent history.

The San Pedro River is cited often in reference to historic arroyos (Bryan 1925, Antevs 1955, Hastings 1959, Hastings and Turner 1965, Martin 1963a, Melton 1965, Rodgers 1965, Cooke and Reeves 1976, Dobyns 1981, Hendrickson and Minckley 1984), but neither the archival nor physical evidence have received more than cursory attention. Unlike the heavily urbanized floodplains along the Santa Cruz River at Tucson, floodplain surfaces and cutbank stratigraphy remain relatively unspoiled along the San Pedro River, particularly in its upper reaches.

When arroyos expanded into the upper San Pedro, they exposed the remains of mammoth in association with Clovis, notably at the Naco, Lehner, and Murray Springs sites. Investigation of these sites has led to an unusually complete record of late Quaternary alluvial history (Haynes 1968, 1987) that contrasts with our haphazard understanding of the more recent floodplain history. We correct for this oversight by evaluating both archival and physical evidence for floodplain evolution before and after historic arroyo cutting on the San Pedro.

In this study, we used archival evidence from the lower and upper basins, but field mapping was limited to the upper San Pedro. The primary objective of the archival research was to describe general floodplain conditions before arroyo cutting and to establish timelines for major floods and cutting episodes. The physical evidence was marshalled to determine rates and causes of channel widening once the arroyo developed, as a prerequisite for understanding how alluvial channels might progress towards equilibrium after entrenchment (Hereford 1993).

2. Archival Evidence

Historical studies of environmental change must depend on documentary sources of variable quality. Standard observations made at regular time intervals, such as those obtained at a stream gage or weather station, usually are unavailable for the periods of interest; for example, neither weather nor discharge measurements exist for the San Pedro River during the critical period of arroyo initiation. In the Southwest, the field notes of the cadastral surveys made by the General Land Office consistently record the width of stream channels, but mention channel depth only sporadically (both before and after arroyo initiation occurred). Were there significant differences between cross sections where channel depths are mentioned and where they are omitted, or is any reference to depth purely whimsical? Can we infer unincised floodplains where the surveyor failed to mention depth, as Bryan (1928) did on New Mexico's Rio Puerco? In 1873, Theodore White, one of the first land surveyors in southern Arizona, surveyed the San Pedro Valley from St. David to just below the Narrows. From the journals of itinerants we know that the river was entrenched at St. David, Tres Alamos, and below the Narrows (Figure 1), with perpendicular banks 3 to 6 m deep as early as the 1850s. White failed to record any channel depths at these same localities (Cooke and Reeves 1976). Was White making a distinction between terraces formed during an earlier erosional episode and active channel depths, a distinction that escaped the itinerants?

Historical sources, such as newspapers, provide descriptions of extreme and rare episodes, most importantly floods. These accounts serve the environmental historian well, because degradation of alluvial stream channels occurs catastrophically during extreme flows. The erosional work done by floods often is described in great detail, as was the case with headcut migration in the Santa Cruz Valley at Tucson in summer 1890 (Hastings 1959, Betancourt 1990). The degree of detail given in the accounts correlates well with distance to large settlements, and coverage of flood damage is patchy, giving the false impression that some reaches were more afflicted than others.

For the San Pedro River, we relied on a variety of primary and secondary sources. The earliest relevant observations are those related to administration of the Presidio of Terrenate, established in 1742 in the headwaters of the San Pedro, and moved to Quiburi near Fairbank (Figure 2) in 1772 (Kessell 1966). Many of the documents pertaining to this presidio are contained in the Archivo General de Indians in Seville, Spain (Beers 1979). The next period for which documentation exists involves the early years (1820s-1830s) following Mexican Independence, when four land grants-- the San Ignacio del Babocomari, the San Rafael del Valle, the San Juan de las Boquillas y Nogales, and the San Pedro (Figure 2)-- were sought, surveyed, and approved (Mattison 1946). A fifth grant was ceded at Tres Alamos in 1852. For the post-Civil War period, we relied mainly on local newspaper accounts.

Pre-entrenchment Conditions

The inability to accurately portray pre-entrenchment conditions has plagued historic arroyo studies. The written record just prior to arroyo formation is patchy and incomplete. In the case of the San Pedro, gaps in written observations can be bridged by stratigraphic records from critical localities. These records can help resolve two questions about pre-entrenchment conditions: 1) which reaches of this interrupted stream had perennial surface flow and which did not, and 2) does evidence exist for unincised floodplains and contemporaneous discontinuous arroyos? In the case of discontinuous arroyos, the evidence could be ambiguous because the observer usually was unaccustomed to making subtle distinctions between inset and superimposed stratigraphic relations between alluvial deposits. Such a distinction is critical to geomorphic interpretation. Figure 3 illustrates the difference between inset and superimposed relations. These relations result from two or more cut-and-fill cycles in which the younger longitudinal gradient is the steepest. A superimposed relation is typical of the area upstream of Lewis Springs; an inset relation occurs locally from Charleston downstream to Fairbank (see Figure 2 for locations). A steep terrace rise near the river, which perhaps had to be "cut down" to help wagons cross the river, could represent an earlier entrenchment, unrelated to current base level, and with an inset stratigraphic relation.

<u>1600s and 1700s</u>. The accounts of Kino, Manje, and Bernal (Karns 1954) in the 1690s and those of Velarde in 1716 contain few relevant observations about channel or flow conditions in the valley, other than the fact that irrigation was practiced on swampy land near Quiburi (near Fairbank).

<u>1820s and 1830s</u>. Attempts to settle the San Pedro increased in the 1820s after Mexican Independence, when several settlers filed for land grants in the bottomlands. This happened at a time when beaver ponds dotted the lower reaches of the San Pedro Valley (Pattie 1905). The

Law of the State of the West, adopted by Mexico in 1825, limited grants to ranchers to 4 square leagues or sitios (ca. 2784 ha). The price of a sitio with running water was $60, and was $10 for dry rangeland. In 1832, Don Ignacio Elias y Gonzales was issued title for 8 sitios, 6 with water, along Babocomari Creek, where they ran about 40,000 head of cattle and a large herd of horses and mules (Christiansen 1983). He and Nepomucino Felix were also granted 4 sitios with water along the San Pedro (the San Juan de las Boquillas y Nogales grant) in 1833. The Boquillas grant was a narrow strip of land on both sides of the river, from Charleston to just south of Fairbank. In 1833, Rafael Elias Gonzales was granted 4 sitios, again with water, along the San Pedro. This was the San Rafael del Valle grant with its southern boundary between Hereford and the Lehner Ranch and extending north to Lewis Springs (Figure 2). Gonzales also received title to the San Pedro grant, another 4 sitios along the San Pedro straddling the international boundary. A selling price of $60 for each sitio along the Babocomari and San Pedro River suggests that relevant reaches of these streams were perennial in the 1830s. The San Pedro remains perennial today from Hereford to Fairbank, while the Babocomari contains two perennial reaches, one near the Brophy Ranch headquarters and another just downstream of the grant's eastern boundary (Brown *et al*. 1981).

1840s to 1860s. Accounts during this period generally indicate marshy and commonly treeless conditions throughout the upper San Pedro, with intermittent flow below Tres Alamos and the Narrows and discontinuous arroyos below the Narrows, at Tres Alamos, and near St. David (Hastings 1959, Hastings and Turner 1965, Dobyns 1981, Hendrickson and Minckley 1984). In 1849, Eccleston (1950) noted that below the Narrows, the river "is lined with a poor growth of swamp willow and other brush, so that it cannot be seen until you come within a few feet of it; then the bank is perpendicular..." Five years later, in the same reach, Parke (1857: 24-26) noted that: "The valley bottom is generally smooth and open, with the streambed curving through it, sometimes a few inches, and at others as much as fifteen feet below the surface of the meadow. At Tres Alamos, the stream is about fifteen inches deep and twelve feet wide, and flows with a rapid current over a light sandy bed, about fifteen feet below its banks, which are nearly vertical. The water here is turbid, and not a stick of timber is seen to mark the meanderings of its bed. In the gorge below [the Narrows] and in some of the meadows, the stream approaches more nearly the surface, and often spreads itself on a wide area, producing a dense growth of cottonwood, willows and underbrush, which forced us to ascend and cross the outjutting terraces. The flow of water, however, is not continuous." Hutton (1859) gave a similar description for the reach just below Tres Alamos in 1857: "The San Pedro has a width of about twelve feet and a depth of twelve inches, flowing between clay banks, ten or twelve feet deep, but below it widens out, and from beaver dams and other obstructions overflows a large extent of bottomland, forming marshes, densely timbered with cottonwood and ash.". Another apparent arroyo just below St. David was described by Bartlett (1854) and Graham (1852) of the International Boundary Commission.

Late 19th Century Floods and Arroyo Cutting

1870s to 1890s. Settlements along the San Pedro were first established in the 1870s, with the arrival of Mormons at St. David and the discovery of silver near Tombstone (Graham 1976, Fulton 1966). In 1884, the anthropologist Adolph Bandelier visited ruins along the San Pedro and described the arroyos near Tres Alamos and St. David: "[At Tres Alamos] the river, now rendered muddy by the washings of the mines worked on its upper course near Contention and Charleston, runs in a cut which is from eight to twelve feet deep... [at St. David] the river runs in a cut with abrupt sides. This cut is 10 to 15 feet deep, and about 25 feet wide (Bandelier 1892: 475-478).". This also agrees with McClintock's (1921) account that the first Mormon settlers encountered an entrenched channel of the San Pedro below St. David in 1877. Hastings and Turner (1965) suggest that extensive mesquite thickets existed where the floodplain was entrenched. Mesquite also dominated in the lower reaches where the flow was intermittent.

In 1879, the town of Charleston (a planned community) and a millsite were founded on opposite sides of the San Pedro, with the intent of using the river's permanent flow for processing ore from the newly-created Tombstone Mining District (Figure 4). Early photographs of Charleston (Figure 5) again beg the question about discriminating between superimposed and inset relations for steep "banks" bordering the San Pedro. Figure 5 is an upstream view of Charleston from Millville showing the position of the inner channel between two older terraces. The date of the channel cutting that produced these erosional terraces remains uncertain. However, major flooding at any time before establishment of Charleston could have formed these terraces and caused valley widening.

The first mention of active arroyo cutting is from the reminiscences of Mary Wood, published in the *Tombstone Epitaph* in 1929. Wood recalled that a flood in August 1881 destroyed the small dam near Millville and the banks of the river were widened and deepened. The years 1881, 1882, and 1883 had unusually wet summers, the only three consecutive years to produce more than 20 cm of rainfall in June-August at Tucson (Betancourt 1990). The wet summer of 1881 produced enough runoff to cause overflow of the active channel and erosion of the terrace on which Charleston was built. An 1883 photograph of Charleston indeed shows some evidence of recent undercutting of the west terrace (Figure 5).

Bryan (1925: 342), in an often cited statement, maintained that "the trench on San Pedro River was cut progressively headward between 1883, when the arroyo formed at the mouth of the river, and 1892, when the headwater fall cut through the boundaries of the Boquillas grant 200 km upstream." He cited a report then in preparation (Bryan et al. 1934), but this manuscript contains no further reference that would warrant an 1883 date for initiation of a headcut at the mouth, or that arroyo development progressed from mouth into the upper San Pedro in less than a decade (Hastings 1959, Rodgers 1965, Cooke and Reeves 1976). Bryan apparently thought that headcut migration was enhanced by increased longitudinal surface slope in each successive sub-basin, contrary to normal steepening upstream exhibited by most streams. Bedrock outcrops at Charleston and the Narrows produce independent base levels in each sub-basin. Over the short term, these outcrops should have restricted propagation of headcuts or coalescence of discontinuous arroyos from one subbasin to another.

Large floods also occurred on the San Pedro River in the summers of 1886 and 1887, and summer and fall of 1890. The newspapers reported overbank flooding in 1886 and 1887, but no mention was made of channel erosion. Hastings (1959), however, cites testimony in a court case that the bed of the river near Tres Alamos was lowered 4 m between 1885 and 1889.

1890s to 1900s. Though in other reaches arroyos might have developed in the 1880s, 1890 does appear to mark the beginning of extensive degradation in the lower San Pedro. In August and September 1890 floods on the San Pedro and Santa Cruz rivers received unusual attention in southern Arizona newspapers. On the San Pedro, most of the bridges were swept downstream. At Dudleyville the San Pedro "caved within 5 meters of Cook's place", indicating extensive channel widening. On October 2, the *Arizona Daily Star* described deepening of the channel near Mammoth by 9 m.

Extensive erosion in the upper San Pedro apparently did not occur until the early 1900s.

In the winter of 1891 flooding again affected the San Pedro Valley, eroding valuable land in some areas and silting other land downstream. Damaging floods occurred again in August 1893, 1894, and July, August, and September of 1896. Above normal summer rains preconditioned the watershed to excessive runoff during a generalized storm in the fall of 1896. This storm produced the third greatest September-October rainfall at Tucson. In October 1896, streams originating in the Whetstones flooded the Benson area; near the mouths of these streams, channels were deepened by as much as 9 m. This storm persisted for two weeks and caused significant damage to settlements and farms along the San Pedro.

It was probably during the 1896 flood that a channel almost 244 m wide and 6 m deep developed at the northern end of the Boquillas Grant, as recorded in an 1899 survey (Figure 1). A survey in 1873 recorded a width of no more than a chain (ca. 20 m) in the same area (Cooke and Reeves 1976). Yet, a channel only 9 m wide and 1.5 m deep defined the river's course at the southern end of the grant near Charleston in 1899. We speculate that in 1899 there was an active headcut somewhere in the 25-km reach between the northern and southern boundaries of the Boquillas grant. In 1909, J. B. Wright recorded a channel width of 130 m at Lewis Springs (Figure 1), which may suggest that the headcut progressed to the northern end of the San Rafael del Valle Grant between 1899 and 1909, possibly during the floods in winter of 1904-1905.

<u>1910s and 1920s</u>. According to several accounts, neither the mainstem nor tributaries became entrenched upstream of Charleston until the 1910s. Ranchers at Hereford told Haury et al. (1959) that between 1910 and 1914 the river channel was narrow and only 0.5-1.0 m deep. The channel from Fairbank to Hereford, a reach of more than 32 km, was probably entrenched in less than 18 years. Haynes (1987) states that Curry Draw on the Murray Ranch became entrenched along the ruts of a wagon road in 1916.

Channel widening and further degradation in the San Pedro Valley occurred in September 1926, when floods produced peak discharges of 2780 m^3s^{-1} at Charleston. This is three times greater than the next highest peak in the 69-year gaged record at Charleston from 1916 to 1987. The 1926 flood is one of the better-documented floods in the early 20th century. Numerous occurrences of channel erosion at bridges were reported from the international boundary to the Gila. The river overflowed its 6-m deep channel at Benson. At St. David, the channel, which was 18 m wide in 1918 and 46 m wide in 1922, widened to 107 m. The second largest gaged flow occurred in August 1940, but by then the channel could accommodate larger flows.

Over the length of the river, the areas of extensive channel widening are near Redington and Benson, where arroyos cut to the greatest depths in the floods of 1890-1926. Degradation and channel widening persist in these areas. Elsewhere, tributaries have been aggrading in recent decades, as have reaches of the mainstem particularly below Mammoth (near the confluence with the Gila) and above Benson.

3. Factors Contributing to Entrenchment

Human Settlement

Overgrazing, trampling of springs and marshes by cattle, eradication of beavers, draining of marshes through ditch diversions, and fuel harvesting in the 1870s and 1880s may have preconditioned the watershed to arroyo cutting in the 1890s. Bahre and Hutchinson (1985) estimate that about 80,000 cords of fuelwood, including mesquite from the floodplains and oaks and junipers from the uplands, were consumed in the Tombstone mining district between 1879 and 1886. By 1890 upland and floodplain vegetation had been seriously reduced by grazing and fuelcutting. A number of new ditches, which concentrated drainage and used cienegas as their source, had been dug in the valley (Bryan et al. 1934, Rodgers 1965). Railroad construction involved lengthy embankments along the San Pedro, which may have impeded sediment contributions from the adjacent bajadas. More significantly, flow was constricted at bridges (Dobyns 1981, Cooke and Reeves 1976).

Earthquake

Another factor that may have preconditioned the valley to widespread arroyo cutting was the 1887 earthquake. On May 3, 1887 an earthquake rocked southern Arizona, northern Sonora, and northwestern Chihuahua (DuBois and Smith 1980). Hydrologic effects were noted within a 160-km radius of Bavispe (Dubois and Smith 1980). The upper San Pedro valley was within the fissured zone, with several reports of liquefaction from Charleston to Tres Alamos. A fissure 32-km long was reported along the San Pedro River north of Benson and issued a considerable stream of water. Some springs went dry, others doubled in flow, and there was a rise of 1 m in the flow depth of the San Pedro, this during the driest month of the year. The earthquake leveled Charleston, while at St. David, it alerted settlers to the presence of artesian water (Fulton 1966, Fulton and Bahre 1967, Tiller 1982).

According to Tevis (1954), a similar earthquake affected the San Pedro Valley in 1800-1810. References to unincised floodplains in the 1850s suggest that if this earlier earthquake occurred, it had no large-scale effects on subsequent channel histories in the San Pedro Valley. However, it cannot yet be discounted that geohydrological phenomena associated with the 1887 earthquake set the stage for arroyo initiation. The earthquake conceivably could explain the remarkable synchroneity of arroyo cutting throughout southern Arizona and northern Sonora. One might expect channel adjustment to a 32-km fissure in the floodplain or to the changed configuration of ground-water surfaces. The immediate withdrawal from artesian aquifers probably produced changes in head that might have accelerated rates of compaction by reducing buoyant forces. The same effect, perhaps not as catastrophic, can stem from pressure losses in artesian aquifers during extremely dry periods. Regardless, investigation of the possible links between the 1887 earthquake and subsequent channel trenching is long overdue. A first step would be to examine evidence for fissures in the 1937 aerial photos of the San Pedro Valley, provided that arroyo cutting did not eliminate such evidence.

Water Table Fluctuation

There is fair agreement that a period of major channel cutting in southern Arizona took place in the middle Holocene (Haynes 1968a, Haynes 1987, Waters 1985), but great discordance over the number and timing of cut and fill cycles during the late Holocene (Waters 1985). Waters (1985) argues that in the late Holocene, streams responded to geomorphic controls irrespective of regional climates. Haynes (1987) maintains that drought-induced fluctuations in regional water tables determined late Holocene cutting and filling. He also suggests that the historic arroyo is just the modern expression of frequent cutting and filling in the late Holocene, which would have happened eventually without human impact. Few would argue that simultaneous cutting and filling on ephemeral streams could lead to ambiguity in the alluvial record. However, there is also danger in assuming that zones of aggradation and degradation migrate systematically to flush sediment from the system, completely out of step with climatic trends (Patton and Schumm 1980). It would be equally difficult to discount the role of a falling water table in promoting arroyo cutting or that of a rising one in enhancing aggradation.

4. Floodplain Evolution after Arroyo Cutting in the Upper San Pedro: Physical Evidence

The channel and floodplain of the San Pedro River, through time, were mapped from Hereford to the northern boundary of the Boquillas Grant, an area that encompasses much of the San Pedro Riparian National Conservation Area. The age of the various channel and floodplain deposits was estimated from analysis of aerial photography taken at five different times and scales (Soil Conservation Service, April 1937, 1:30,000; USGS, January 1955, 1: 20,000; US Air Force, October 1970, 1:55,000; Soil Conservation Service, October 1978, 1:25,000; Bureau of Land Management, September 11, 1986, 1:6,600). Ages were assigned by the first appearance of a particular deposit in the photographs. The area of the entrenched channel (here defined as the area between the walls of the post-entrenchment terraces) was mapped on sequential, stereoscopic small-scale aerial photography to evaluate rates of channel widening. The channel walls are readily identifiable in stereoscopic aerial photographs because the walls form a nearly vertical, continuous feature that separates two broad surfaces of different elevation.

Pre-entrenchment Alluvium

Late Holocene (4,000 yr. BP to present) alluvium, inset against the St. David Formation, can be divided into pre-entrenchment alluvium, which forms a terrace that occupies most of the inner valley, and post-entrenchment alluvium, which represents the active floodplain of the San Pedro River (Figure 6). Near Hereford, the pre-entrenchment alluvium forms a two-stepped terrace separated by 0.5 to 1.0 m of relief. Lenses of dark, carbonaceous sediments, or cienega deposits, mark the former heights of the water table in the pre-entrenchment alluvium. The pre-entrenchment alluvium correlates with the "Escapule Ranch formation" of Haynes (1987), which can be traced from Curry Draw into the inner valley near Lewis Springs. Near Hereford a sinuous abandoned channel (1 m deep and 10-20 m wide) on the lower terrace was probably the active channel of the San Pedro River before arroyo cutting.

Post-entrenchment Alluvium

From youngest to oldest, the post-entrenchment alluvium consists of the active channel, floodplain, and terrace of the San Pedro River, although alluvial fans have formed contemporaneously. The active channel is inset from 1 to 10 m below the pre-entrenchment terrace. Entrenchment in the San Pedro National Riparian Conservation Area is greatest below Lewis Springs where it ranges from 5-10 m deep. Upstream of Lewis Springs, the river is entrenched only 1-5 m below the pre-entrenchment terrace.

Deposition of the alluvial fans and sheetwash deposits began slightly before entrenchment of the San Pedro River. The deposits are cut by the entrenched channel of the San Pedro River, suggesting that deposition began before channel entrenchment. At Walnut Gulch, historic artifacts dating from the turn of the century occur at the basal contact, and artifacts are present locally within the alluvium. Deposits of similar age are also present in Curry Draw (Haynes 1987). In short, the Teviston alluvium and its correlatives in the inner valley resulted from tributary stream entrenchment and increased hillslope erosion that began before the entrenchment of the main channel.

Rate of Channel Enlargement

The spatial distribution of the post-entrenchment alluvium (Figure 7) indicates clearly that the area of the channel and floodplain have enlarged since initial entrenchment around the turn of the century. In an alluvial system with a strong component of lateral accretion such as the San Pedro River, progressively younger floodplains form as the channel migrates (Huckleberry et al. this volume). Channel migration simultaneously erodes the pre-entrenchment alluvium while providing space for subsequent floodplain deposition. Two important questions emerge regarding this process: what is the rate of widening of the high-flow channel and is the process complete? The process of channel widening is poorly understood. Thus, it is not known whether the widening process is self-limiting or controlled by external factors such as climate or land use.

Figure 8 illustrates expansion of the channel from pre-entrenchment to 1986 in a 2-km reach of the river beginning 3.2 km downstream of the Hereford Bridge. Channel area increased rapidly from entrenchment to 1955, but the rate of enlargement slackened since then as shown in Figure 9, which illustrates the cumulative area of the entrenched channel as a function of time. The increase of channel area is approximately an exponential function of time, and follows a "rate law", which describes the time-dependent adjustment of many disturbed physical systems (Graf 1988). Considering the entire area and assuming that entrenchment occurred by 1900, the estimated rate of enlargement from 1900-1955 was 0.109 km2 yr-1, and from 1956-1986 the rate was only 0.024 km2 yr-1. Thus, the rate of channel enlargement has declined in recent years. This probably signifies stabilization of the channel and the end of significant widening.

Floods and Channel Widening

The morphology of the channel is controlled largely by the frequency of channel-forming floods (the control variable). The annual flood series at Charleston (Hirschboeck this volume) shows a clear pattern of relatively frequent large floods (defined as events in the upper quartile of all flows) during the first part of the 20th century. Seventeen floods equal to or greater than the 75th percentile occurred between 1916 and 1955, an average rate of about one such flood every 2.4 years. This period includes the flood of record in 1926. Most of these large floods occur during the summer run-off season.

In contrast, only four floods larger than the upper quartile occurred from 1956-1987, an average rate of one such flood about every eight years. Only one of these four floods, the flood of October 9, 1977, was comparable in size to the largest floods of the earlier period. Reduced frequency of large floods on the San Pedro after 1955 runs counter to trends noted in adjacent watersheds notably the Santa Cruz River (Webb and Betancourt 1992). Less frequent large floods after 1955 probably stem in part from increased channel storage due to greater channel areas and sinuosities, which seem to have stabilized during the last five decades, as well as perhaps to increased revegetation of the watershed.

Channel Widening and Equilibrium

Widening of the San Pedro River channel could not continue indefinitely. Once the channel cross-section is capable of transporting the water and sediment load of the post-entrenchment discharge regimen, it should stabilize and cease to widen. The negligible rate of channel enlargement since about 1955 indicates that the widening process has ended or slowed greatly (Hereford 1993). In terms of geomorphic equilibrium, the river system has adjusted to the entrenchment disturbance and has probably attained a new equilibrium with a quasi-stable channel configuration.

This transition from pre- to post-entrenchment equilibrium is analyzed diagrammetrically in Figure 10. The effect of an increase in flooding is to increase the channel area after a reaction or lag time. Thus, the pre-entrenchment equlibrium was disturbed by a change of flood frequency probably beginning in the early 1880s, when destructive floods were first described in the upper San Pedro River valley. An additional disturbance with unknown effect was the 1887 earthquake. The reaction time to these disturbances began about 1880 and lasted until entrenchment began between 1890 and 1908. The period of disequilibrium and rapid increase of channel area is the relaxation time, or the time it takes to attain a new quasi-stable equilibrium. The relaxation time was about 55 years, assuming that entrenchment began by 1900 and that the channel was essentially stabilized by 1955.

The relaxation time for channel stabilization was probably controlled by factors influencing the frequency of channel-forming floods. This variable is affected by feedback mechanisms, climate, and land use. The feedback is between vegetation and the expanding channel. As the channel expands, more room is provided for riparian vegetation, which has the effect of reducing peak-flood discharge (Burkham 1972). In addition, larger channel area increases transmission losses, compounding the influence of vegetation. This feedback process shortens the time to stabilization, because vegetation increases boundary shear stress, eventually minimizing further bank erosion. Climate directly controls flood frequency through rainfall variations, and indirectly controls flood frequency through its effect on vegetation both within and out of the channel.

Changes in grazing practices and development of water-retention structures probably shortened the time required for channel stabilization. Generally, these changes served to reduce runoff and peak flows. The number of cattle grazing in the upper basin decreased since entrenchment from a historic high of 36,000 cattle in 1890 to 7,500 by 1964, well within grazing capacity (Rodgers 1965, Wagoner 1961). In addition, numerous small water-retention structures have been built in small tributaries of the river. Although their overall effect is unknown, these stock ponds and small reservoirs were designed to reduce runoff.

5. Summary

The historical record suggests that in the mid-19th century the San Pedro was a continuously perennial stream from its source near Cananea to just beyond the Narrows. Flow was interrupted (spatially intermittent) in the lower reaches, with the dry discontinuities outdistancing limited surface flow from ground-water outcroppings. Apparent discontinuous arroyos up to 6 m deep at St. David, Tres Alamos, and below the Narrows transitioned a short distance downstream into cienegas dammed by beaver. Mesquite thickets occupied dry and incised reaches, while mostly treeless conditions characterized the unincised, marshy floodplains. Treeless conditions could imply permanently saturated soils, where reducing conditions would limit tree growth and favor graminoids (Hendrickson and Minckley 1984).

The exact timing of arroyo initiation is still uncertain. Bryan's (1925) statement that arroyos started at the mouth in 1883 and progressed headward 200 km to Boquillas grant by 1892 cannot be substantiated. Though in other reaches arroyos might have developed in the 1880s, 1890 does appear to mark the beginning of extensive degradation in the lower San Pedro. Extensive erosion in the upper San Pedro apparently did not occur until the early 1900s. Newspaper accounts, survey records, and other written records describe extensive channel erosion in association with the series of large floods that occurred near the turn of the 19th century.

Today on the San Pedro River, post-entrenchment alluvium deposits occupy the lowest topographic level of the inner valley which is 1-10 m below the pre-entrenchment terrace. A widespread, locally dense riparian forest has developed simultaneously with deposition of the post-entrenchment alluvium. The nature of post-entrenchment deposits imply an entrenched, meandering, low-sinuosity alluvial system. The post-entrenchment alluvial deposits are successively younger across the floodplain surface, indicating that the channel has widened since initial entrenchment. Channel area increased rapidly from initial entrenchment until at least 1955; since 1955 channel area has increased only slightly. Peak-flood discharge of the San Pedro River declined substantially after 1955. Our conclusions are that the channel is largely stabilized and that equlibrium or near equilibrium conditions exist.

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FIGURE CAPTIONS

Figure 1. Maps showing width and depth observations from cadastral surveys 1873-1933, amended from Cooke and Reeves (1976).

Figure 2. Map of upper San Pedro River valley showing locations of current and historical features.

Figure 3. Superimposed and inset stratigraphic relations and their geomorphic expression.

Figure 4. Plat of Charleston in 1879 by A.J. Mitchell. Adapted from Tiller (1982).

Figure 5. A. Photograph of Charleston taken by Carleton Watkins in 1883 looking southwest toward Huachuca Mountains. San Pedro River runs from left to right through well-defined channel; B. Same view in 1960 (Plate 51a & b in Hastings and Turner, 1965).

Figure 6. Geologic cross-section showing correlation of surficial deposits and geomorphology of the inner valley of the San Pedro River in the vicinity of Lewis Springs. The geologic relations, geomorphology, and deposits are typical of the upper San Pedro.

Figure 7. Geologic map and cross-section of the post-entrenchment alluvium exposed on a point bar north of Hereford.

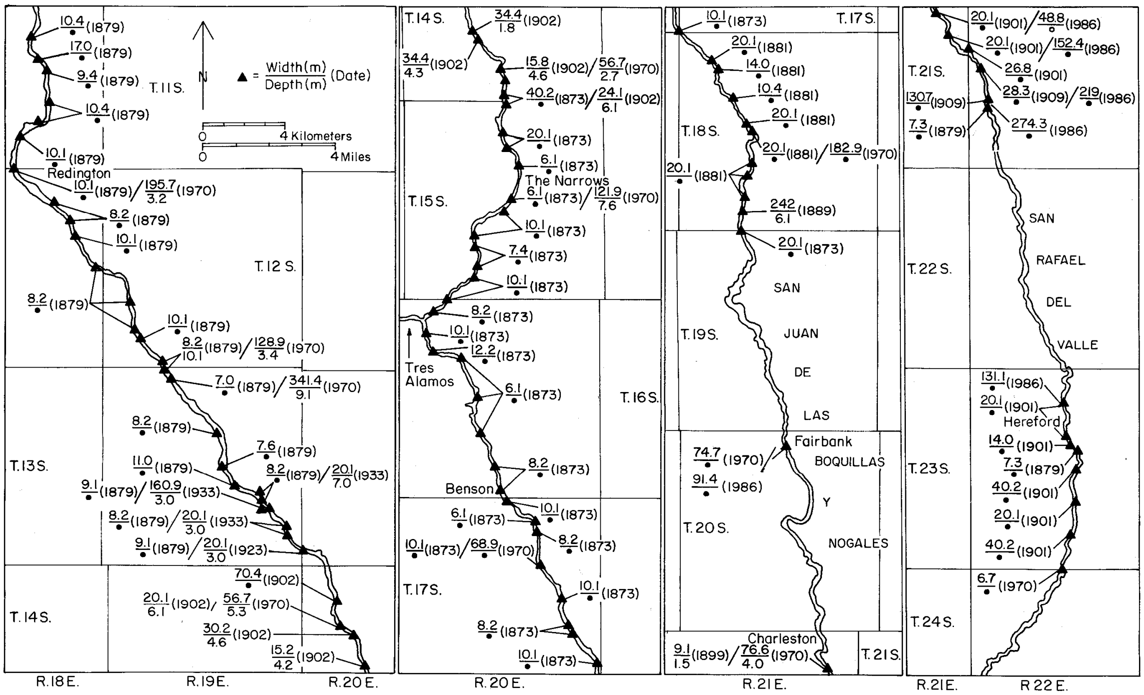
Figure 8. Maps showing the pre-entrenchment channel and expansion of the post-entrenchment channel as compiled from sequential aerial photography since 1937, and from cadastral survey notes and plats at the turn-of-the century.

Figure 9. Time series showing cumulative area of the entrenched channel. Channel expansion slowed appreciably by at least 1955.

Figure 10. Conceptualization of channel equilibrium in terms of control and response variables,

based on Graf (1988: 41) and Knighton (1984: 179).Figure

1


N
▲ = Width(m)/Depth(m) (Date)
0 4 Kilometers
0 4 Miles
T.11S.
T.12 S.
T.13S.
T.14S.
R.18E.
R.19E.
R.20 E.
10.4/• (1879)
17.0/• (1879)
9.4/• (1879)
10.4/• (1879)
10.1/• (1879)
Redington
10.1/• (1879)/195.7/3.2 (1970)
8.2/• (1879)
10.1/• (1879)
8.2/• (1879)
10.1/• (1879)
8.2/10.1 (1879)/128.9/3.4 (1970)
7.0/• (1879)/341.4/9.1 (1970)
8.2/• (1879)
7.6/• (1879)
11.0/• (1879)
8.2/• (1879)/20.1/7.0 (1933)
9.1/• (1879)/160.9/3.0 (1933)
8.2/• (1879)/20.1/3.0 (1933)
9.1/• (1879)/20.1/3.0 (1923)
70.4/• (1902)
20.1/6.1 (1902)/56.7/5.3 (1970)
30.2/4.6 (1902)
15.2/4.2 (1902)
T.14 S.
T.15 S.
T.16 S.
T.17S.
R.20 E.
34.4/1.8 (1902)
34.4/4.3 (1902)
15.8/4.6 (1902)/56.7/2.7 (1970)
40.2/• (1873)/24.1/6.1 (1902)
20.1/• (1873)
6.1/• (1873)
The Narrows
6.1/• (1873)/121.9/7.6 (1970)
10.1/• (1873)
7.4/• (1873)
10.1/• (1873)
8.2/• (1873)
10.1/• (1873)
12.2/• (1873)
Tres Alamos
6.1/• (1873)
8.2/• (1873)
Benson
10.1/• (1873)
6.1/• (1873)
8.2/• (1873)
10.1/• (1873)/68.9/• (1970)
10.1/• (1873)
8.2/• (1873)
10.1/• (1873)
T.17S.
T.18 S.
T.19S.
T.20 S.
T.21S.
R.21 E.
10.1/• (1873)
20.1/• (1881)
14.0/• (1881)
10.4/• (1881)
20.1/• (1881)
20.1/• (1881)/182.9/• (1970)
20.1/• (1881)
242/6.1 (1889)
20.1/• (1873)
SAN
JUAN
DE
LAS
BOQUILLAS
Y
NOGALES
Fairbank
74.7/• (1970)
91.4/• (1986)
Charleston
9.1/1.5 (1899)/76.6/4.0 (1970)
T.21S.
T.22 S.
T.23 S.
T.24 S.
R.21E.
R 22 E.
20.1/• (1901)/48.8/• (1986)
20.1/• (1901)/152.4/• (1986)
26.8/• (1901)
1307/• (1909)
28.3/• (1909)/219/• (1986)
7.3/• (1879)
274.3/• (1986)
SAN
RAFAEL
DEL
VALLE
131.1/• (1986)
20.1/• (1901)
Hereford
14.0/• (1901)
7.3/• (1879)
40.2/• (1901)
20.1/• (1901)
40.2/• (1901)
6.7/• (1970)

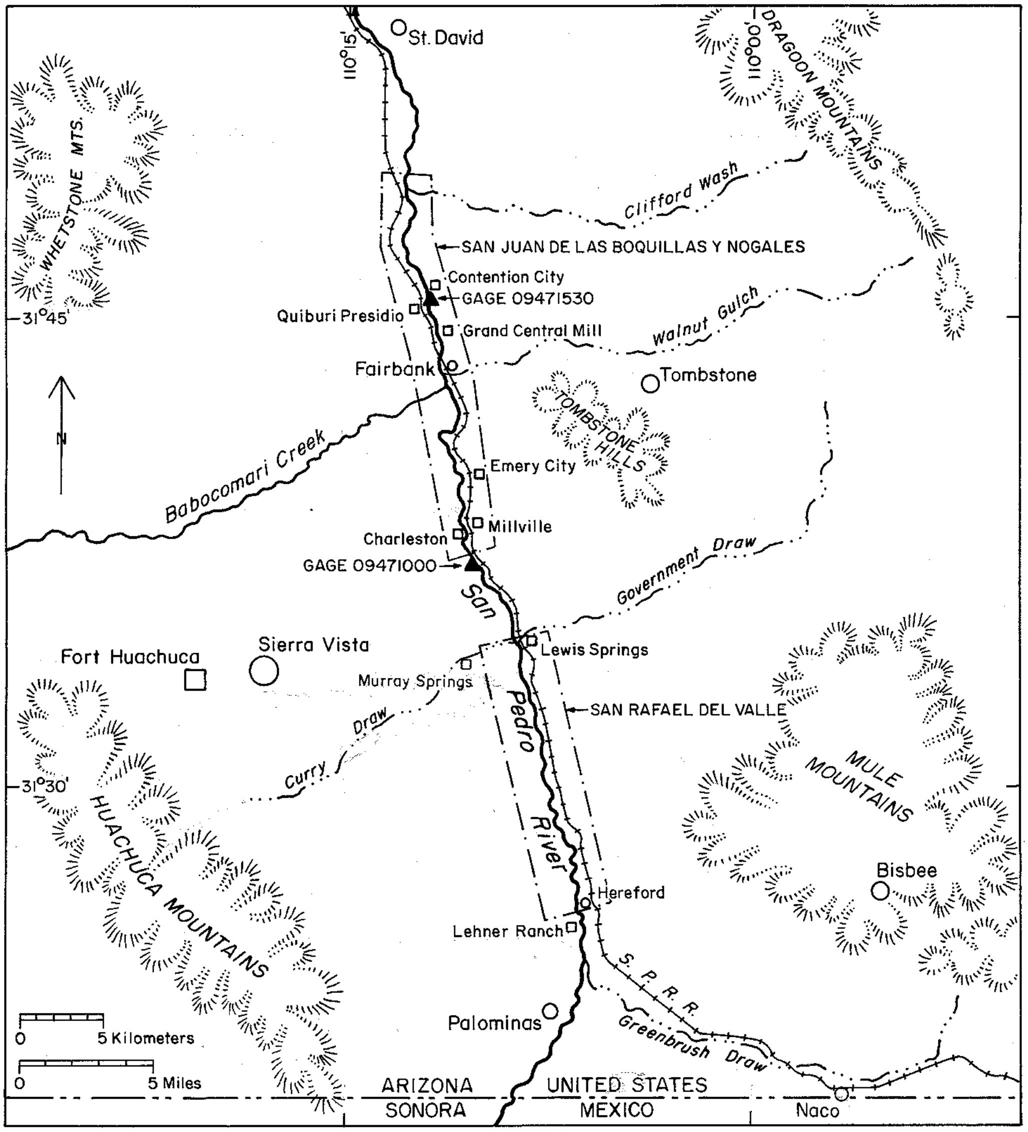

St. David
110°15'
110°00'
DRAGOON MOUNTAINS
WHETSTONE MTS.
Clifford Wash
SAN JUAN DE LAS BOQUILLAS Y NOGALES
Contention City
GAGE 09471530
Quiburi Presidio
Grand Central Mill
Walnut Gulch
31°45'
Fairbank
Tombstone
TOMBSTONE HILLS
N
Babocomari Creek
Emery City
Millville
Charleston
GAGE 09471000
San Pedro River
Government Draw
Fort Huachuca
Sierra Vista
Lewis Springs
Murray Springs
SAN RAFAEL DEL VALLE
Curry Draw
31°30'
MULE MOUNTAINS
HUACHUCA MOUNTAINS
Bisbee
Hereford
Lehner Ranch
S. P. R. R.
Greenbrush Draw
Palominas
0 5 Kilometers
0 5 Miles
ARIZONA
SONORA
UNITED STATES
MEXICO
Naco

Figure 2

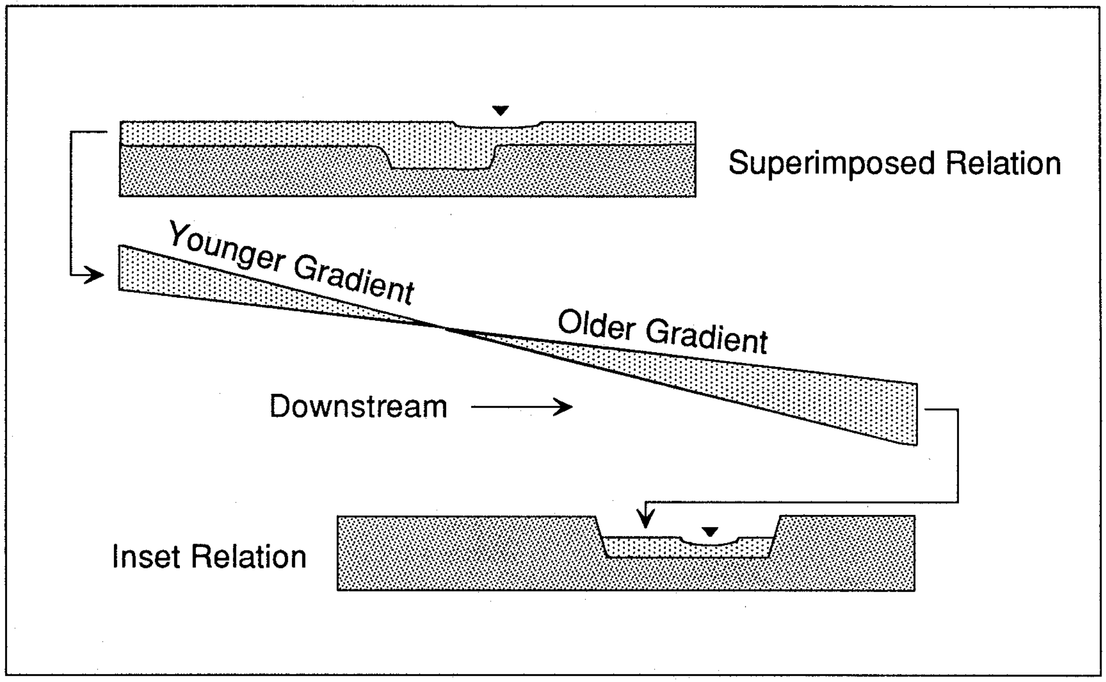

Superimposed Relation
Younger Gradient
Older Gradient
Downstream
Inset Relation

Figure 3

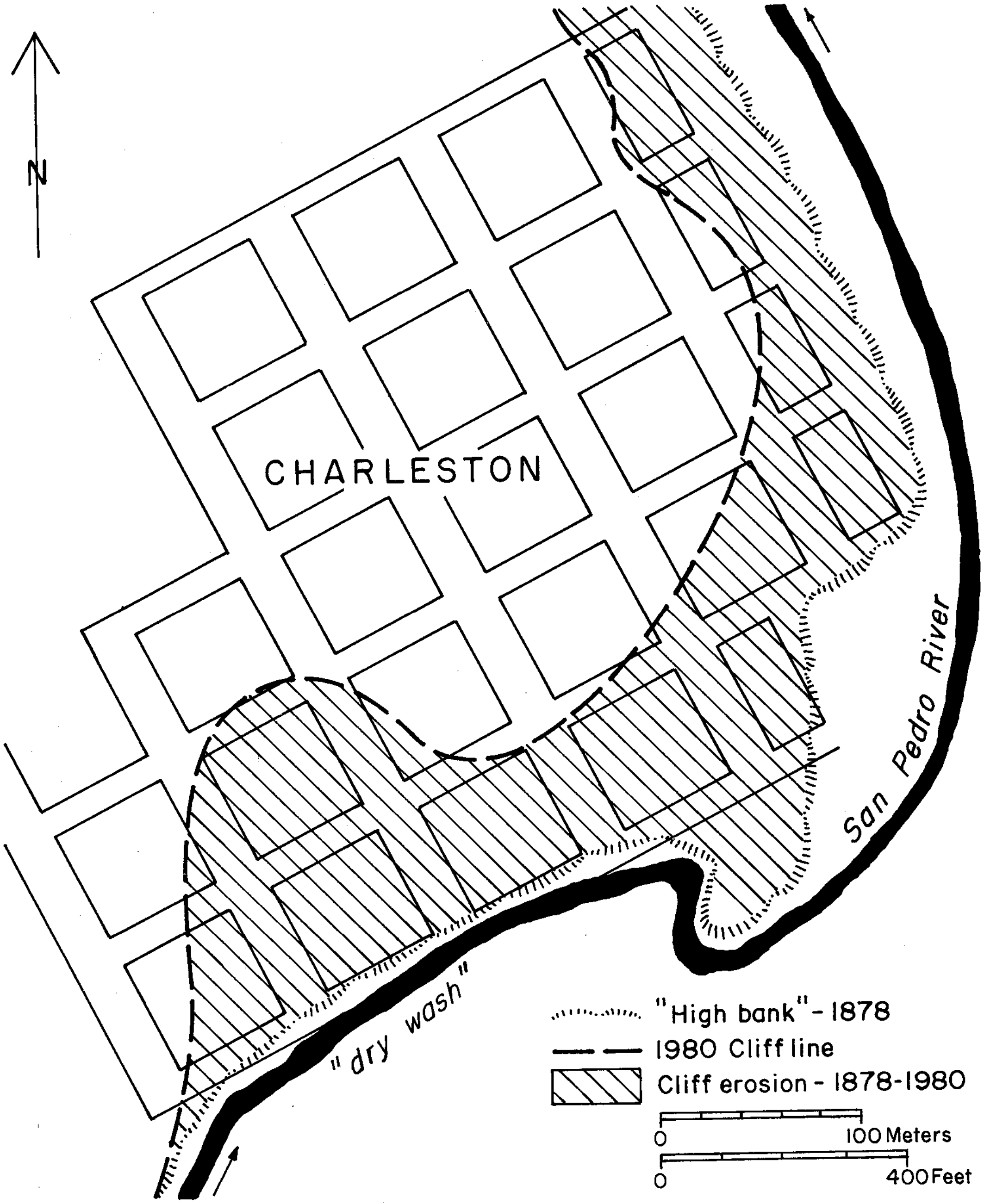

N
CHARLESTON
San Pedro River
"dry wash"
"High bank" - 1878
1980 Cliff line
Cliff erosion - 1878-1980
0
100 Meters
0
400 Feet

Figure
4

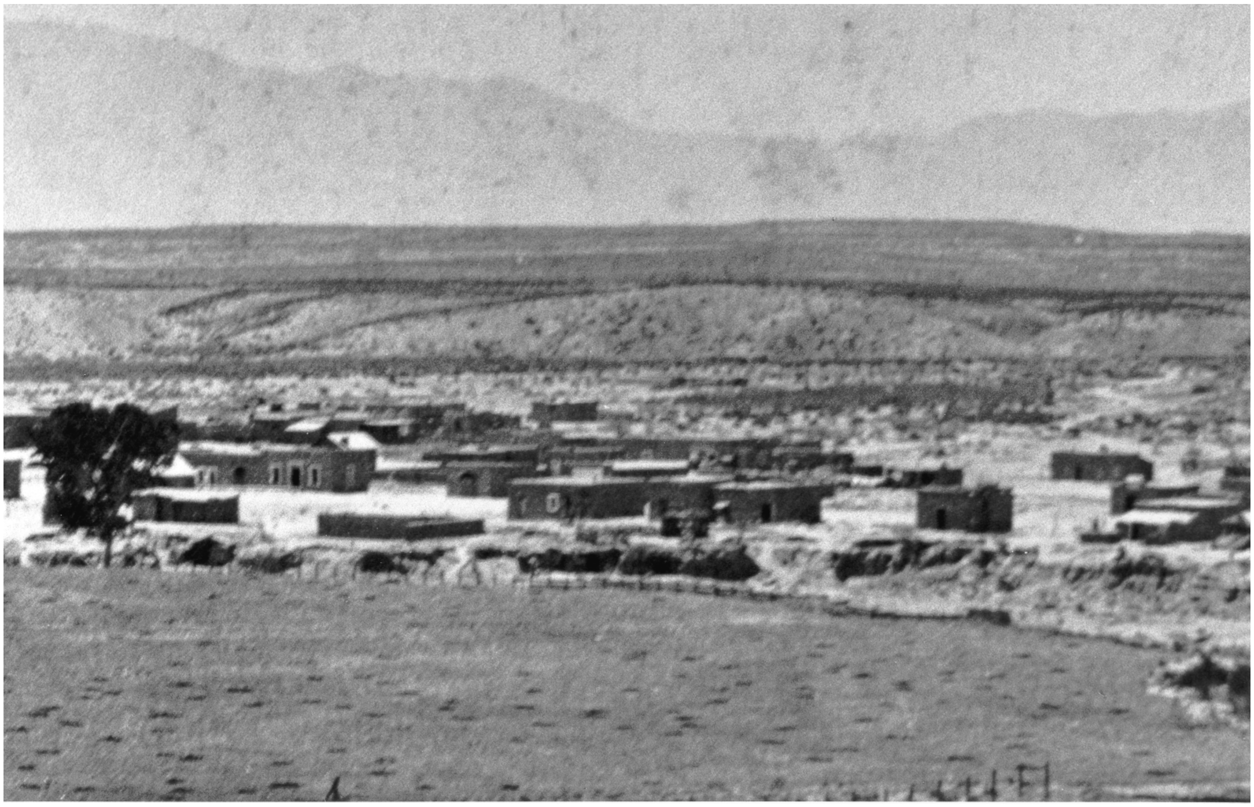


Figure 5A

Figure 5B

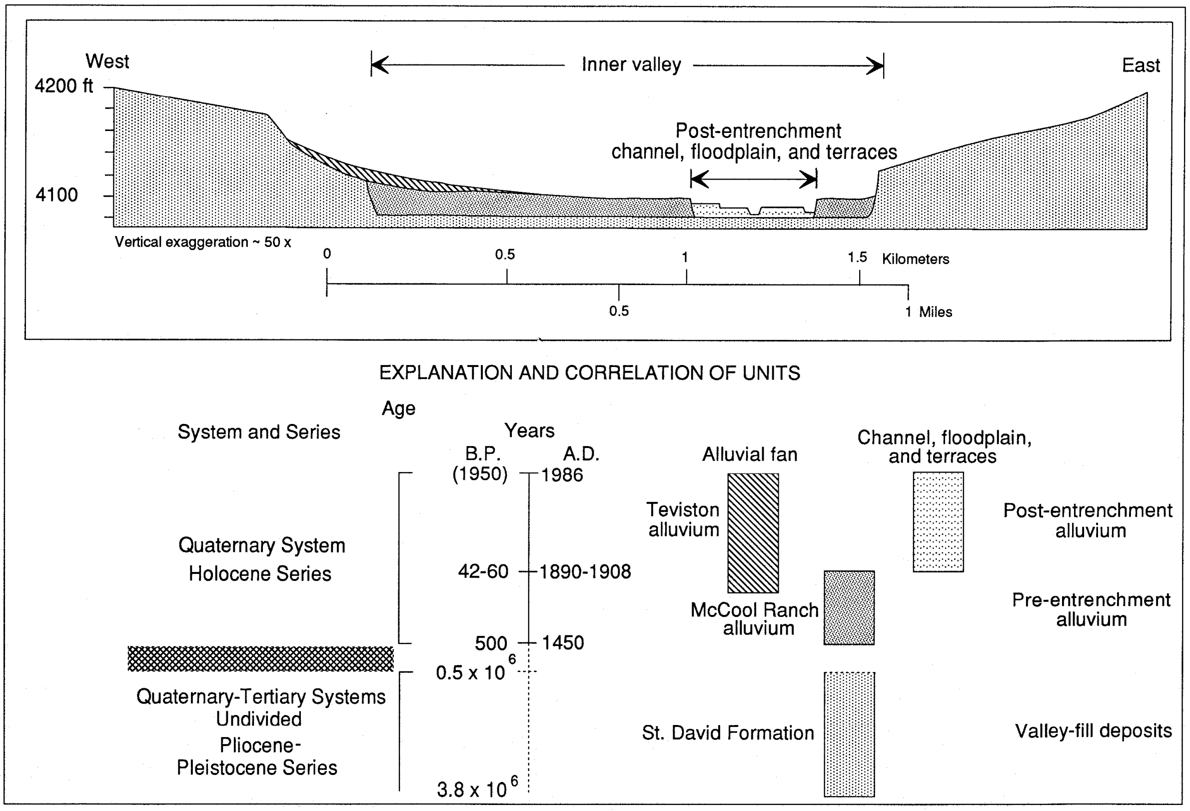

West
East
Inner valley
4200 ft
4100
Post-entrenchment
channel, floodplain, and terraces
Vertical exaggeration ~ 50 x
0
0.5
1
1.5 Kilometers
0.5
1 Miles
EXPLANATION AND CORRELATION OF UNITS
Age
System and Series
Years
B.P.
A.D.
(1950)
1986
42-60
1890-1908
500
1450
0.5 x 10^6
3.8 x 10^6
Quaternary System
Holocene Series
Quaternary-Tertiary Systems
Undivided
Pliocene-
Pleistocene Series
Alluvial fan
Channel, floodplain,
and terraces
Teviston
alluvium
McCool Ranch
alluvium
St. David Formation
Post-entrenchment
alluvium
Pre-entrenchment
alluvium
Valley-fill deposits

Figure 6

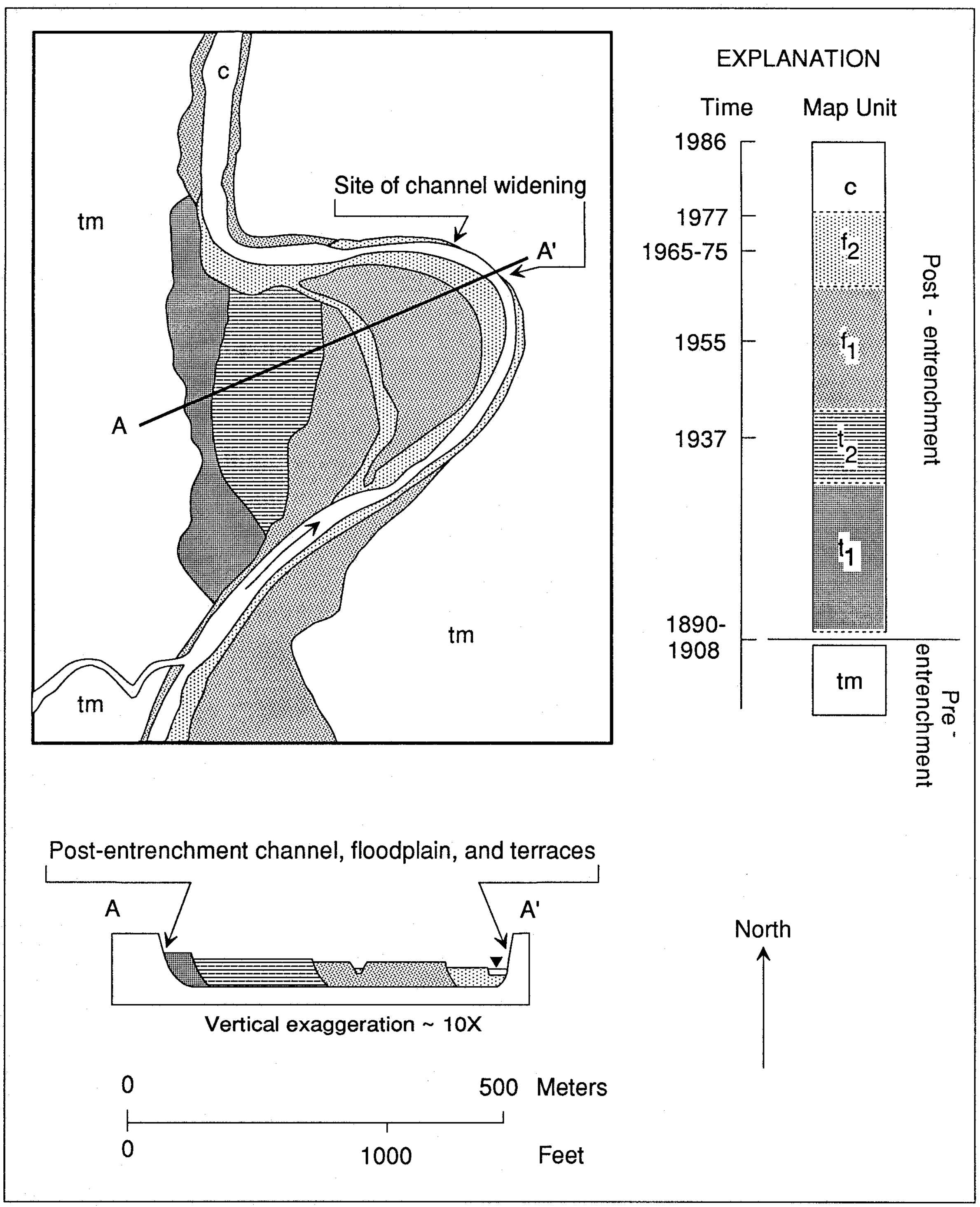

c
tm
Site of channel widening
A'
A
tm
tm
EXPLANATION
Time
Map Unit
1986
1977
1965-75
1955
1937
1890-
1908
c
f_2
f_1
t_2
t_1
tm
Post - entrenchment
Pre -
entrenchment
Post-entrenchment channel, floodplain, and terraces
A
A'
Vertical exaggeration ~ 10X
0
500 Meters
0
1000
Feet
North

Figure 7

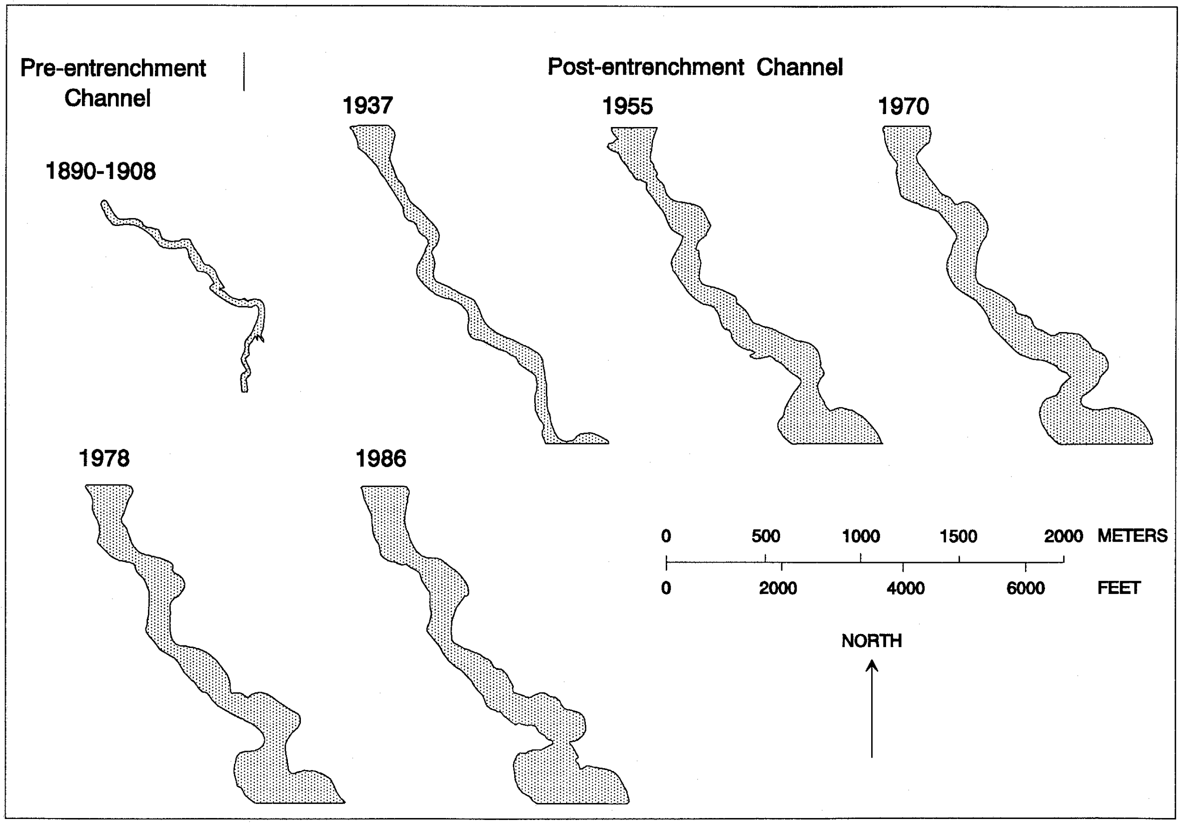

Pre-entrenchment Channel
Post-entrenchment Channel
1890-1908
1937
1955
1970
1978
1986
0
500
1000
1500
2000
METERS
0
2000
4000
6000
FEET
NORTH

Figure 8

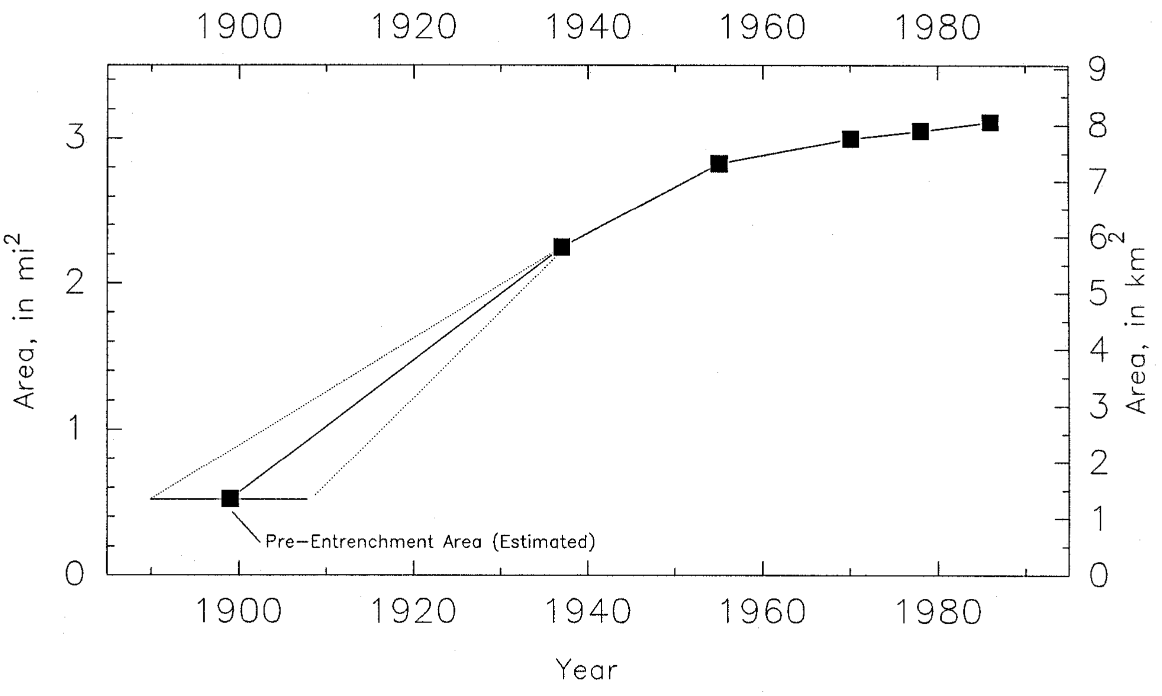

1900
1920
1940
1960
1980
Area, in mi^2
0
1
2
3
Area, in km^2
0
1
2
3
4
5
6
7
8
9
Pre-Entrenchment Area (Estimated)
Year

Figure 9

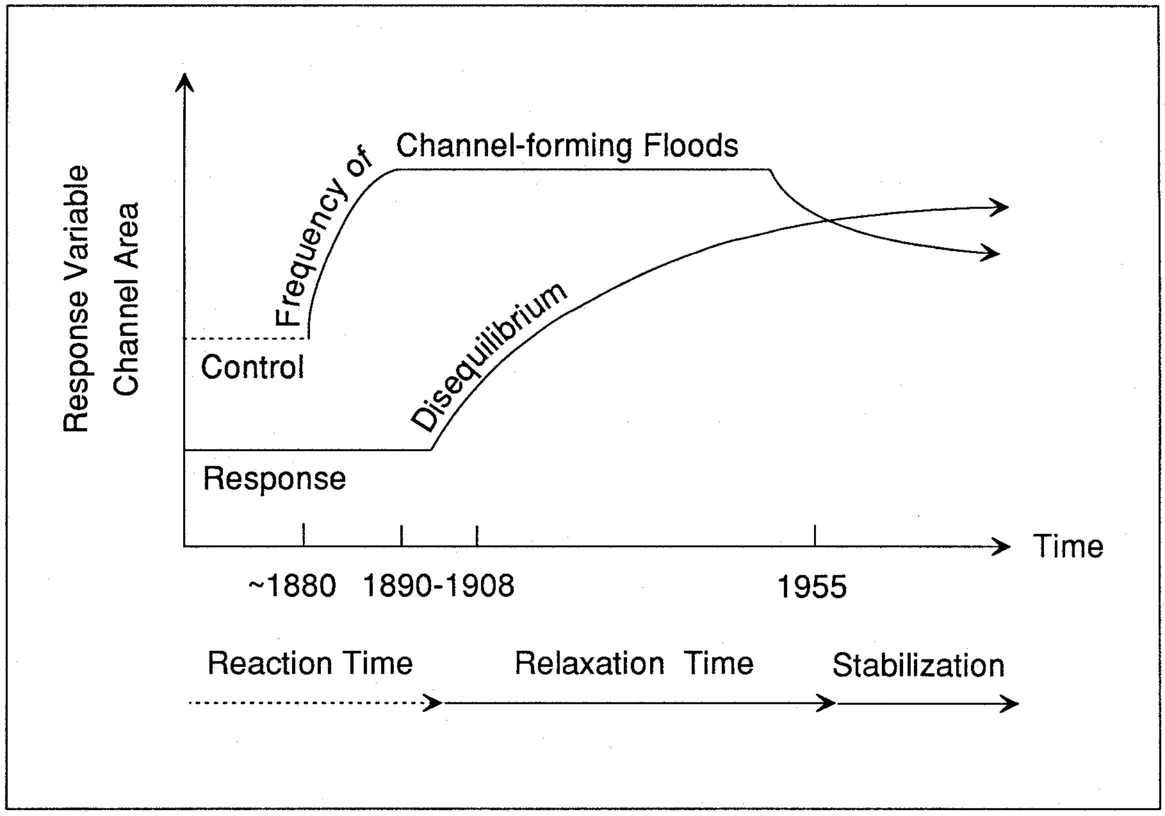

Response Variable
Channel Area
Frequency of Channel-forming Floods
Control
Disequilibrium
Response
Time
~1880
1890-1908
1955
Reaction Time
Relaxation Time
Stabilization

Figure 10

Accession Number	PB90-172925
Title	Arid Lands: Hydrology, Scour, and Water Quality.
Publication Date	1988
Media Count	80p
Personal Author	H. W. Hjalmarson R. H. Webb S. L. Rathburn B. M. Reich E. D. Cobb
Abstract	The 9 papers in the report deal with the following areas: Flood-hazard zonation in arid lands; Paleoflood hydrologic research in the Southwestern United States; Need for new rainfall intensity atlas analyses in the west; Peak-flow data-collection methods ...
Keywords	Arid land Bridge piers Failure Flood plain zoning Highway bridges Hydrology Rainfall Soil erosion Water quality Water treatment
Source Agency	National Academy of Science Transportation Research Board
NTIS Subject Category	50A - Highway Engineering 50D - Soil & Rock Mechanics 48G - Hydrology & Limnology
Corporate Author	Transportation Research Board, Washington, DC.
Document Type	Technical report
Title Note	N/A
NTIS Issue Number	9010
Contract Number	N/A

With discussion of human induced changes to the natural and ordinary base flow along , sediment contribution to and the morphology along the natural channel of the San Pedro River .

Transportation Research Record 1201

Contents

Flood-Hazard Zonation in Arid Lands

H. W. HJALMARSON

Potential flood hazards in arid southern and western Arizona stem from different geomorphic and hydrologic characteristics and can be grouped into zones. The zonation is based on the physical features of the terrain, the sources of flooding, the expected frequency of flooding, and the expected erosion and sediment deposition. Various combinations of these factors create differing degrees of hazard. Distributary flow areas have stream channels that convey only a small fraction of the 100-year peak discharge and channels that can completely fill with sediments during a single flood. A basic understanding of the common and different flood hazards of areas in southwestern Arizona can lead to effective flood-plain management and design of hydraulic structures.

Desert floods in the southwestern United States result from large amounts of intense rainfall in the steep headwater areas. When this happens, the normally dry channels can suddenly host dangerous, debris-laden torrents (*1*). Typical floods are characterized by a rapid rise and cessation of discharge that are dramatically referred to as flash floods. Discharge generally is decreased by infiltration as the flood wave moves downstream over sandy alluvial channels (*2*). Large amounts of debris are carried down the channels, and the shapes of the channels generally change during flooding. Channels scour and fill during flooding, and channel banks wetted by floodwater often collapse after flooding.

Bridges on base-level streams often fail because of scour. Culverts located in aggrading alluvial areas fill with alluvial debris, and bank protection is ineffective. Many lives have been lost because of bridge failure, and damage to public and private property has been considerable.

This paper presents some generalizations about the nature of flooding in the deserts of southern Arizona that are based largely on the relationship between flood hazards and desert landforms. Flood hazards unique to the desert areas are described, and zones of potential hazard are characterized. Limitations of Federal Emergency Management Agency guidelines (*3*) are identified.

GENERAL CHARACTERISTICS

Degrees and types of potential flood hazard in the desert are related to geomorphic characteristics. Figure 1 illustrates the relationship between geomorphology and flood hazard and lists some general characteristics of the flood-hazard zones. Zone 1 is defined as the area inundated by the 100-year flood on base-level streams, which conforms to the present regulatory flood used by the Federal Emergency Management Agency (FEMA) (*3*). Zone 2 includes land adjacent to zone 1 that is subject to erosion by floods but not subject to inundation by the 100-year flood. Zone 3 includes relatively flat undissected areas where floodflow is shallow and unconfined; it includes former flood plains of base-level streams. Zone 4 includes areas of distributary flow, such as alluvial fans, where the amount of floodflow at a particular location is impossible to predict. Zones 5 and 6 include a variety of landforms where the 100-year flood is confined to rigid channels that generally drain areas less than 100 mi^2.

The mountainous areas (zone 6) are the source of weathered rock debris, and the stream channels usually have very little fine-grained material. A sharp break is often present in the gradient at the junction of the mountain front and the piedmont plain (zone 5) (fig. 2). Pediment areas are sparsely covered by a thin veneer of detritus, and stream channels have a mixture of fine- and coarse-grained material, including boulders. The alluvial fan and the base-level plain (fig. 1) have a wide variety of forms caused by natural and human-induced erosion and deposition that have occurred along the entire desert profile including base-level streams (*4*).

The channels of several alluvial streams have become entrenched because a balance was not maintained between factors such as flow, sediment discharge, slope, meander pattern, channel cross-section, and roughness. For example, minor fluctuations in meteorological conditions over a few years can alter the movement, transport, and production of sediment in a basin. During drier years, sediment can accumulate in stream channels, and subsequent wetter years may cause the sediment to be flushed from the basin. Reaches of channel with conditions of both uniform flow and nonuniform flow may appear to be aggrading or degrading. Thus, a reach of channel on an alluvial stream will not necessarily remain stable over a period of a few years.

ZONE 1

Zone 1 includes the channel and parts of the flood plain that would be inundated by the 100-year flood on playas, base-level streams, and larger tributaries. This zone has a high potential for flooding because floodflow normally is concentrated in defined channels and land adjacent to the channels. The velocity of flow in the channels is high, and the adjacent land is susceptible to erosion.

Historic information indicates that the current defined channels for base-level streams were not present until late in the nineteenth century and early in the twentieth century when some channels became entrenched (*3, 5*). The cause of entrenchment is the subject of considerable debate among hydrologists, but a strong argument can be made for change

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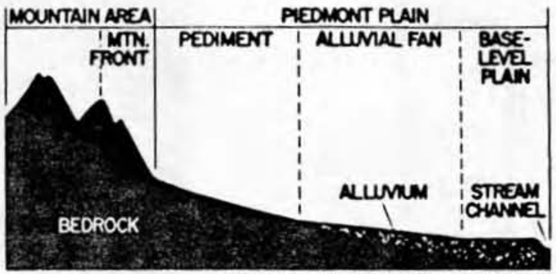
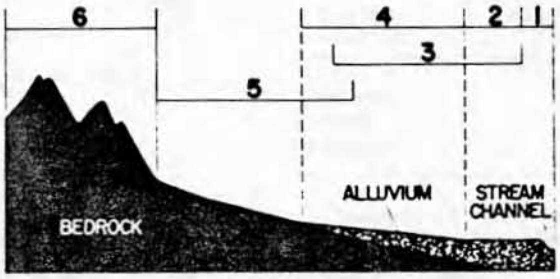
U.S. Geological Survey, 300 West Congress Street, Tucson, Arizona 85701-1393.



Characteristic desert profile modified from (3)

A. Geomorphic components



B. Flood-hazard zones

Zone	Description
1	Extent of the 100-year flood on base-level stream.
2	Part of flood plain that may be inundated by rare large floods and (or) eroded by frequent small floods.
3	Flooding from sheetflow, standing water, and water that collects in depressions.
4	Flooding in channels and sheetflow on slightly dissected alluvial plains. Flow can be distributary and there is a greater than average chance of sediment deposition.
5	Flooding confined to defined channels of small tributary streams.
6	Sheetflow and flooding in defined clean-scoured channels.

FIGURE 1 Geomorphic features and flood-hazard zones of typical mountain-plain desert profile.

of climate. Floodflow in entrenched channels is more confined and the channel beds are less rough. Flood-wave celerity is greater and wave dispersion is less than for pre-entrenchment conditions. The entrenchment has had a significant effect on the flood characteristics of several base-level streams. Channel beds and banks can scour greatly in short periods during floodflow.

Zone 1 includes a variety of trenched and untrenched channels. Floodwater that is confined within a vertical walled arroyo only a few hundred feet wide can spread over an unchanneled valley for several miles downstream (figs. 3 and 4). Runoff that enters the desert-plain areas crosses progressively more alluvium where there is a great potential for infiltration (fig. 5). Burkham (*2*) found that the amount of loss along channels in the Santa Cruz River basin is related to the length of reach and the infiltration capacity of the channel.

Bridges on base-level streams become vulnerable to failure when the stream channel that supports the bridge is scoured. The abutments of many bridges in southern Arizona failed

FIGURE 2 View looking north at the western slopes of the Tortolita Mountains. The sharp break in land slope at the junction of the mountain front and piedmont plain is typical of mountain-plain deserts.

FIGURE 3 View looking downstream at the entrenched channel of the Santa Cruz River at Tucson, Arizona. Floodwater of the 100-year flood is confined within the channel of the reach. Lateral erosion of the channel banks is restricted by massive soil-cement banks. Interstate 10 is located to the left of the 200-foot-wide by 20-foot-deep river channel. Since 1914, the channel has widened about 100 feet and deepened about 15 feet.

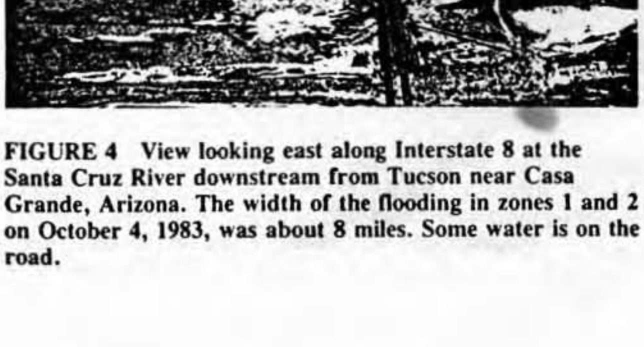
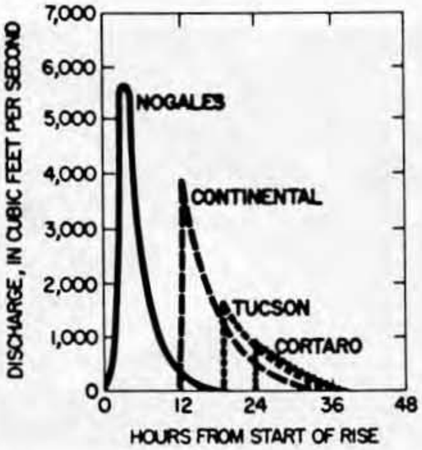


FIGURE 4 View looking east along Interstate 8 at the Santa Cruz River downstream from Tucson near Casa Grande, Arizona. The width of the flooding in zones 1 and 2 on October 4, 1983, was about 8 miles. Some water is on the road.



Gaging station	Miles from Nogales	Average annual runoff, in percent[1]
Continental	50	29
Tucson	79	19
Cortaro	88	14

[1] Amount of the average runoff at the Nogales gage that reached the indicated gage (1940-46, 1952-68).

FIGURE 5 Typical flow event showing transmission losses and attenuation of peaks for the Santa Cruz River, a base-level stream in southern Arizona (*7*).

during the flooding of October 1983 (figs. 6 and 7). Local scour around abutments and piers is a major cause of bridge failure on base-level streams in Arizona and throughout the United States (*8*).

Playa surfaces are rather flat, generally smooth, and composed of silt and clay. Many small, poorly defined channels are distributary or serve as distributary channels during floodflow as water crosses low divides. For example, during the large storm of early October 1983, runoff from Ash Creek, which is an unentrenched stream draining an area of about 500 square miles, spread laterally for more than 3 miles as floodflow entered the Willcox Playa. Nearly 2 miles of Interstate 10 near the town of Willcox was inundated with shallow floodwater, which resulted in highway closure for a few hours.

ZONE 2

Zone 2 includes areas adjacent to Zone 1 that could potentially be inundated by rare floods larger than the 100-year flood if the conveyance of the main channel changed or the hydraulic gradient changed or was eroded by floodflow. The potential hazard resulting from inundation is less than for areas in zone 1. For areas subject to erosion, the potential hazard is variable and can be greater than that for zone 1. Land adjacent to banks on the outside of bends or at constrictions or obstructions can erode quickly and extensively during frequent small flows of long duration (fig. 8).

Hazards in zone 2 are related more to lateral bank erosion than to inundation, and, at present, FEMA does not include

FIGURE 6 View looking south at one of many abutment failures resulting from floodwaters of October 1983 in southeastern Arizona. The scene is Interstate 10 at the Gila River on October 4, 1983. Flow is to the right.

expected bank movement in the definition of hazard degree. In fact, FEMA does not accept water-surface computations reflecting channel scour even where scour during floodflow is a common occurrence. Many models that predict channel scour, such as HEC-6, are in use, but the models do not consistently produce reliable results for all channels. Thus, improved models are needed to reliably define bank erosion for non-arbitrary flood-plain management of zone 2.

Many zone 2 floods originate in the surrounding mountains, where there is little soil and much exposed rock. Floodflow from these areas may carry sediment that is greater than the load. When floods confined in the channels reach the base-level streams (zone 1), the water picks up sediment from the channel banks. Floodflow in the steep, smooth channels can carry much sediment; thus, the banks in zone 2 areas can erode laterally tens of feet and even 100 feet or more during a single flood.

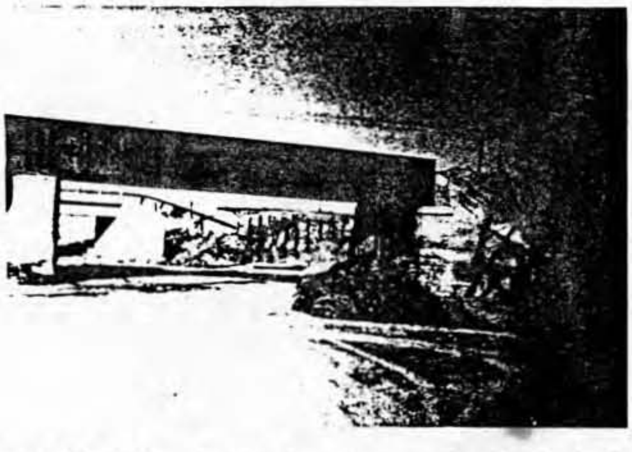


FIGURE 7 View looking downstream at the right bank of Rillito Creek at the Southern Pacific and Interstate 10 bridges at Tucson, Arizona. The failure of the wire-rock revetment at the abutments is typical for base-level streams in the area.

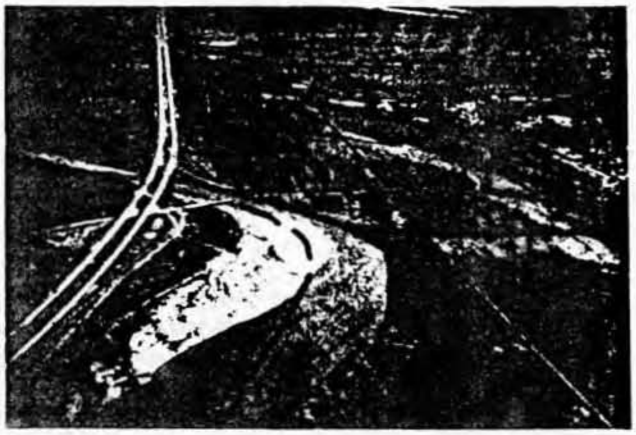


FIGURE 8 View looking south and upstream at the Santa Cruz River at Interstate 19 on October 3, 1983. The right bank abutment of the northbound lane failed and the left bank abutment of the bridge to the right of Interstate 19 was destroyed during flooding on October 1 and 2. The dashed line approximately represents the location of the left bank of the entrenched channel before the flood.

ZONE 3

Zone 3 is former flood plain of base-level streams and other relatively flat undissected areas. Areas are subject to sheetflow of a few inches to about 2 feet deep from floodflow originating in higher zones (figs. 9 and 10). Sheetflow a few inches deep can result from direct rainfall. Runoff generally is unconfined, and flow velocities generally are less than 2 or 3 square feet. The erosion hazard is low except along the few short incised channels.

Floodwater entering zone 3 spreads laterally and coalesces with floodwater entering the zone at other locations. Decreasing depth and velocity of flow as the width increases results in a reduced sediment-carrying capacity. Large amounts of sediment are deposited because of this spreading. Another

FIGURE 9 View looking northeast at floodwater from a small confined wash debouching onto land in zone 3. Floodflow spread to a width of more than 1 mile about half a mile downstream from the confinement. Flooding was on June 22, 1972, upstream from the Arizona canal east of Scottsdale, Arizona.

FIGURE 10 View looking south and downstream at sheetflow in zone 3 on June 22, 1972. The scene is in northeast Phoenix at 44th Street between Bell and Greenway Roads.

factor contributing to sediment deposition is loss of flow due to infiltration.

Culverts and bridges in zone 3 are usually not subject to serious erosion hazards unless the structure causes excessive backwater. Where excessive backwater does occur, the high head and corresponding high velocities through the structure opening can result in hazardous erosion of material supporting the structure. Sediment deposition resulting in the filling of structure openings, such as culverts, with debris is an occasional problem.

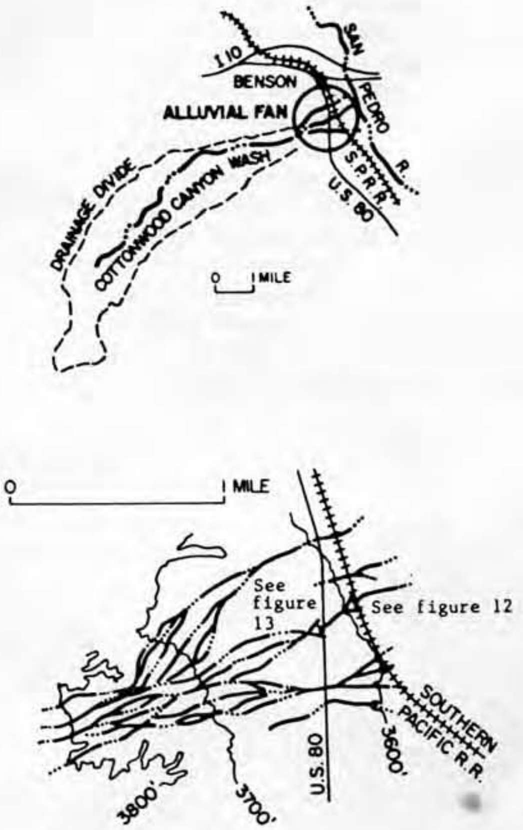


FIGURE 11 Alluvial fan showing contours and distributary channels on Cottonwood Canyon Wash at Benson, Arizona.

ZONE 4

Floodwater entering zone 4 from confined channels in zones 5 and 6 spreads into distributary channels (fig. 11) with a corresponding decrease of velocity and depth. The amount of flow also is decreased by infiltration into the sandy beds. There is less water and less energy to transport sediment, and thus sediment is deposited in and along the channels to form a mound of alluvial material. Channels completely fill during flash flows, and culvert and bridge openings become ineffective (figs. 12 and 13). Frequent cleaning of culvert and bridge openings is needed at many stream channels in zone 4.

Zone 4 includes the slightly dissected alluvial slopes that commonly exhibit a distributary drainage system. The flood potential of zone 4 has often been overlooked (9). Bajadas and single alluvial fans (fig. 14) are typical landforms in the aggrading area. The rate of sediment deposition, one aspect of the dynamic behavior of the fans, is complex and variable (*3*, *5*). Some fans seem to aggrade at a rapid rate, and the active channels change frequently. Many of the fans in southern Arizona appear to be less dynamic than fans in areas of southern California (*10*) and Nevada (*11*), where tectonic activity is greater. Also, on the basis of soil characteristics such as the age of the bajada soils (*12*), the alluvial slopes in some areas are relatively stable; apparently, little aggradation or degradation occurred during the Holocene epoch (about the past 10,000 years). Many alluvial fans are present in southern Arizona (*13*), and they may occupy about 30 to 40 percent of the area.

FEMA has presented methods for evaluating flood hazards on alluvial fans that assume channels downstream from the fan apex are equally likely to occur any place on the fan

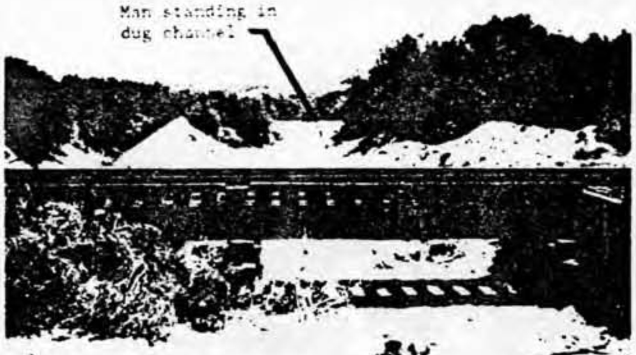


FIGURE 12 View looking downstream at railroad bridge in south Benson, Arizona. The opening was completely filled during a 1-hour flash flood on July 6, 1981. Note the depth of the channel where the filled material has been removed about 100 yards downstream from the bridge. See figure 11 for location of photograph.

FIGURE 13 View looking downstream at culvert on U.S. Highway 80 in south Benson, Arizona. The opening was nearly filled during the flash flood of July 6, 1981. Floodflow velocities in the main channel downstream from the culvert were very high and a local resident observed two standing waves about 20 feet apart at the flood peak. See figure 11 for location of photograph.

surface (*4*). Although this assumption may be valid for estimating the flood hazard of highly active fans, it may not be applicable for the many fan surfaces in southern Arizona that are relatively inactive. The more stable fans have a defined network of distributary channels with some abandoned channels that presently head on the fan surface. Floodflow is more likely in the defined channels that head in mountains, less likely in the abandoned channels, and unlikely on much of the high ground between the channels. Although the amount of discharge in a particular branch of a divided channel is difficult to determine, the likelihood of floodflow at any location on the fan surface is not equal.

The topographic relief across single alluvial fans and bajadas is variable and is an index of the age of the landform. The local relief between channels in zone 4 is commonly less than 5 feet but occasionally more than 20 feet. Alluvial fans with small local relief tend to be more active than alluvial slopes with large relief.

The filling of the stream channel shown in figures 12 and 13 may be offsetting the potentially hazardous headcutting of the channel. The stream is tributary to the San Pedro River, which is entrenched. Tributaries to the San Pedro River also have become entrenched near the river (fig. 15). The hazardous conditions shown in figures 14 and 15 are representative of the variable and dynamic behavior of streams in southern Arizona.

Floodwater on inactive fans generally is in entrenched channels that anastomose, divide, and combine. Much of the land clearly is above the 100-year flood, but flood hazards on fans are unpredictable. Possible consequences of floods in the low-lying land and channels include:

1. Channel erosion and lateral bank movement.
2. Channel filling with deposited sediment and the associated increased flooding of adjacent flood plain.
3. Lateral shifting (avulsion) among distributary channels.

The FEMA type of flood hazard assessment (random distribution of flood depth and velocity) may not be applicable. Flood hazard assessment for bridge or culvert design is difficult because flood response at any given location on channels in zone 4 is unpredictable.

ZONE 5

Zone 5 is defined as the pediment and upper alluvial plain areas with defined channels that commonly form a tributary system. The surface of the pediment areas is a complex mixture of rock, alluvium, and thin soils of various ages. Stream channels commonly have slopes from 0.02 to 0.04 with an upper limit of about 0.2 (*3*). Channel beds in the pediment or upper area of the zone are often composed of scattered boulders with cobbles, gravel, and some sand. Channel beds in the upper alluvial areas tend to have fewer boulders and more sand. The potential for significant scour of the channel

FIGURE 14 View looking east at distributary channels of zone 4 on the western slopes of the Tortolita Mountains north of Tucson, Arizona. The land in about the top quarter of the photograph is in zone 5.

FIGURE 15 View looking downstream from U.S. Highway 80 at small scoured channel of a tributary to the San Pedro River located 0.6 mile south of the filled channel shown in figures 12 and 13.

bed and banks in the pediment area is low. Marked scour along some channels in the upper alluvial plain area can occur, but the general potential for scour is not great. Debris flows, defined here as slurries of sediment and water with a sediment weight-percentage above 80 percent, that are potentially hazardous can occur in zone 5.

The boundary between zones 4 and 5 generally coincides with the boundary between Quaternary and Tertiary valley-fill deposits. In some places, the tributary-defined channels characteristic of zone 5 extend into the Quaternary deposits. The small distributary channels of zone 4 rarely extend upslope in the Tertiary deposits. In some places, the boundary that separates zones 4 and 5 is a transition area several hundred feet wide.

The greatest potential hazard in zone 5 is from flooding in the channels and narrow flood plains that occupy the lowlands between the defined ridges. Marked scouring occurs along some of the channels and flood plains, and floods carry large amounts of sediment. In many channels, the depth of flooding depends on the amount of erosion and deposition that takes place during the flood. The depth of flooding generally does not exceed 10 ft except where channels are obstructed, on the outside of sharp bends, and on the few channels that drain areas of more than about 100 mi^2. The depth of floodwater also increases behind debris jams and manmade obstructions. The degree of potential flood hazard of the larger washes in zone 5 is similar to that in zone 1 but with less potential for scour. The main channel of some washes is deceptively small, and large amounts of floodwater will spread over wide areas adjacent to the channel.

ZONE 6

Mountain areas that include steep, well-drained slopes composed mostly of rock are characteristic of zone 6. Interspersed among the rock surface are scattered thin debris mantles and thin soils. Stream channels are steep, scoured, and rocky. Channels of streams draining basins of a few tenths of a square mile are well defined.

The dominant hazard is along the defined channels where flood velocities are high; velocities in the large channels may be as much as 15 feet per second. Sheetflow accompanied by debris flow may occur along some steep slopes. Peak-discharge rates of as much as 500 cubic feet per second from a 0.1-square-mile area can be expected an average of once every 100 years. A large part of the flood-hazard potential in this zone can be attributed to sudden flooding from summer thunderstorms and the high velocity of flow.

If the potential for debris flows exists, then the hazard associated with a debris flow may be the greatest in this zone. The potential for debris flows is directly related to the amount and size of unconsolidated material on steep, nonvegetated slopes.

TABLE 1 TYPE AND DEGREE OF FLOOD HAZARD FOR ZONES

Type of hazard	Flood-hazard zone					
	[1]1	2	3	4	5	6
Inundation of land along channels	high[2]	moderate	moderate	high[2]	moderate	low
Velocity of floodflow	high	moderate	low	high[2]	high	high
Scour of channel bed	high	moderate	low	moderate	low[3]	low
Lateral bank erosion	high	high[2]	low	high[2]	low	low
Sediment deposition	low[4]	low	high[5]	high[5]	low	low
Debris flows	low	low	low	low	moderate	high

[1] High incidence of bridge failure because of scour of piers, abutments, and roadway approaches.

[2] The assumption on which FEMA guidelines is based may not be applicable for fan surfaces that are relatively inactive.

[3] Moderate in upper alluvial plain areas and in large channels.

[4] Moderate to high in unchanneled reaches.

[5] Conveyance of many culverts and bridges reduced because of sediment deposition.

DISCUSSION AND SUMMARY

Geomorphology plays an important role in determining flood hazard. Although this fact is common knowledge, structures continue to fail or become less effective, at least in part because of flood-plain management regulations that may not be applicable for some zones. The hazards that commonly plague engineering works are the lateral bank erosion in zone 2, the scour of channel beds in zone 1, and the sediment deposition and unpredictable flow paths in zone 4.

The relative degree and type of hazard for the six zones are summarized in table 1.

The zonation is based on distinct geomorphic and hydrologic differences between the zones, but there is some overlap (see fig. 1). Zones 2 and 3, for example, can define the hazard of the same land where there is a potential for lateral movement of the banks of channels in zone 1 and also for sheetflow from local rainfall or from runoff from zones 4 or 5. Alluvial fans have a wide variety of flood characteristics, and thus specific areas can be best described by zones 3, 4, or 5. In general, large areas of fans will exhibit characteristics of a single zone.

This general zonation is not intended to replace the detailed engineering definition of hydrologic and geologic characteristics of a particular site of interest. Rather, the zonation of flood hazards can be useful to practicing engineers for the general identification of the type and degree of flood hazard.

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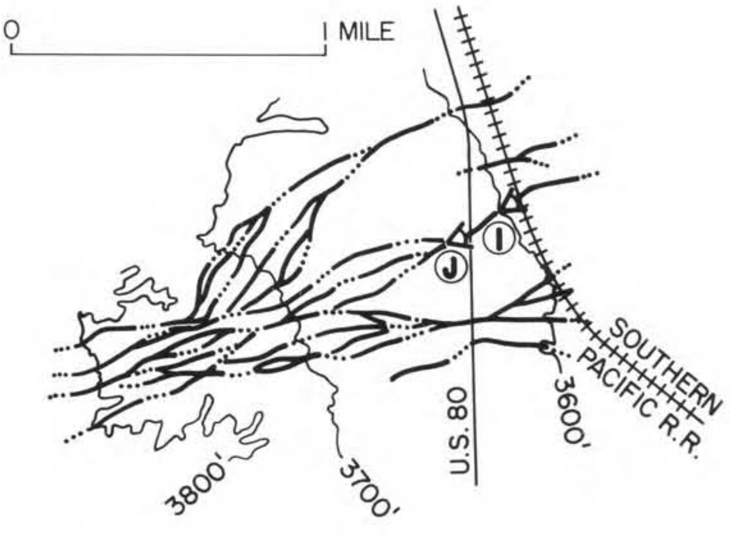
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View looking downstream from U. S. Hwy 80 at small channel located 0.6 mile south of Cottonwood Canyon Wash. San Pedro River is about 1 mile beyond this site. There is several feel of head cutting at the exit of this culvert.

Schumm, S. A., 1968. RIVER ADJUSTMENT TO ALTERED HYDROLOGIC REGIMEN-MURRUMBIDGEE RIVER AND PALEOCHANNELS, AUSTRALIA, USGS Professional Paper 598, 65 pp.

Schumm discusses the affects of altering vegetation cover in watersheds and thereby changing tributary runoff and sediment contribution. "For example, the control of tributary runoff and sediment contribution to an alluvial channel will-if both runoff and ·the type of sediment load are significantly altered - induce a long-term adjustment of the river system. The induced changes may be difficult to recognize in a short span of time, but they will, nevertheless, be significant over very long reaches of alluvial rivers, especially in arid, semiarid, and subhumid climatic regions. Depending on the type of sediment load transported by the river, quite different types of adjustment can occur." These photos of channels in south Benson clearly show the variable nature of tributary channel adjustment.

Early accounts of the base flow along the San Pedro River and also the variable channel morphology in the Tres Alamos area also suggest major changes in dimensions, pattern, and shape of the San Pedro River channel in response to man-induced alterations of hydrologic regimen occurred as a result of diversion for irrigation and over grazing of cattle. For example, Parke stated "At the Tres Alamos the stream is about fifteen inches deep and twelve feet wide, and flows with a rapid current over a light, sandy bed, about fifteen feet below its banks, which are nearly vertical. The water here is turbid, and not a stick of timber is seen to mark the meanderings of its bed. In the gorge below, and in some of the meadows, the stream approaches more nearly the surface, and often spreads itself on a wide area, producing a dense growth of cotton-wood, willows and underbrush, which forced us to ascend and cross the terraces. The flow of water, however, is not continuous. One or two localities were observed where it had entirely disappeared, but to rise again a few miles distant, clear and limpid." Tres Alamos is a ghost town. Settled 1874. In 1768 Spanish soldiers from the Presidio de Tucson farmed the Tres Alamos area along the San Pedro River to supply food for the Presidio. Later, in 1830, Mexican farmers settled in the area, establishing more permanent farming operations and transporting their produce through the Redington Pass to Tucson with the protection of soldiers from the Presidio.

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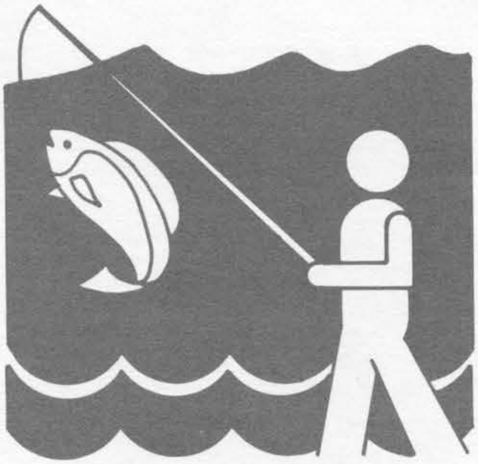
Methods of Assessing Instream Flows for Recreation

COOPERATIVE
INSTREAM FLOW
SERVICE GROUP

INSTREAM FLOW INFORMATION PAPER: NO. 6

FWS/OBS-78/34
JUNE 1978



Cooperating Agencies:

Fish and Wildlife Service
Environmental Protection Agency
Heritage Conservation and Recreation Service
Bureau of Reclamation

U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

COOPERATIVE INSTREAM FLOW SERVICE GROUP

The Cooperative Instream Flow Service Group was formed in 1976 under the sponsorship of the U.S. Fish and Wildlife Service. Primary funding was provided by the U.S. Environmental Protection Agency. The group operates as a satellite of the Western Energy and Land Use Team. It is a part of the Western Water Allocation Project, Office of Biological Services.

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While the Fish and Wildlife Service is providing the initiative and leadership, the IFG is conceived as a multi-agency, multi-disciplinary program which is to become a "center of activity," providing a focus for the increasing importance of instream flow assessments.

The multi-agency, multi-disciplinary nature of the group is provided through the Intergovernmental Personnel Act transfer of state personnel, and details from other Federal agencies.

Interagency Energy-Environment
Research and Development Program
Office of Research and Development
U.S. Environmental Protection Agency

FWS/OBS-78/34
June 1978

METHODS OF ASSESSING INSTREAM FLOWS FOR RECREATION

Instream Flow Information Paper No. 6

by

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Cooperative Instream Flow Service Group
Western Energy and Land Use Team
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Fish and Wildlife Service
U.S. Department of the Interior

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[1] Detailed to the Cooperative Instream Flow Service Group from the Heritage Conservation and Recreation Service.

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ABSTRACT

The Instream Flow Group (IFG) has conducted research into methods of quantifying instream flow needs for fish, wildlife, and recreation. This paper describes two techniques developed by IFG for performing recreational instream flow studies. The single cross section method is relatively simple and provides a base flow figure which will provide for the boating activities which make use of the of river. The incremental method is more sophisticated and may be used to develop recommendations regarding streamflows required for various types of recreation, or to provide a recreation analysis of any streamflow. Streamflow suitability criteria for recreation are presented for both methods.

INTRODUCTION

It has been long recognized that there are many competing demands for the use of stream water. Diverting stream water for irrigation, water supply, and energy developments can deplete streamflows to the point where opportunities for recreation and the associated environmental values of the stream are seriously impaired. Numerous water planning studies, both basin-wide and project oriented, have emphasized the need to quantify the amount of water required to support recreation, fish and wildlife resources, and to maintain aesthetic conditions.

The tools and techniques for estimating streamflows required for recreation and aesthetics, and for insuring reasonable consideration of recreation and aesthetics in the allocation of stream water, are currently undergoing study. Instream flow requirements and values for recreation, in the past, have often been based only upon the amount required to maintain a fishery. However, several studies have indicated that recreation and aesthetic requirements, at times, may not be the same as for a fishery.

This paper presents the techniques of assessing instream flows for recreation. These techniques were developed by the Cooperative Instream Flow Service Group and closely parallel techniques used to assess instream flows for fisheries. The data collection procedures, the physical and hydraulic simulation of the stream, and the computer models which analyze the data are the same for both fisheries and recreation. The major difference between the two techniques is the response of the individual fish or recreationist to various physical parameters of stream flow. These responses to stream flow by different user groups are the criteria which are basic to the methods introduced here.

The first method is called the single cross section approach. This method is useful primarily for identifying flows below which a recreation activity is not feasible and results in a so called "minimum" flow recommendation.

The second method is called the incremental method. With this method the recreation planner is able to analyze various flows and determine the recreation potential of a stream at different flows.

This paper is being distributed with four objectives in mind. These are:

1. To bring the problem of preserving instream flows to the attention of recreation agencies and the research community in order to encourage more research in this vital and neglected area.

2. To discuss the development of the recreation probability-of-use curves and of recreation criteria in general, which are necessary for quantifying instream water requirements for recreation.

3. To obtain review and comment on the recreation criteria and probability-of-use curves, and to request data which may be used to test or improve the criteria or curves.

4. To describe the two approaches for assessing stream flows and discuss how various recreation planning processes can be served by their application.

Both methods of instream flow analysis discussed in this paper utilize computer modeling techniques. Both approaches also require that streamflow data be collected. The single cross section approach, as its name implies, requires that information be collected at only one location on the stream. The incremental method requires that data be collected at multiple locations on the stream. In addition to cross sectional data, data relating the streamflow parameters to recreation potential are necessary. These data are termed recreation criteria.

Recreation criteria for instream flow methodologies are the recreation activity information bases necessary to describe a relationship between the quantity of water flowing in a stream, and the quantity and 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 a short time during a boating trip, and the remainder of the trip will be over water of greater depths and widths. An important assumption is that all water greater than the minimum is equally useful for the activity (i.e., more is better until bank-full stage).

A computer program (IFG-1) has been developed which predicts width and depth across the transect of any stage (water surface elevation). The output shows discharge and the width with depth equal to or greater than a specific depth. Different water surface elevations may be put into the computer model which are translated into flow in cubic feet per second. When a flow provides the minimum width and depth necessary for an activity, discharge may be considered minimum. Such a minimum indicates that significant losses, if not elimination of this activity, will occur if minimum flow is not equaled or exceeded.

THE INCREMENTAL METHOD

This method, more sophisticated than the single cross section method, describes a relationship between the amount of water in a reach of stream and the associated recreation potential. The incremental method can describe the potential for any recreation activity at any streamflow. A major difference between the methods is that the single cross section method can only be used to identify low flow and cannot be used to assess the recreation potential at any other flow; the incremental method can be used to assess the potential at other flows or to calculate the change in receation potential caused by a change in stream flow.

The incremental method involves a modeling procedure whereby the surface area of a stretch of stream is calculated. In addition to the total surface area of the reach of stream, the area which has certain depths and velocities is calculated. The usable surface area for each activity is then calculated by use of depth and velocity requirements.

It is necessary to make three assumptions regarding the relationship between the quantity of water and the recreation uses of the water: (1) water depth and water velocity are the two streamflow components which are most important in determining whether or not a certain recreation activity may be safely and pleasurably engaged in[1]; (2) there are

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[1] Other parameters such as water quality and temperature are also very important in determining the amount of instream recreation use but in many cases are not significantly influenced by flow. Width is also important but is considered outside of the computer model (i.e., width is not a part of the calculation of usable surface area).

certain measures of water depth and water velocity which may be considered minimum, maximum, and optimum for an activity; and (3) the measurement of water surface area which meets certain requirements of depth and velocity is a viable method of describing recreation potential for instream recreation uses.

This method is comprised of four components: (1) computer simulation of a stream reach, (2) determination of the combinations of stream depth and velocity, (3) determination of a composite probability-of-use for each combination of depth and velocity, and (4) calculation of a weighted usable surface area.

1. Simulation of the Stream. The stream reach simulation model utilized in this approach uses several cross sectional transects, each of which is subdivided into subsections. For any stage (water surface elevation) the mean depth and velocity of each subsection is calculated. Typically, a transect would be established across a pool, a riffle, and an intermediate area. Together these cross sectional measurements would represent a stream reach which may extend several miles. In Table 2 a 100 foot length of stream is represented.

Table 2. Depth velocity matrix showing total surface area of stream in square feet.

Depth (ft)	Velocity in feet per second				
	<0.5	0.5-1.0	1.0-1.5	>1.5	Total
<1	500	400	100	0	1,000
1-2	600	700	800	300	2,400
2-3	100	300	500	100	1,000
>3	0	0	100	0	100
Total	1,200	1,400	1,500	400	4,500

2. Distribution of Combinations of Depth and Velocity. The output of the stream reach simulation model is in the form of a matrix showing the surface area of a stream having different combinations of depth and velocity. Table 2 illustrates a depth velocity matrix. The outlined number in the upper left matrix cell refers to 500 square feet per 100 feet of stream having a combination of depth less than 1.0 foot and velocity less than 0.5 foot per second. This figure is the sum of the areas within the stream reach with this combination of depth and velocity.

In order to evaluate the effect of these physical changes upon a streams desirability for recreation, it is necessary to develop an information base for each recreation activity. Such an information base should identify a relationship between depth and velocity of the water, and the desirability of such water for each recreation activity. The information base, called recreation criteria, has been developed and is set forth in the following pages.

3. Composite Probabilities-of-Use. Determination of the probability-of-use for an activity on a certain area of water requires multiplying the probability-of-use for the depth by the probability-of-use for the velocity. For example, from Figure 1 the probability-of-use for the depth of 2.6 feet is 0.9. The probability-of-use for the velocity of 6 feet per second is 0.24. The composite probability-of-use for a depth of 2.6 feet <u>and</u> a velocity of 6 feet per second, is 0.216 (0.9 x 0.24). The probability-of-use is also the weighting factor for calculation of the weighted usable surface area.

4. Weighted Usable Surface Area. The weighted usable surface area equates an area of low desirability to an equivalent area of optimal desirability. For example, if 1,000 square feet of surface area had a composite probability-of-use of 0.216 (see above) it would have a weighted usable surface area of 216 square feet (total surface area times composite probability-of-use). These 1,000 square feet of surface area would be considered to have the same recreation potential as 216 square feet of surface area having optimum depths and velocities.

An example of a matrix is shown in Table 3. In each cell of the matrix, the upper number refers to the surface area of a stream having a depth velocity combination as indicated. The numbers in parentheses refer to the weighted usable surface area.

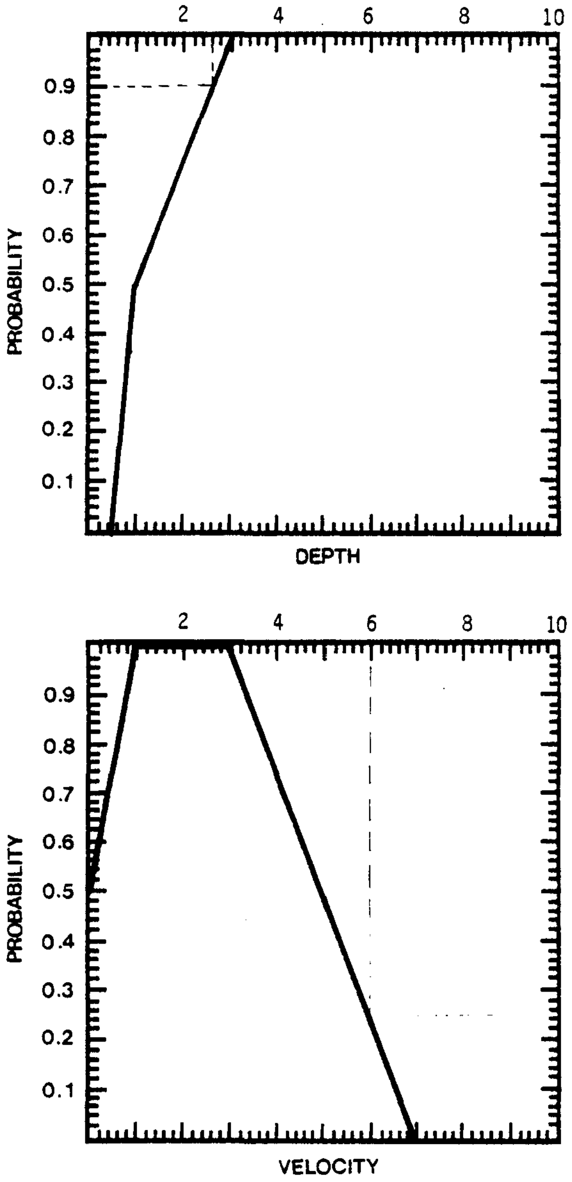

Figure 1. Probability-of-use curve for stream fishing (boat non-power) in relation to depth and velocity.

Table 3. Total surface area of stream and (weighted usable surface area) for a hypothetical recreation activity in square feet.

Depth (ft) and (Probability-of-use)	Velocity in feet per second and (probability-of-use)				
	<0.5 (1.0)	0.5-1.0 (0.8)	1.0-1.5 (0.4)	>1.5 (0)	Total
<1 (0)	500 (0)	400 (0)	100 (0)	0 (0)	1,000 (0)
1-2 (0.3)	600 (180)	700 (168)	800 (96)	300 (0)	2,400 (444)
2-3 (0.8)	100 (80)	300 (192)	500 (160)	100 (0)	1,000 (432)
>3 (1.0)	0 (0)	0 (0)	100 (40)	0 (0)	100 (40)
Totals	1,200 (260)	1,400 (360)	1,500 (296)	400 (0)	4,500 (916)

A separate matrix is required for each recreation activity being considered. A separate matrix is also developed for each of a number of different flows and a different weighted usable surface area is calculated for each flow. Comparison of the matrices provides information on the "best flow" or shows the change in weighted usable surface area due to a change in flow.

RECREATION CRITERIA FOR THE INCREMENTAL METHOD

Recreation activity definitions and a discussion of criteria are presented below.

Minimum and Maximum Criteria

Criteria, as discussed in this section, refer to the parameters of depth and velocity, and deal with the minimum and maximum values. The assumption is made that the recreation activity in question cannot be engaged in outside of the range described by the minimum and maximum values. Optimum values are determined in a somewhat different manner and will be discussed later. Minimum and maximum criteria are of two major types: (1) physical criteria and (2) safety criteria. Regarding physical criteria, recreation activities have certain physical or absolute limits or requirements which must be met (i.e., a boat requires a certain minimum depth of water to float). In the case of safety criteria there are no absolutes; however, it can generally be stated that certain depths or velocities may be unsafe for the average participant. Safety criteria may also be considered a preferred physical limitation.

Optimum Criteria

Minimum and maximum criteria are used to establish the range of depths and velocities which provide a usable surface area for river recreationists. It is also possible to identify a preferred depth or velocity or range of preferred depths and velocities which could be called optimum. Obviously, optimum will not be agreed upon by all recreationists since they represent such a heterogeneous group. However, the total range can be narrowed and a preferred range established. An optimum value of depth or velocity or a preferred range of depths and velocities will be that value or range of values which is usable to the largest number of potential participants.

There are "psychological" criteria that also might be used for selecting optimum depths or velocities. Psychological criteria relate to the quality of the experience. However, in order to evaluate the quality of the experience, one must determine what experience is sought. A number of the recreation activities included in this report have expectations that appear to be unrelated to flow. Therefore, for such activities only the physical and safety criteria need to be considered. Other activities have flow-related expectations and it appears that the experience desired and expected should be a part of the criteria. According to Schreyer and Nelson (1978) the "white water" activities, have an "action-excitement" expectation, and certain types of water are necessary to realize that expectation. Stream depths and/or velocities which produce action-excitement are not easily identified because of the differing skill levels and experience of recreationists. Consequently, psychological criteria, in terms of depth or velocity, are not listed at this time.

The activities which have action and excitement as an expectation are the last four activities listed under boating (below). However, not all of the persons who engage in these activities seek action and excitement. Therefore, a wide range of optimum velocity values is necessary to include the action excitement expectation as well as the other expectations. Each of these four activities may be viewed as two separate activities, one which occurs on tranquil water and one which occurs on non-tranquil water.

Recreation Activities

The stream-oriented recreation activities considered in this report are shown below:

Fishing	Water Contact	Boating
Wading	Swimming	Sailing
Boat, power	Wading	Low power
Boat, nonpower	Water skiing	High power
		Canoeing-Kayaking
		Rowing-rafting-drifting
		Tubing-floating

Definitions

Fishing
Wading: fishing while walking in the stream.
Boat power: fishing from a power boat.
Boat nonpower: fishing from a nonpower boat.

Water Contact
Swimming: propelling oneself through the water with no, or only occasional, contact with the bottom.
Wading: walking in the water, including water play.
Water skiing: being towed behind a boat on skiis.

Boating
Sailing: wind powered boating.
Low power: power boating, motor less than 50 horsepower.
High power: power boating, motor greater than 50 horsepower.
Canoeing-kayaking: using a canoe or kayak in a river.
Rowing-rafting-drifting: using a row boat, raft, or drift boat in a river.
Tubing-floating: floating on a device which is not a full-sized boat or raft. May include inner tubes, small rafts, air mattresses, etc. This activity is also a water contact activity. It is placed here for its similarity to rowing-rafting-drifting.

PROBABILITY-OF-USE CURVES

Development of recreation probability-of-use curves builds upon the recreation criteria discussed in the previous section. Minimum, maximum, and optimum criteria are translated into probablities-of-use and recreation probability curves are developed.

The recreation criteria may be graphed with depth (or velocity) on the X axis and the desirability of certain depths for the recreation activity in question along the Y axis (Figure 2).

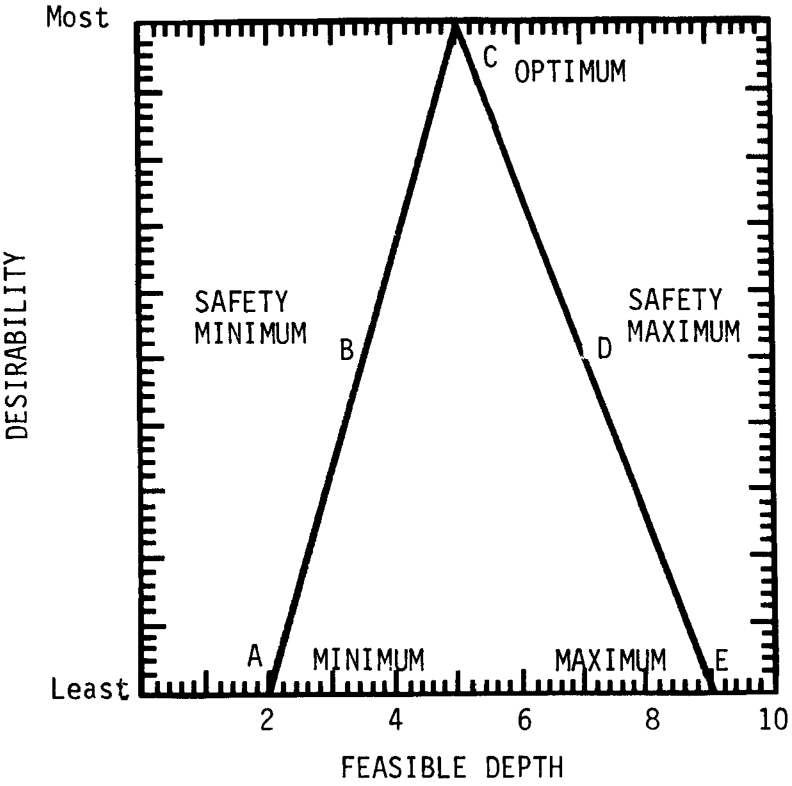

Figure 2. Desirability of stream depth graph for a hypothetical recreation activity.

The physical minimum is shown on the graph as "A" and is the least desirable depth at which the activity is possible. Preferred low flows are the least depth at which the activity can be participated in safely is shown as "B" on the graph. Safety values are somewhat arbitrary because they depend upon experience and skill of the recreationist. In this context, it is assumed that it is an average figure, and that up to 50 percent of the potential participants will find depths between "A" and "B" usable. Point "C" on the graph indicates the most desirable or optimum depth and it is assumed that 100 percent of the potential participants would find such a depth usable. Point "D" indicates the preferred or safety maximum and "E" indicates the physical maximum.

If the Y axis is changed from a desirability scale to a probability scale, with 1.0 on top and 0 on the bottom, the "probability-of-use" may be read off the Y axis.

If Figure 2 represents a probability-of-use curve for an activity in a region where the resource is experiencing capacity use, then the following assumptions can be stated:

1. Areas having depths less than "A" or greater than "E" will have no use.

2. Areas having depths equal to "C" will be experiencing capacity use.

3. Areas having depths equal to "B" and "D" will be experiencing 50 percent of the use of area "C."

Appendix A sets forth the depth and velocity criteria in tabular and graphic forms and defines depths and velocities in terms of desirability as follows:

Optimum	Depth or velocity usable by all; probability-of-use or weighting factor 1.0
Acceptable	Depth or velocity between safety limit and optimum; probability-of-use or weighting factor 0.5-0.99
Marginal	Depth or velocity between physical and safety limits; probability-of-use or weighting factor 0.01-0.49
Unacceptable	Depth or velocity unusable; probability-of-use or weighting factor 0.0

Appendix B shows the probability-of-use curves which are developed from the depth and velocity criteria.

APPLICATION

There are situations where the single cross section method or the incremental method is best suited to do instream flow studies.

The single cross section approach is best suited to situations where:

1. A minimum of time is available.
2. A low flow recommendation is all that is necessary.
3. The low flow recommendation will be exceeded for most of the recreation season.

The incremental method is best suited to situations where:

1. Increments of flow need to be analyzed.
2. The change in streamflow needs to be related to change in recreation potential.
3. The most "exact" answer, available with today's state-of-the-art, is desired.

Opportunities for preserving instream flows for recreation may occur within several programs and processes. Planners did not always take advantage of these opportunities in the past because no method existed by which to quantify the instream flow need.

Opportunities exist within the State water adjudication procedures wherein all water rights will be adjudicated including the Federal reserved rights. When the purpose of the Federal reservation of land includes recreation, the quantity of water necessary to accomplish the purpose must be quantified, and this includes the instream flow required.

Both Federal and State wild and scenic river programs contain language that may be used to preserve instream flows for recreational or aesthetic purposes. The licensing and relicensing procedures of the hydroelectric utility companies call for exhibits to be prepared which describe the recreation resource and the benefits to the public from such a license or project.

Whenever a water project is proposed the impact of the project on recreation is studied. The incremental method will permit the stream portion of such analysis to take its place alongside the reservoir portion.

Use of the incremental method will permit full consideration of recreation by water management agencies as they make decisions about water allocation, conduct hearings for diversion permit requests, or determine low flows.

In general, whenever proposals are made which will change an existing streamflow or flow regime, the impact upon recreation can be determined and be considered in the planning process.

LIMITATIONS

The limitations of the methods discussed in this paper should be understood prior to field testing.

The single cross section is limited to making minimum flow recommendations to accommodate the boating recreation activities. It is less exact than the incremental method and the location of the cross sectional measurement is critical.

The incremental method may be used to describe the impact of a change in flow or used to identify an optimum flow. However, there is no such thing as an optimum flow or flow regime for recreation. Each recreation activity has its own unique flow requirement and frequently flow requirements conflict among activities. For example, a greater flow resulting in higher velocities may benefit the white water boaters, but would all but eliminate fishing while wading. Usually a flow recommendation would be provided in terms of a flow regime. The recommendation of a flow regime would recognize the variable supply of water throughout the year as well as the periods of greatest demand for instream water. A flow regime for recreation would take into account the greater recreation demand during the recreation season, during the weekends, and perhaps even during the daylight hours.

Use of the incremental method can provide only a measure of recreation potential and cannot provide adequate information for developing a recommended flow regime based on the demand for recreation. If such a recommendation is necessary, or if knowledge of a change in recreation use or benefits, due to a change in flow, is desired, a demand-supply study should be undertaken. A demand-supply study would use the output from the incremental method as the supply component.

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1. Schreyer, Richard and Martin L. Nelson. 1978. Westwater and Desolation Canyons: Whitewater River Recreation Study. Institute for the Study of Outdoor Recreation and Tourism. Utah State Univ., Logan, UT. 164 pp.

INSTREAM FLOW INFORMATION PAPERS ISSUED

1. Lamb, Berton Lee, Editor. Guidelines for Preparing Expert Testimony in Water Management Decisions Related to Instream Flow Issues. Fort Collins, Colorado, Cooperative Instream Flow Service Group, July 1977, 30 pages. (NTIS Accession Number: PB 268 597; Library of Congress Catalog Card No. 77-83281).

2. Lamb, Berton Lee, Editor. Protecting Instream Flows Under Western Water Law: Selected Papers. Fort Collins, Colorado, Cooperative Instream Flow Service Group, September 1977, 60 pages. (NTIS Accession Number: PB 272 993; Library of Congress Catalog Card No. 77-15286).

3. Bovee, Ken D., and Cochnauer, Tim. Development and Evaluation of Weighted Criteria, Probability-of-Use Curves for Instream Flow Assessments; Fisheries. Fort Collins, Colorado, Cooperative Instream Flow Service Group, December 1977, 49 pages. (NTIS Accession Number: PB ; Library of Congress Catalog Card No. -).

4. Bovee, Ken D. Probability-of-Use Criteria for the Family Salmonidae. Fort Collins, Colorado, Cooperative Instream Flow Service Group, January 1978, 88 pages. (NTIS Accession Number: PB : Library of Congress Catalog Card No. -).

5. Milhous, Robert R. and Ken D. Bovee. Hydraulic Simulation in Instream Flow Studies: Theory and Techniques. Fort Collins, Colorado, Cooperative Instream Flow Service Group, May 1978, pages. (NTIS Accession Number: PB ; Library of Congress Catalog Card No. -).

6. Hyra, Ronald. Methods of Assessing Instream Flows for Recreation. Fort Collins, Colorado, Cooperative Instream Flow Service Group, May 1978, 49 pages. (NTIS Accession Number: PB ; Library of Congress Catalog Card No. -).

APPENDIX A

CRITERIA DEVELOPMENT

Sources of Information Used to Develop the Criteria of Appendix A:

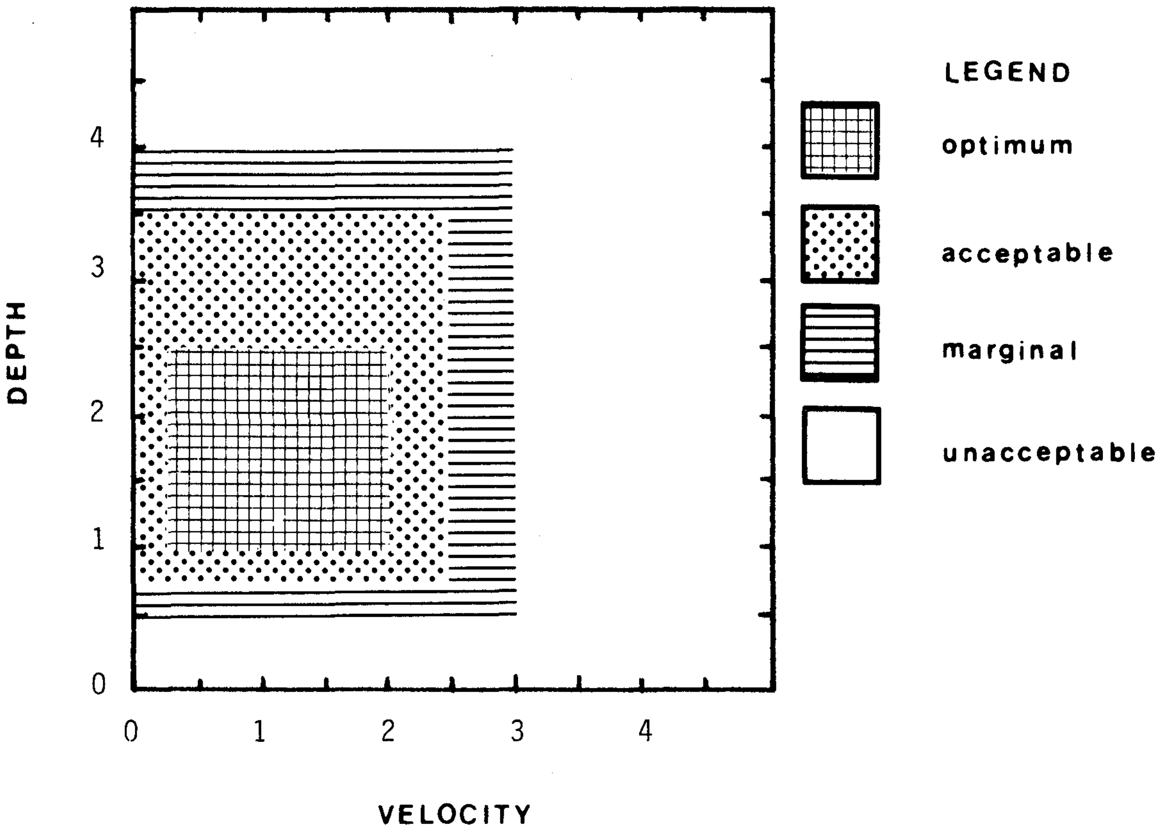
1. Christiansen, M.L. 1975. Development of Resource Requirements Determinants for Selected Activities. Watershed Recreation Research Report.
2. Scott, J. and R. Hyra. 1977. Methods for Determining Instream Flow Requirements for Selected Recreational Activities in Small and Medium Sized Streams. Paper presented at AWRA Conference, Tucson, Arizona.
3. Thompson, J. and R. Fletcher. 1972. A Model and Computer Program for Appraising Recreational Water Bodies. Department Forest Sci. Utah State Univ., Logan, Utah, pp. 48.
4. U.S. Bureau of Outdoor Recreation. 1977. Recreation and Instream Flow. Volumes 1 and 2, Jasen M. Cortell and Associates, Waltham, Massachusetts. pp.252.
5. U.S Bureau of Outdoor Recreation. 1977. Resource Requirements for Water Related Recreation. S.E. Regional Office. Draft Report. pp. 15.
6. U.S. Corps of Engineers. 1963. Channel Improvement for Navigation Snake River Downstream From Weiser, Idaho. Detailed Project Report. pp. 77.

FISHING WADING

CRITERIA

	PHYSICAL	SAFETY	OPTIMUM
DEPTH			1.0-2.5 ft
minimum	0.5 ft	0.75 ft	
maximum	4.0 ft	3.50 ft	
VELOCITY			0.25-2.0 fps
minimum	0.0 fps	0.0 fps	
maximum	3.0 fps	2.5 fps	

COMMENTS: Depth in ft multiplied by velocity in fps should equal 10 or less. Safety depends upon height and weight of individual as well as substrate type.

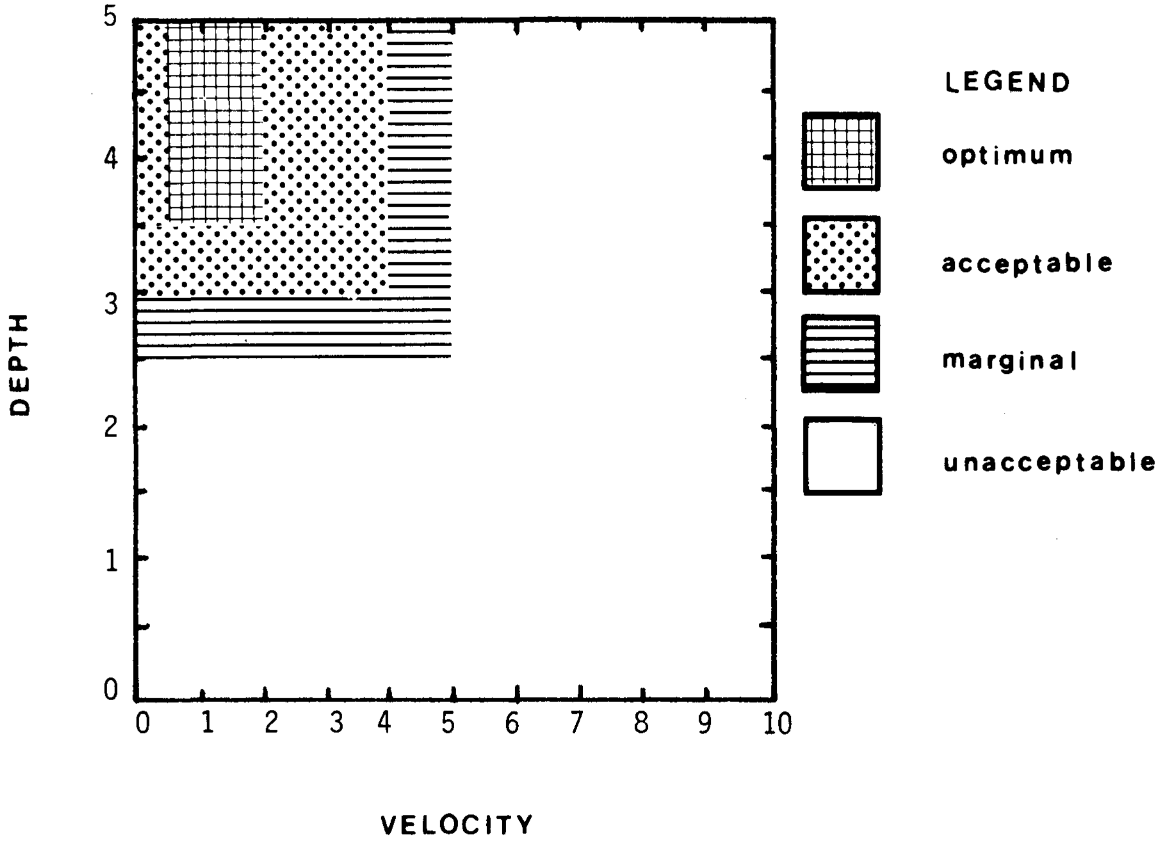


FISHING BOAT POWER

CRITERIA

	PHYSICAL	SAFETY	OPTIMUM
DEPTH			3.5 ft +
minimum	2.5 ft	3.0 ft	
maximum	NA	NA	
VELOCITY			0.5-2.0 fps
minimum	0 fps	0 fps	
maximum	5 fps	4 fps	

COMMENTS: Size of boat and motor important. Generally includes boats of low power.

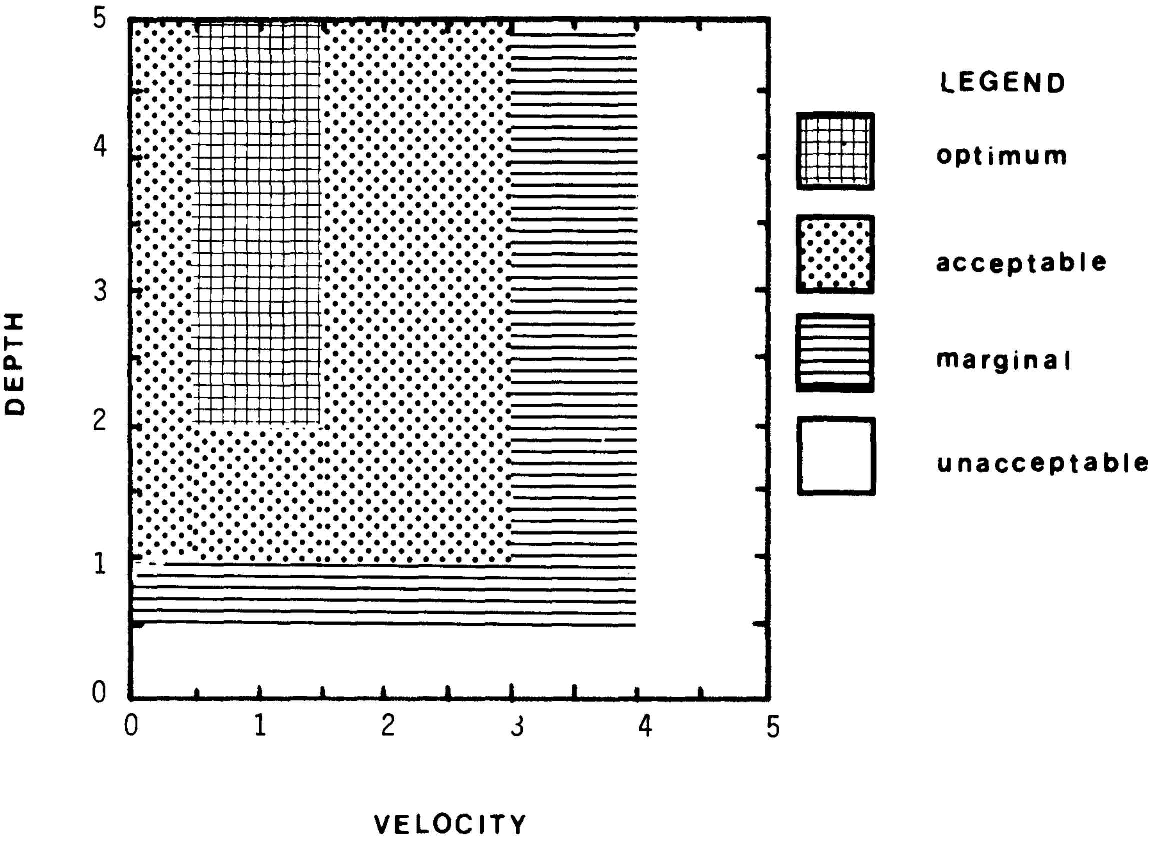


FISHING BOAT NON-POWER

CRITERIA

	PHYSICAL	SAFETY	OPTIMUM
DEPTH			2.0 ft +
minimum	0.5 ft	1.0 ft	
maximum	NA	NA	
VELOCITY			0.5-1.5 fps
minimum	0 fps	0 fps	
maximum	4 fps	3 fps	

COMMENTS: Type boat important.

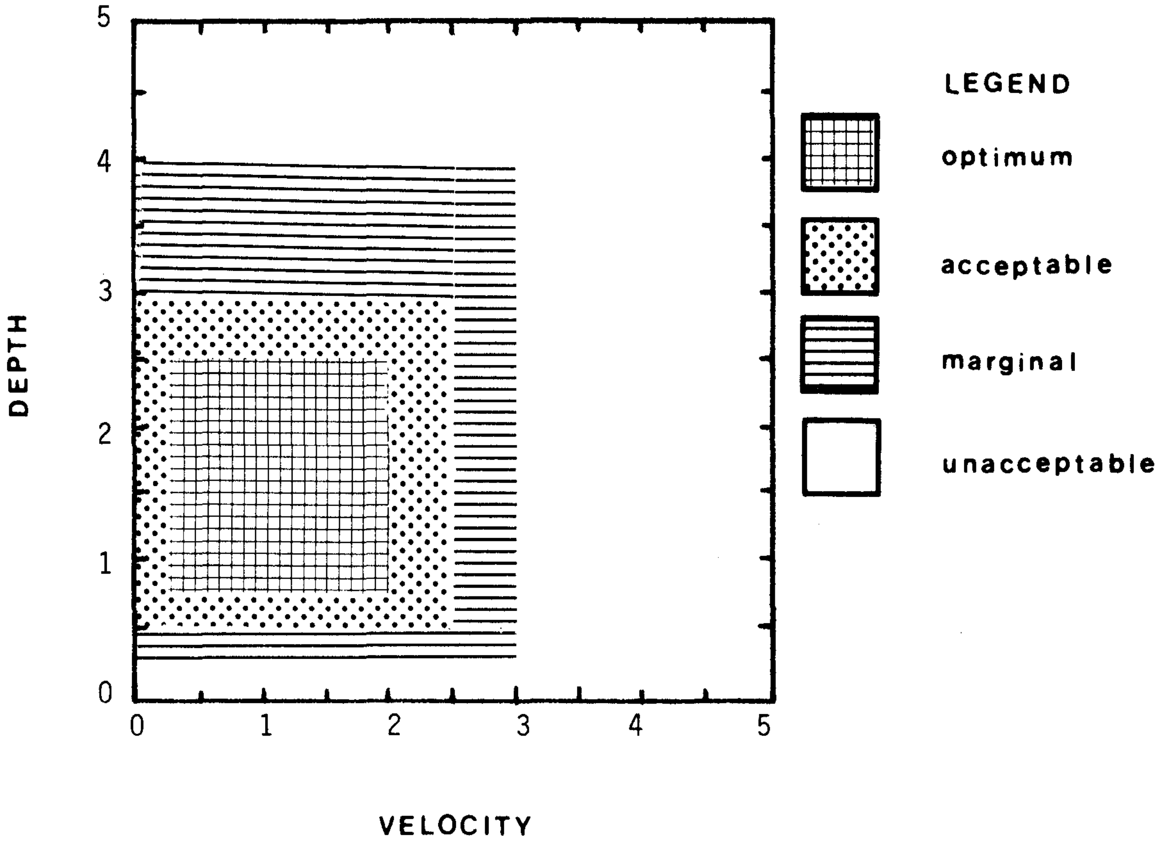


WATER CONTACT WADING

CRITERIA

	PHYSICAL	SAFETY	OPTIMUM
DEPTH			0.75-2.5 ft
minimum	0.25 ft	0.5 ft	
maximum	4.0 ft	3.0 ft	
VELOCITY			0.25-2.0 fps
minimum	0 fps	0 fps	
maximum	3.0 fps	2.5 fps	

COMMENTS: Depth in feet multiplied by velocity in fps should equal 10 or less. Saftey depends upon height and weight of individual as well as substrate type.

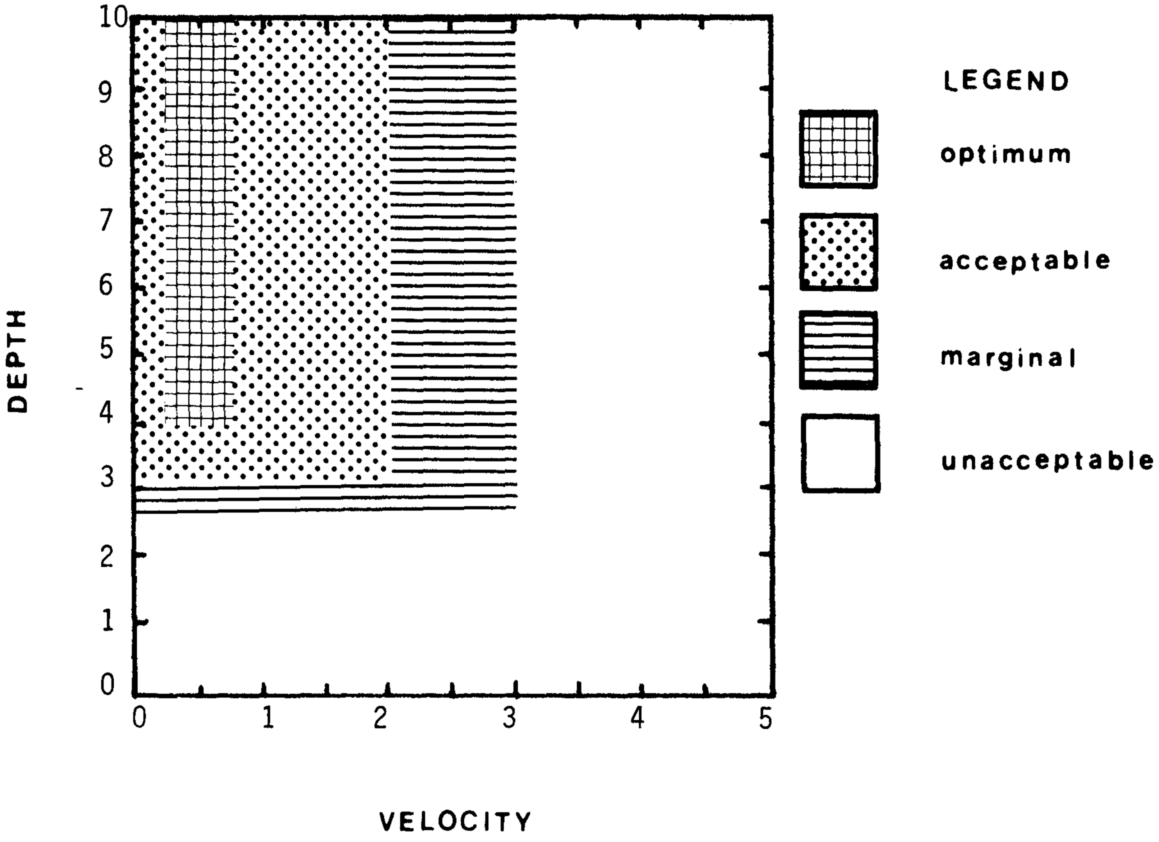


WATER CONTACT SWIMMING

CRITERIA

	PHYSICAL	SAFETY	OPTIMUM
DEPTH			4 ft +
minimum	2.5 ft	3.0 ft	
maximum	NA	NA	
VELOCITY			0.25-0.75 fps
minimum	0 fps	0 fps	
maximum	3.0 fps	2.0 fps	

COMMENTS: Water quality, temperature, slope of beach, visibility and underwater slope important. Depth safety criteria does not permit diving.

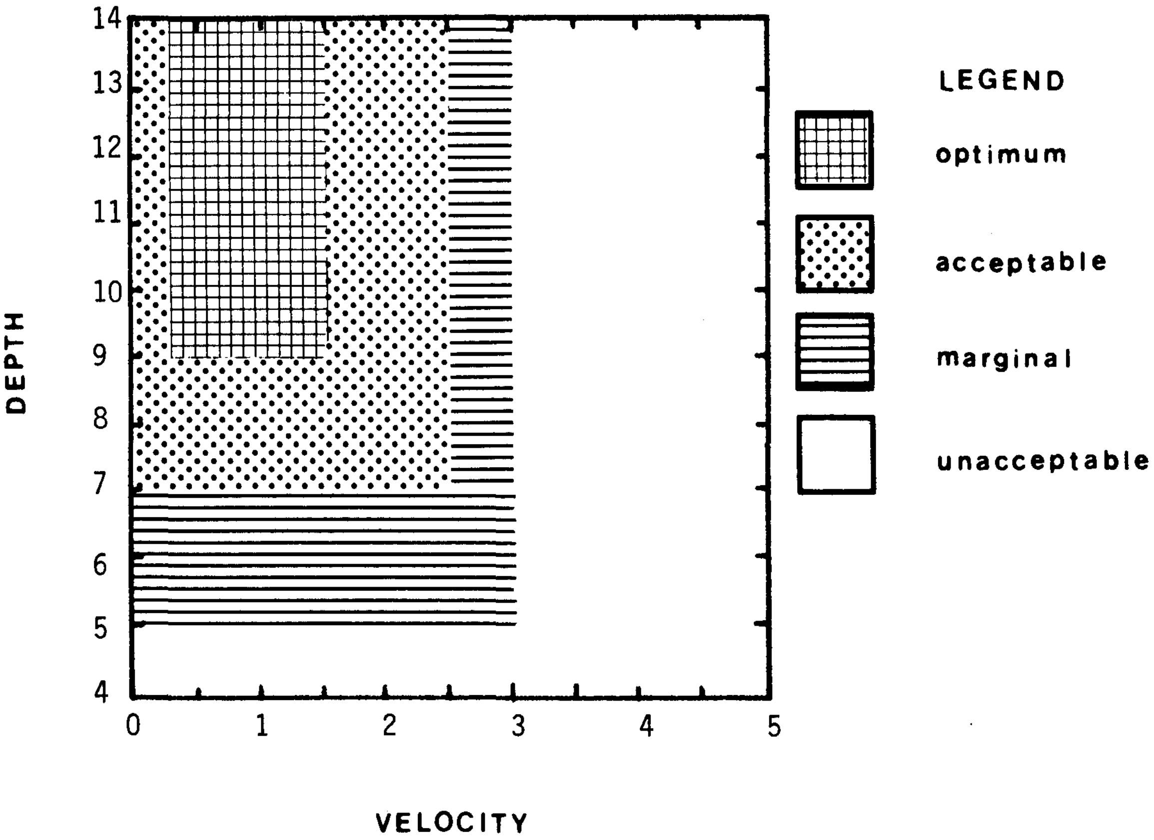


WATER CONTACT WATER SKIING

CRITERIA

	PHYSICAL	SAFETY	OPTIMUM
DEPTH			9 ft +
minimum	5 ft	7 ft	
maximum	NA	NA	
VELOCITY			0.25-1.5 fps
minimum	0 fps	0 fps	
maximum	3.0 fps	2.5 fps	

COMMENTS: Width is critical also.

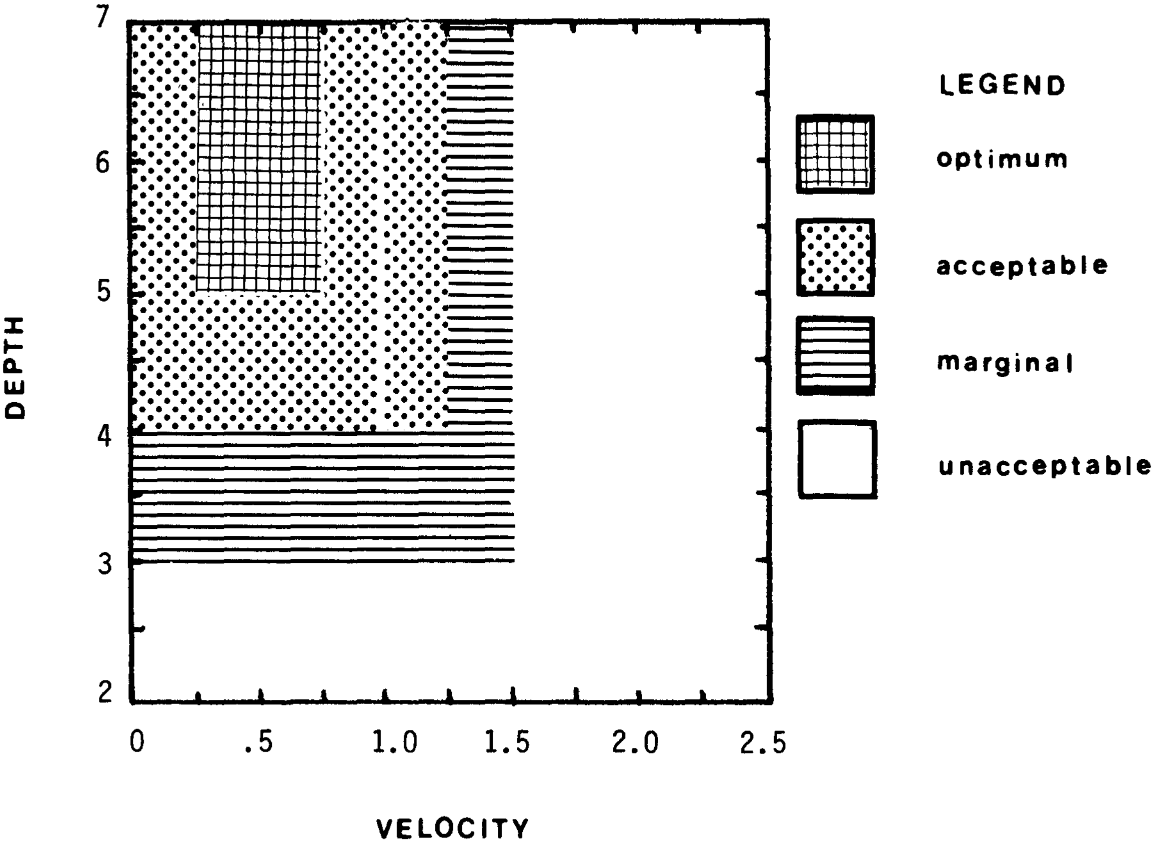


BOATING SAILING

CRITERIA

	PHYSICAL	SAFETY	OPTIMUM
DEPTH			5 ft +
minimum	3 ft	4 ft	
maximum	NA	NA	
VELOCITY			0.25-0.75 fps
minimum	0 fps	0 fps	
maximum	1.5 fps	1.25 fps	

COMMENTS: Keel or centerboard depth is critical.

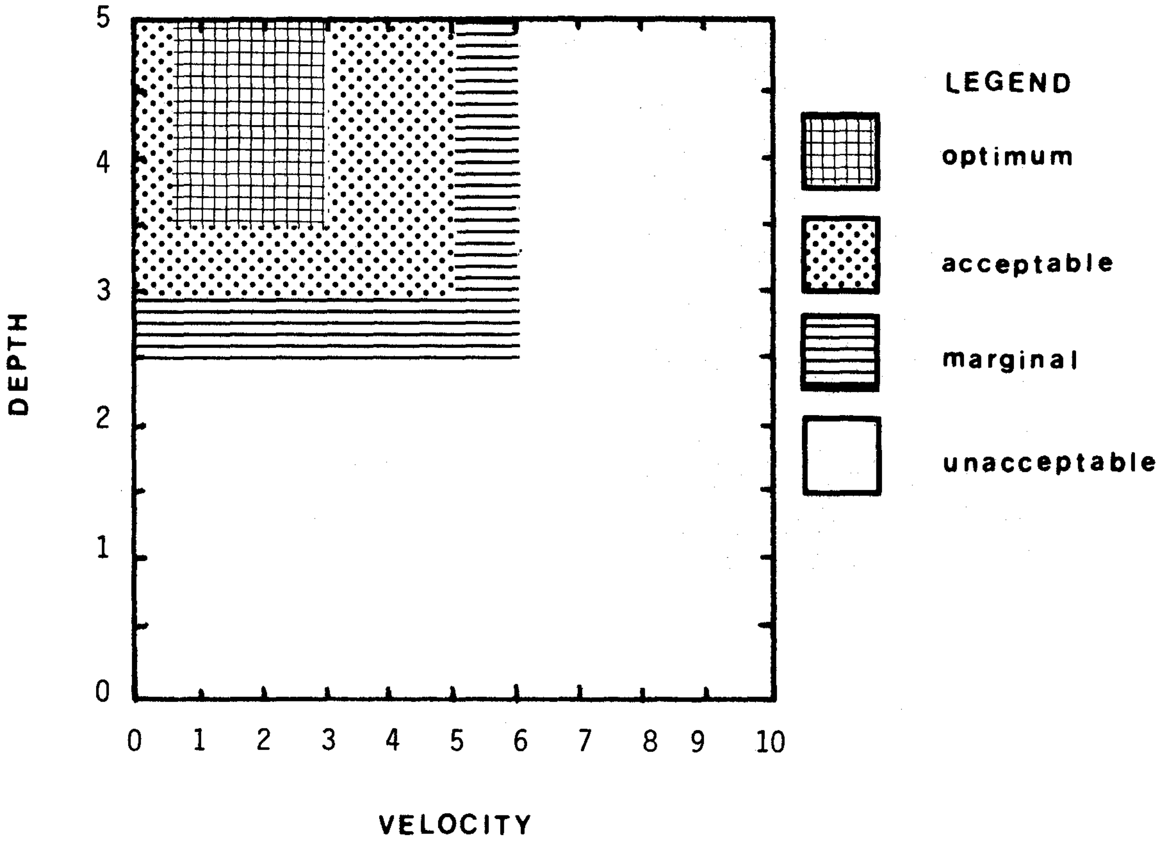


BOATING LOW POWER

CRITERIA

	PHYSICAL	SAFETY	OPTIMUM
DEPTH			3.5 ft +
minimum	2.5 ft	3.0 ft	
maximum			
VELOCITY			0.5-3.0 fps
minimum	0 fps	0 fps	
maximum	7 fps	6 fps	

COMMENTS: Low power boats are less than 50 hp.

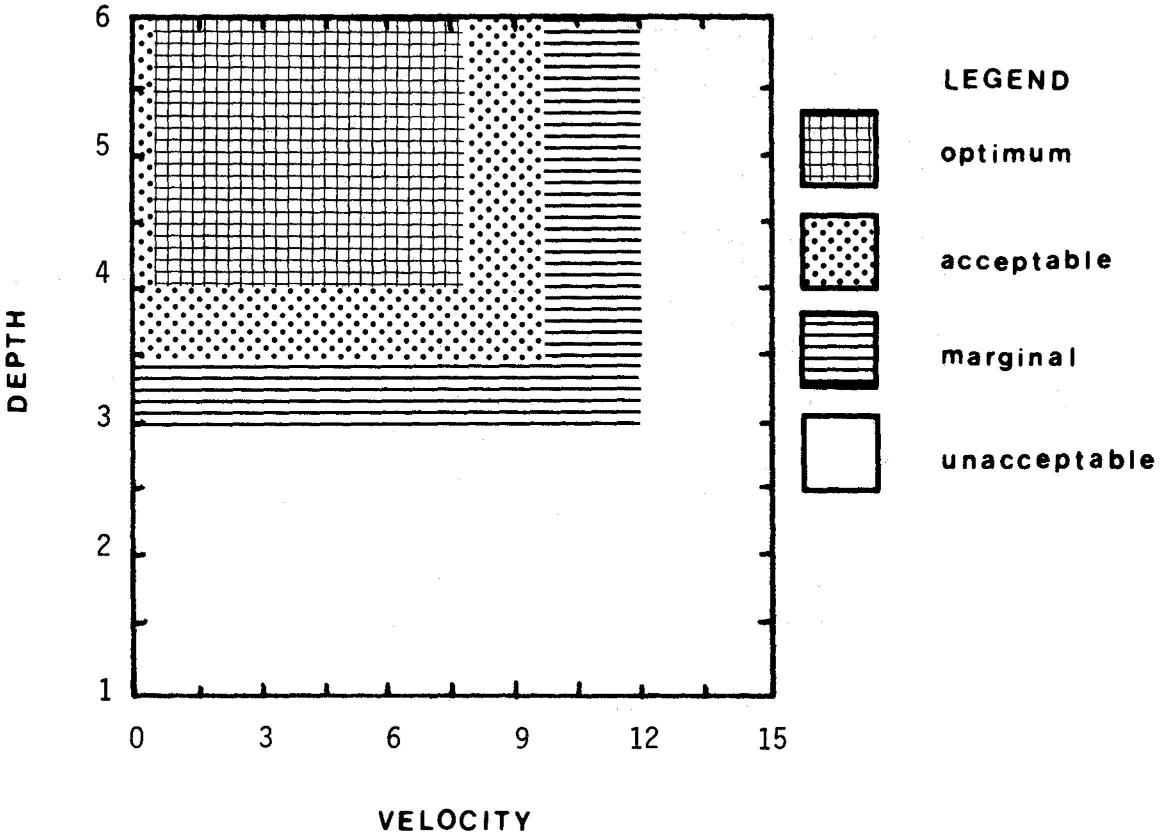


BOATING HIGH POWER

CRITERIA

	PHYSICAL	SAFETY	OPTIMUM
DEPTH			4.0 ft +
minimum	3.0 ft	3.5 ft	
maximum	NA	NA	
VELOCITY			0.5-8.0 fps
minimum	0 fps	0 fps	
maximum	12.0 fps	10.0 fps	

COMMENTS: High power is greater than 50 hp. Jet boats or sleds require only 1.0 ft ± water depth. Higher velocities safe only under certain conditions.

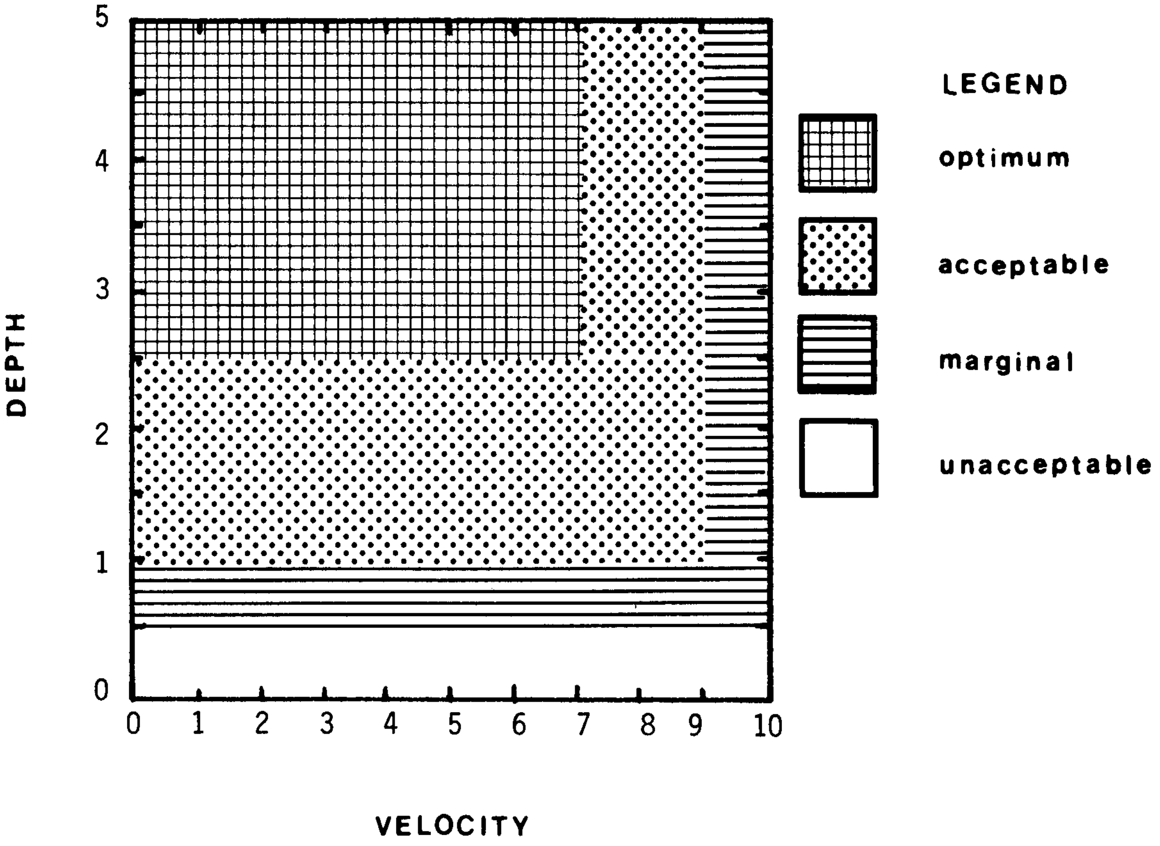


BOATING CANOEING-KAYAKING

CRITERIA

	PHYSICAL	SAFETY	OPTIMUM
DEPTH			2.5 ft +
minimum	0.5 ft	1.0 ft	
maximum	NA	NA	
VELOCITY			0.5-7.0 fps
minimum	0 fps	0 fps	
maximum	10.0 fps	9.0 fps	

COMMENTS: Higher velocities exclude open canoes. Higher velocities safe only under certain conditions.

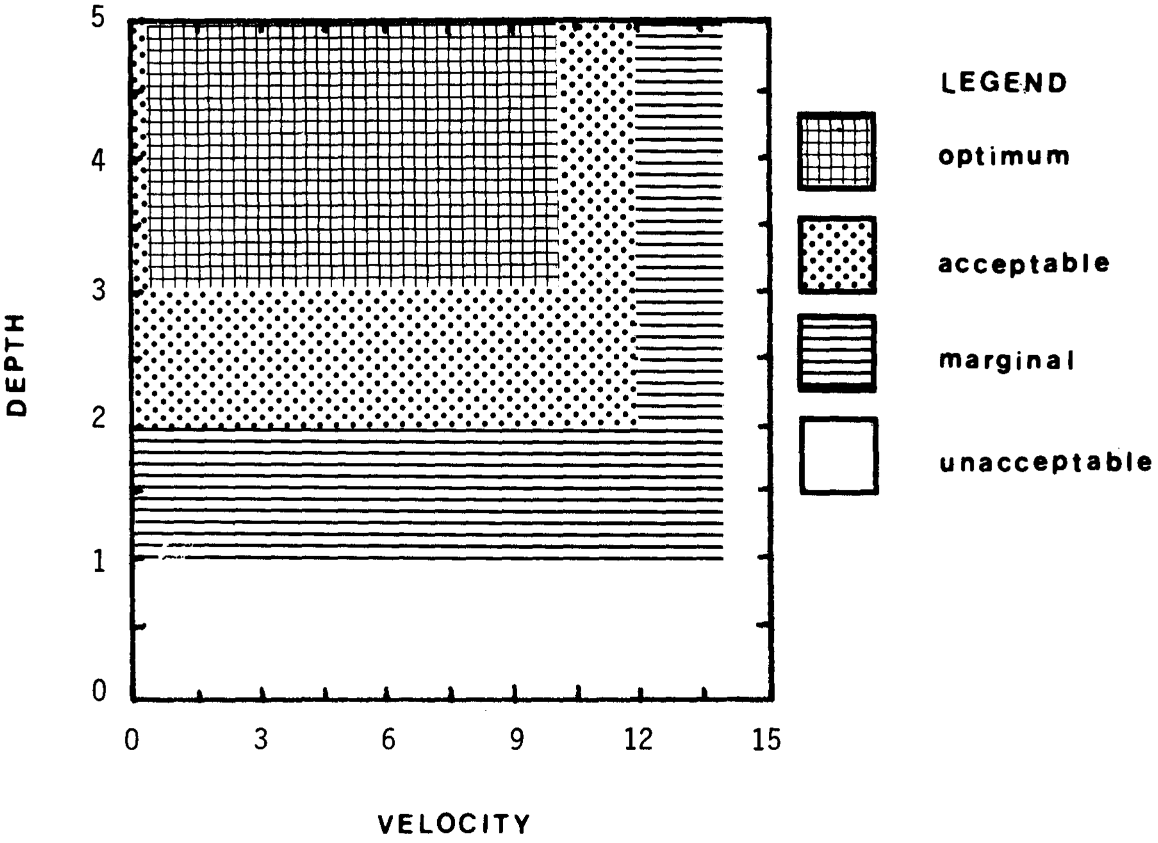


BOATING ROWING-RAFTING-DRIFTING

CRITERIA

	PHYSICAL	SAFETY	OPTIMUM
DEPTH			3.0 ft +
minimum	1.0 ft	2.0 ft	
maximum	NA	NA	
VELOCITY			1.0-10.0 fps
minimum	0 fps	0 fps	
maximum	14.0 fps	12.0 fps	

COMMENTS: Higher velocities require boats/rafts of a type specifically designed for white water. Higher velocities safe only under certain conditions.

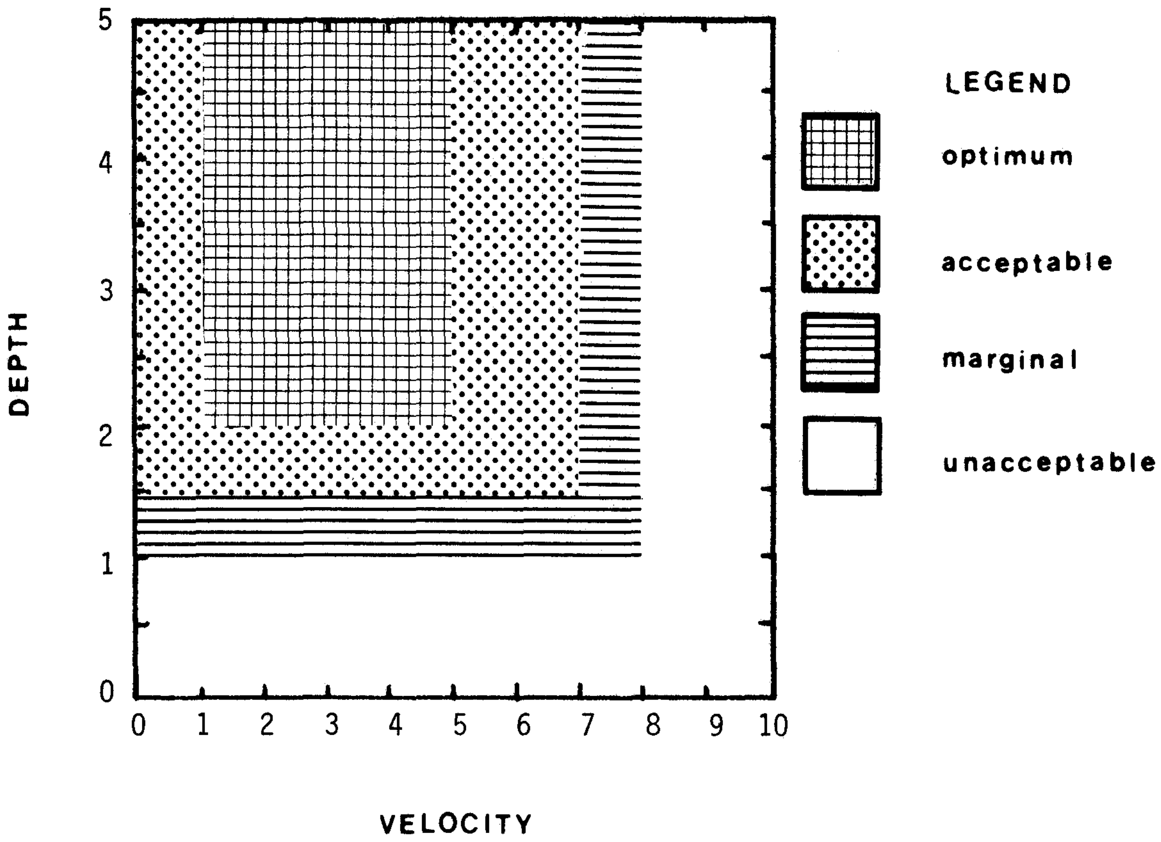


BOATING TUBING-FLOATING

CRITERIA

	PHYSICAL	SAFETY	OPTIMUM
DEPTH			2.0 ft +
minimum	1.0 ft	1.5 ft	
maximum	NA	NA	
VELOCITY			1.0-5.0 fps
minimum	0 fps	0 fps	
maximum	8.0 fps	7.0 fps	

COMMENTS: Higher velocities safe only under certain conditions.



APPENDIX B

PROBABILITY-OF-USE CURVES

FISHING WADING

700000

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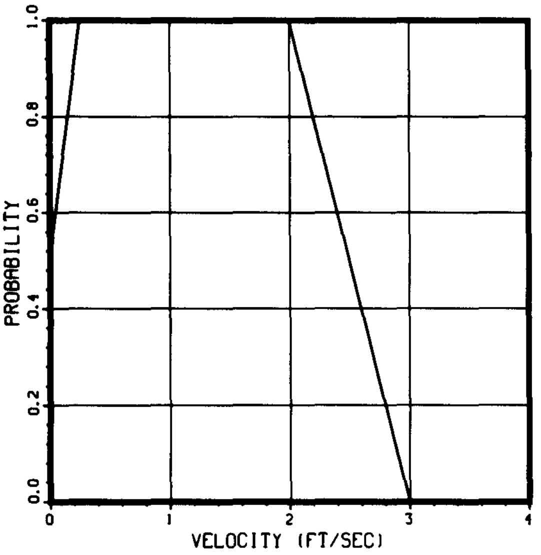
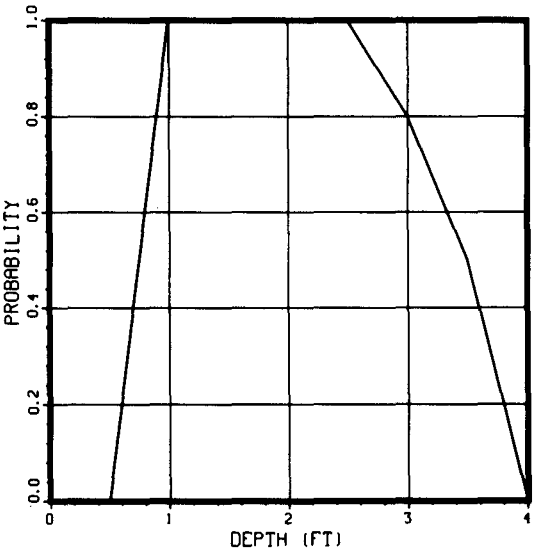
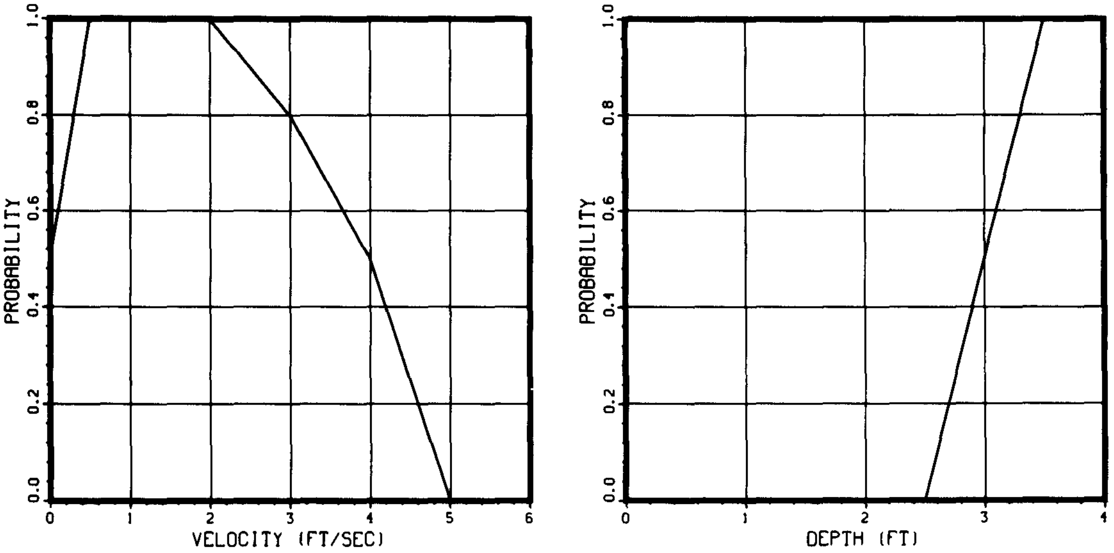




FISHING BOAT POWER

700100

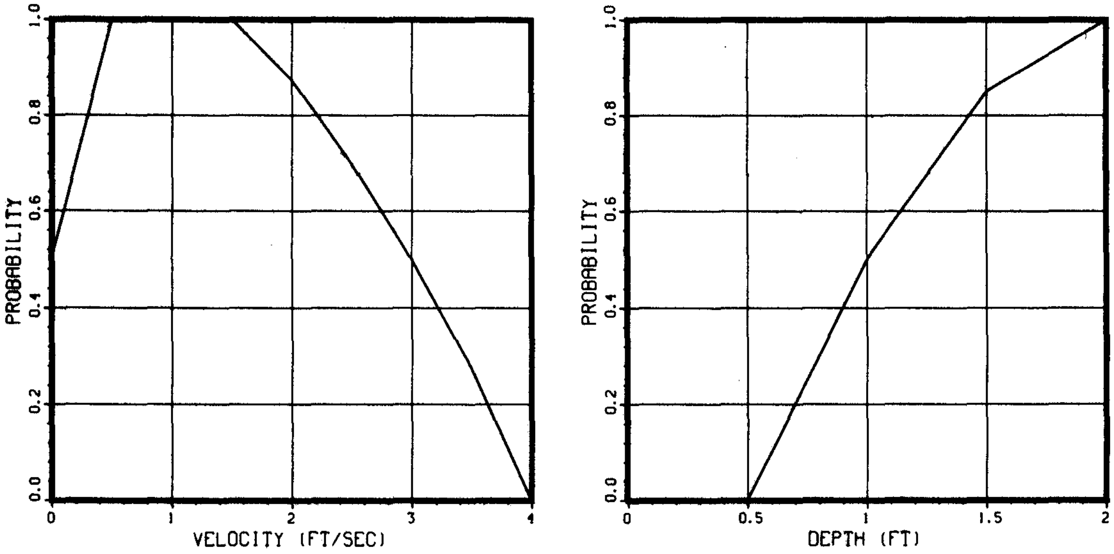
78/06/26.



FISHING BOAT NON POWER

700200

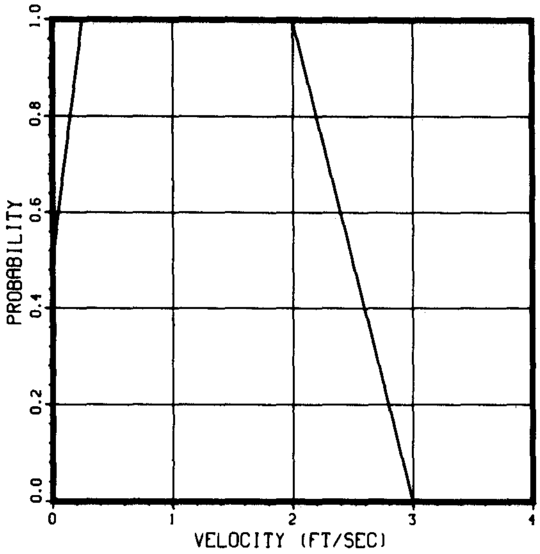
78/06/26.

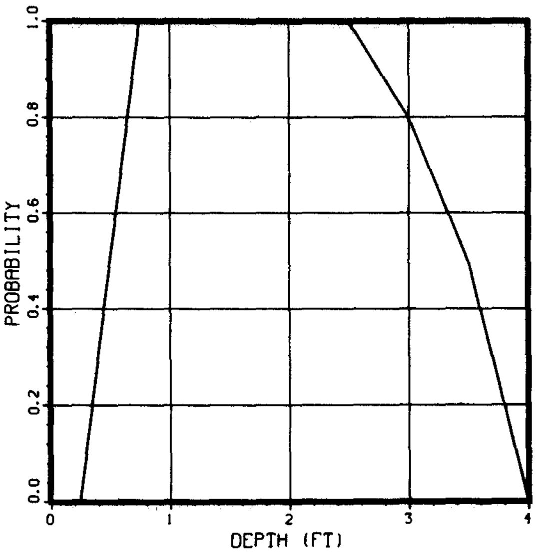


WATER CONTACT WADING

710100

78/06/26.





WATER CONTACT SWIMMING

710000

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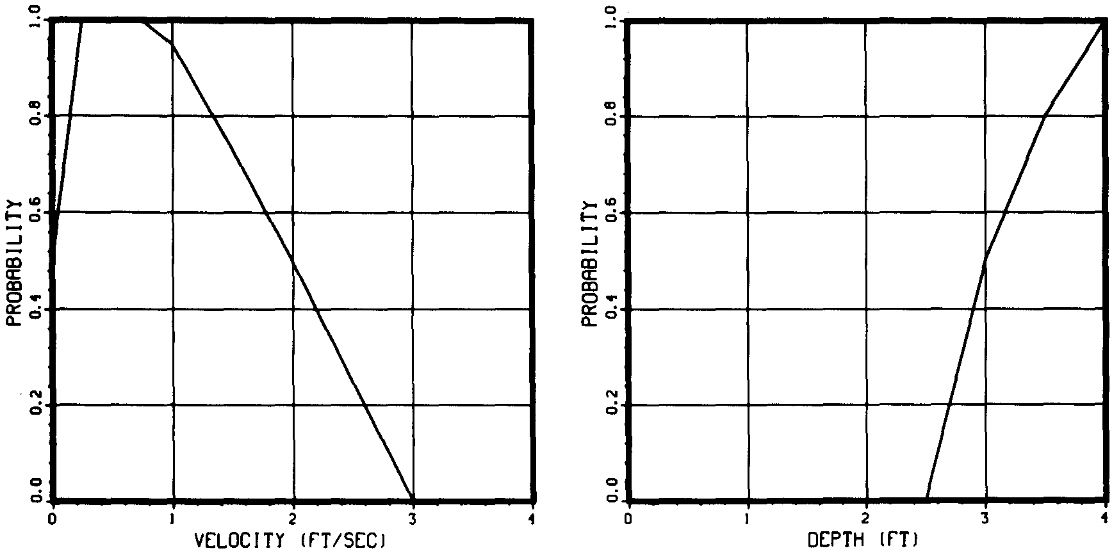

WATER CONTACT WATER SKIING

710200

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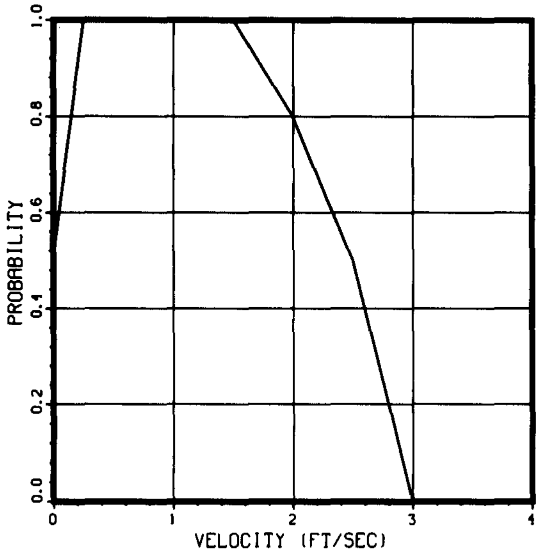
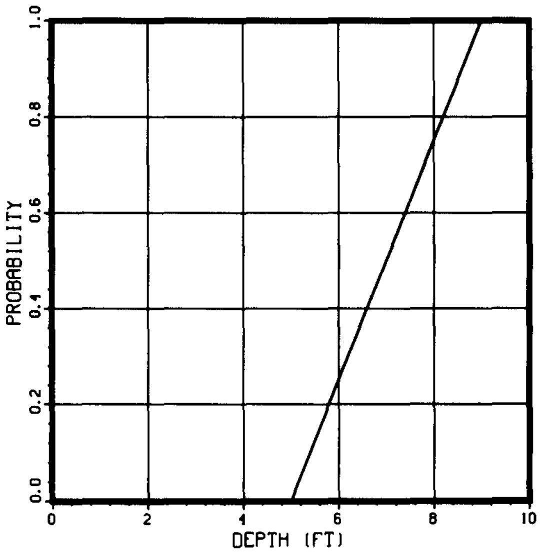
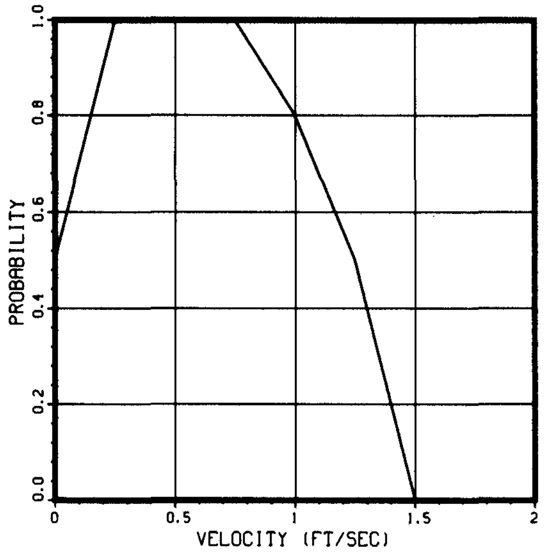
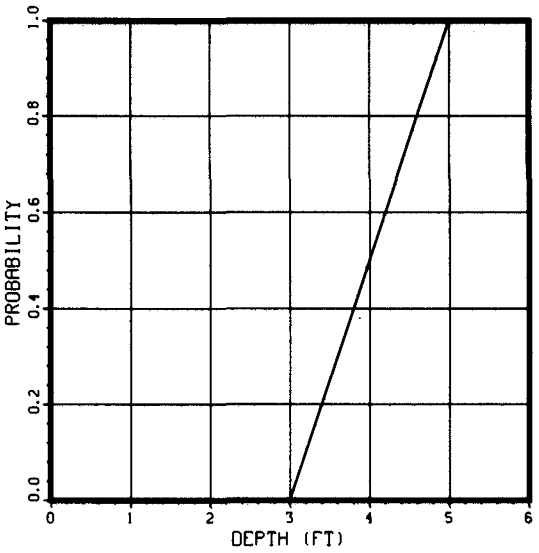




BOATING SAILING

720000 78/06/26.

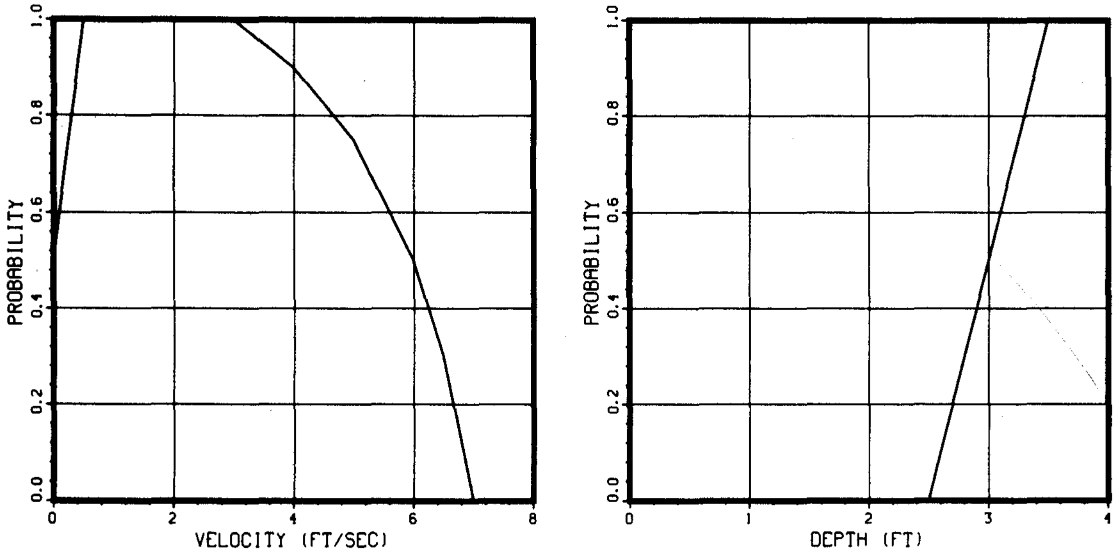




BOATING LOW POWER

720100

78/06/26.



BOATING HIGH POWER

720200

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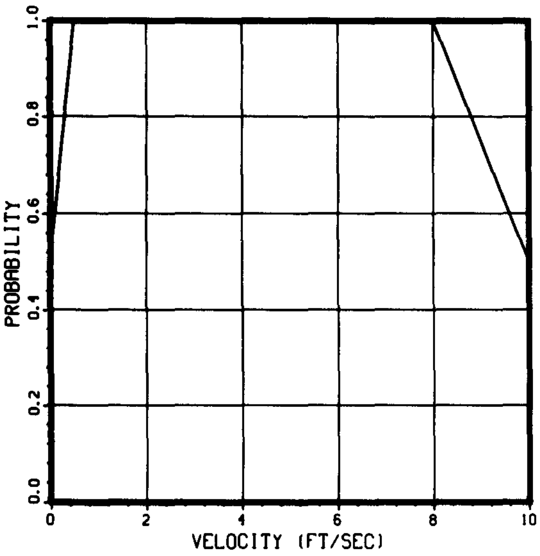
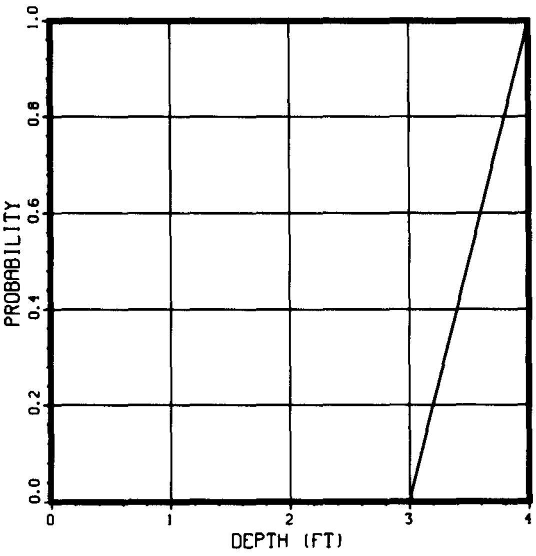


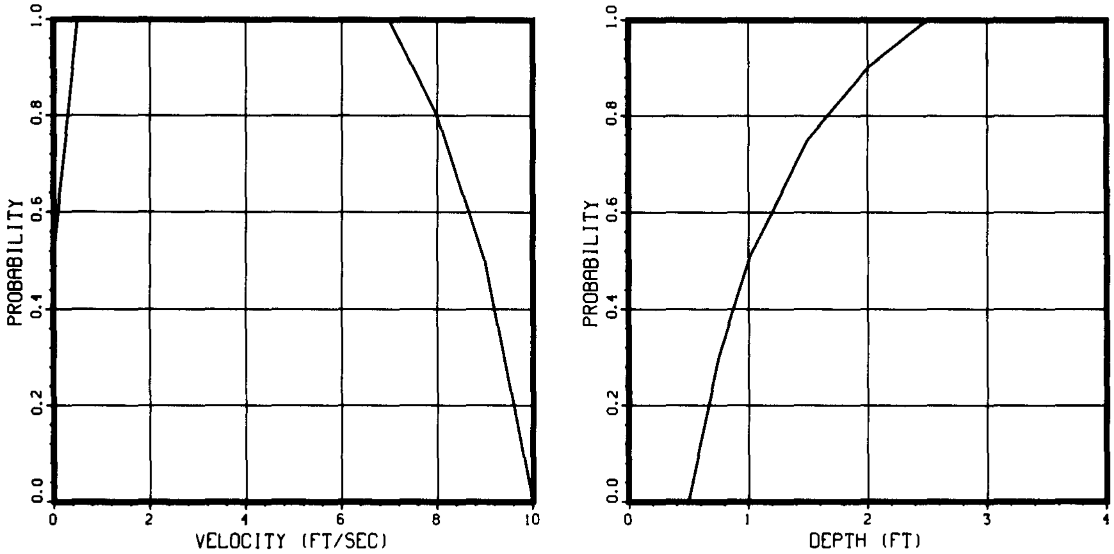


NOTE: Velocity plots have a maximum of 10 fps. The curves for the velocity for this activity reaches a probability of 0.0 at 12 fps.

BOATING CANOEING KAYAKING

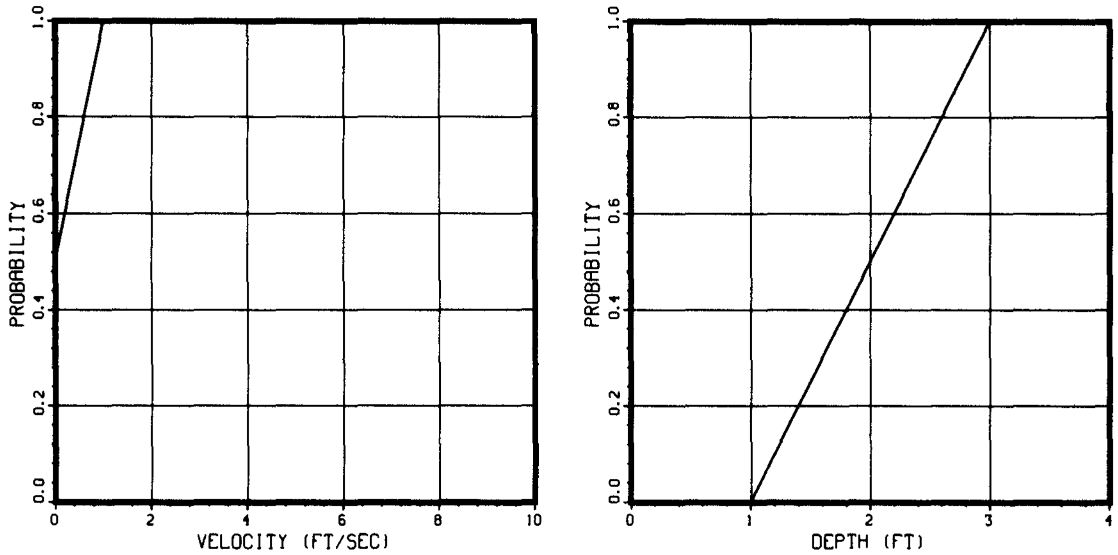
720300

78/06/26.



BOATING ROWING RAFTING DRIFTING

720400 78/06/26.

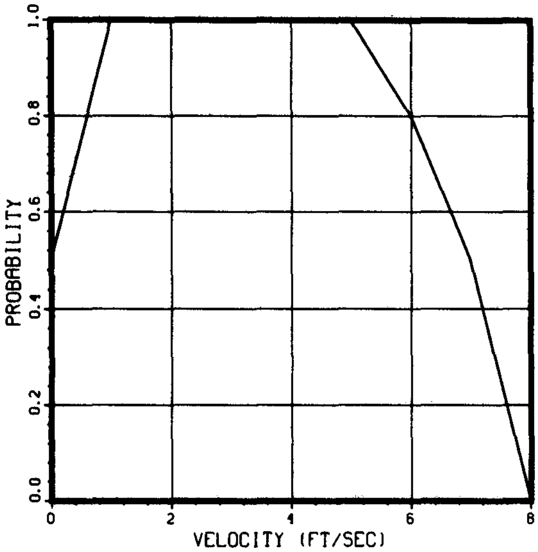


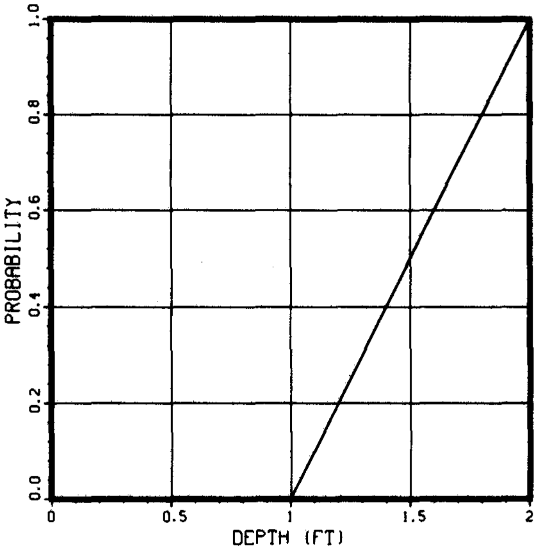
NOTE: Velocity plots have a maximum of 10 fps. The curve for the velocity for this activity is at a probability of 1.0 at 10 fps, a 0.5 probability at 12 fps, and a 0.0 probability at 14 fps.

BOATING TUBING FLOATING

720500

78/06/26.





U. S. Department of the Interior

Fish and Wildlife Service

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March 3, 1849

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U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
PB-275 269

Recreation and Instream Flow. Volume 1 Flow Requirements, Analysis of Benefits, Legal and Institutional Constraints

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Prepared for

Bureau of Outdoor Recreation, Washington, D C

Jul 77

Recreation and Instream Flow

Vol. 1

Flow Requirements
Analysis of Benefits
Legal and Institutional
Constraints

Submitted to

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Bureau of Outdoor Recreation

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JULY 1977

Prepared by

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Waltham Massachusetts

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SECTION 2

THE RELATIONSHIP OF INSTREAM FLOW TO TYPES OF AQUATIC RECREATION

The first step in establishing the flow-to-activity relationship is the setting of the requirements governing recreation activities. These are of two types. First, there are physical criteria which must be met if an activity is to be possible. These can be expressed in terms of width, depth, and velocity. If these conditions are met in a stream, regardless of absolute discharge, then the activity is possible. A second set of criteria helps to determine the desirability of the stream for the activity. These are site and stretch-specific and may or may not be flow related. Examples of this would be the presence of clear, clean water and sandy beaches for swimming or long stretches of water suitable for boating, rather than only a few hundred feet of such water bounded by major rapids or waterfalls.

The second step in this process is to determine the ability of a given stream to meet these requirements as a function of discharge. It is not possible to say in absolute terms that a discharge of so many cfs (cubic feet per second) is suitable for a certain activity. It is possible, however, to say that a discharge of so many cfs is suitable for particular activities in a particular river.

The final step in the process is an analysis of the expected recreation potential on a particular stream as a function of discharge and, ultimately, the recommendation of a flow level, that will support the widest range of recreational uses. This is accomplished by applying the techniques of hydraulic geometry to the stream in question to determine the relationship between stream flow and physical characteristics (width, depth, and velocity). These may then be compared to the physical criteria required by various recreational activities to determine those that may be supported at various stream flows. The stream is then examined for site and stretch characteristics that might either favor or eliminate activities. A determination can thus be made as to the suite of activities compatible with a particular reach of a stream and a definite flow for that suite of activities can be recommended. This recommendation might be in the form of a single flow which maximized a certain suite of activities at all times, or a set of seasonal, monthly, weekly or even daily flows which offer suitable conditions for different suites of activities at different times of the year (e.g. white water canoeing in the spring and swimming, wading, and fishing in the summer).

2.1 FLOW-RELATED REQUIREMENTS FOR RECREATION

For purposes of river evaluation, what is needed is a set of clearly defined physical parameters relating recreational potential to flow. The criteria presented here are intended to meet this need. The data are drawn from a number of sources (primarily Thompson and Fletcher, 1972 and U.S. Dept. of the Interior, Bureau of Land Management, 1972) and modified or extended in some cases. They provide a clear physical description of those conditions in a stream which will support an activity, those which are optimal for the activity, and those which preclude the activity. The main descriptors will be width, depth, and velocity, since these are the main characteristics of a stream which change in response to changing flow. A summary of these is presented in Table 2. Of secondary importance will be those auxiliary conditions which influence the desirability of the activity, such as sand bottoms for swimming; those which might eliminate a physically possible activity, such as a low-flow die-off of fish; and those which might influence the potential market for an activity, such as the presence of a competing, higher quality resource in the immediate area.

2.1.1 Fishing

Fishing depends upon, first, the survival and catchability of desirable species of fish, and second, the ability of fishermen to pursue and capture them. The first requirement has been studied extensively by fisheries departments throughout the nation. Survival conditions are usually specified in terms of a requisite minimum percentage of Average Annual Flow (AAF) to support spawning, hatching, rearing, and passage at appropriate times of the year.

Catchability may also be flow related. The first requirement is that the simple survival criteria of adults of the target species be met. For trout and many other salmonids, these are met if the water is relatively clean, temperatures are less than 60°F to 65°F, and velocities are low enough that the fish can maintain their position in the stream (4 to 8 feet per second). Smallmouth bass will survive in less clean waters and at temperatures into the 90's but may have more limited capacity to deal with high velocity flow. (Stalnaker, 1975)

The willingness of the fish to bite is the other factor which must be considered in catchability. This is perhaps the least understood area in fisheries. The upper bounds for fish catching can be established rather simply. If velocities exceed 5 to 10 feet per second, even strong salmonids are either swept downstream or retreat to sheltered areas (D.L.Tennant, 1975). This may occur for warm water species at about 2 to 4 feet per second. Depth limits the other end of the flow scale. If depths are reduced below six inches, most fish worth catching

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

Maximum Conditions -

For a normal-sized, adult fisherman in chest waders, Depth = 4 feet, Velocity = 2.5 feet. At any lesser depth, the product of depth (ft.) and velocity (ft/sec) should be less than 10. Where the bottom is uneven, rocky, or slippery, the maximum conditions are shifted downward.

Optimum Conditions -

These are determined by the catchability of the species being pursued. The ability of the fisherman to pursue the fish by wading is assured by any flow yielding less than maximum depths and velocities.

2.1.1.2 Boat Fishing

Some assumptions are required to set flow criteria for boating in pursuit of fish. It is assumed that fishing occurs from a canoe or similar shallow draft craft and that power boats are small fishing boats, equipped with a motor of 15 horsepower or less. Canoes, when unpowered, can negotiate (with great difficulty) water as shallow as 3 inches and can turn around in little more than their own length. A limit of 6 inches is more realistic if hang-ups are to be avoided. Paddling, as opposed to poling, becomes possible at a depth of 2 feet. Safety for a fishing party is optimized if the occupants can "walk out" after capsizing, implying a depth of less than five feet. There is no maximum depth for canoeing, but there are maximum velocities. Competent, but not expert, paddlers can handle a canoe effectively in waters as fast as 6 feet per second; at this velocity, backpaddling is just sufficient to hold the boat steady in the current. Faster water would make manuevering more difficult, and a firm upper boundary is reached at a velocity of 15 feet per second - even strong paddlers could not make sustained headway against such a velocity. A velocity of 10 feet per second would tax many boaters.

Small power boats offer an advantage in that they can make headway against relatively strong currents without exhausting the fisherman. They, too, however, become unmanueverable and find difficulty in upstream progress in currents of 10 feet per second. Depth limits are less generous than for canoes. With a short-shaft motor, depths of less than 2 feet will often cause propeller fouling on bottom growth. With motors up, negotiating water between 6 inches and 1 foot is possible. Turning within one boat length is feasible, but difficult.

The following criteria govern fishing from small non-powered and low-powered fishing craft.

Minimum Conditions -

Depth = 6 inches for canoes, 1 foot for small power boats. There is no lower limit for velocity. Width can be as narrow as one times the length of the craft being used, or, more realistically 25 feet. (In narrower streams, wading or bank fishing would be preferred to boat fishing).

Maximum Conditions -

Velocity = 10 feet per second. There are no width and depth maxima for boating in pursuit of fish. Velocity maxima should be for short distances only.

Optimum Conditions -

Depth = 2 to 5 feet. Velocity less than 5 feet per second. Width greater than 25 feet.

2.1.1.3 Bank Fishing

Bank fishing, to a high degree, is independent of stream flow from the anglers viewpoint. The activity is possible, although perhaps non-productive, at no flow and can be carried out at any flow that does not over-top or make inaccessible the banks of the stream. Optimal bank fishing flow depends upon the catchability of the fish being sought. In the sense of maximizing the chance of capturing a fish, it is the lowest flow that will sustain the population. This low level of flow minimizes the mobility of the fish. Such a condition, however, cannot be recommended since it would quickly lead to destruction of the fisheries resource.

2.1.2 Non-Tranquil Water Boating

Boating in non-tranquil water (white water, wildwater) is an activity of relatively broad aesthetic appeal, but relatively minor numerical participation. The demands placed on a boater by white water are sufficient to discourage many potential participants. None-the-less, much of the literature on water based recreation concerns this activity and its general popularity is growing rapidly.

There are four common forms of white water craft, each with its own advantages, disadvantages, and criteria for use. Perhaps the most common is the open canoe, usually from 15 to 17 feet in length, which is used by both serious and casual white water boaters. Kayaks are among the most popular craft for the veteran white water boater. On larger rivers, or with larger parties, wooden or aluminum drift boats and rafts are the crafts of choice.

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.

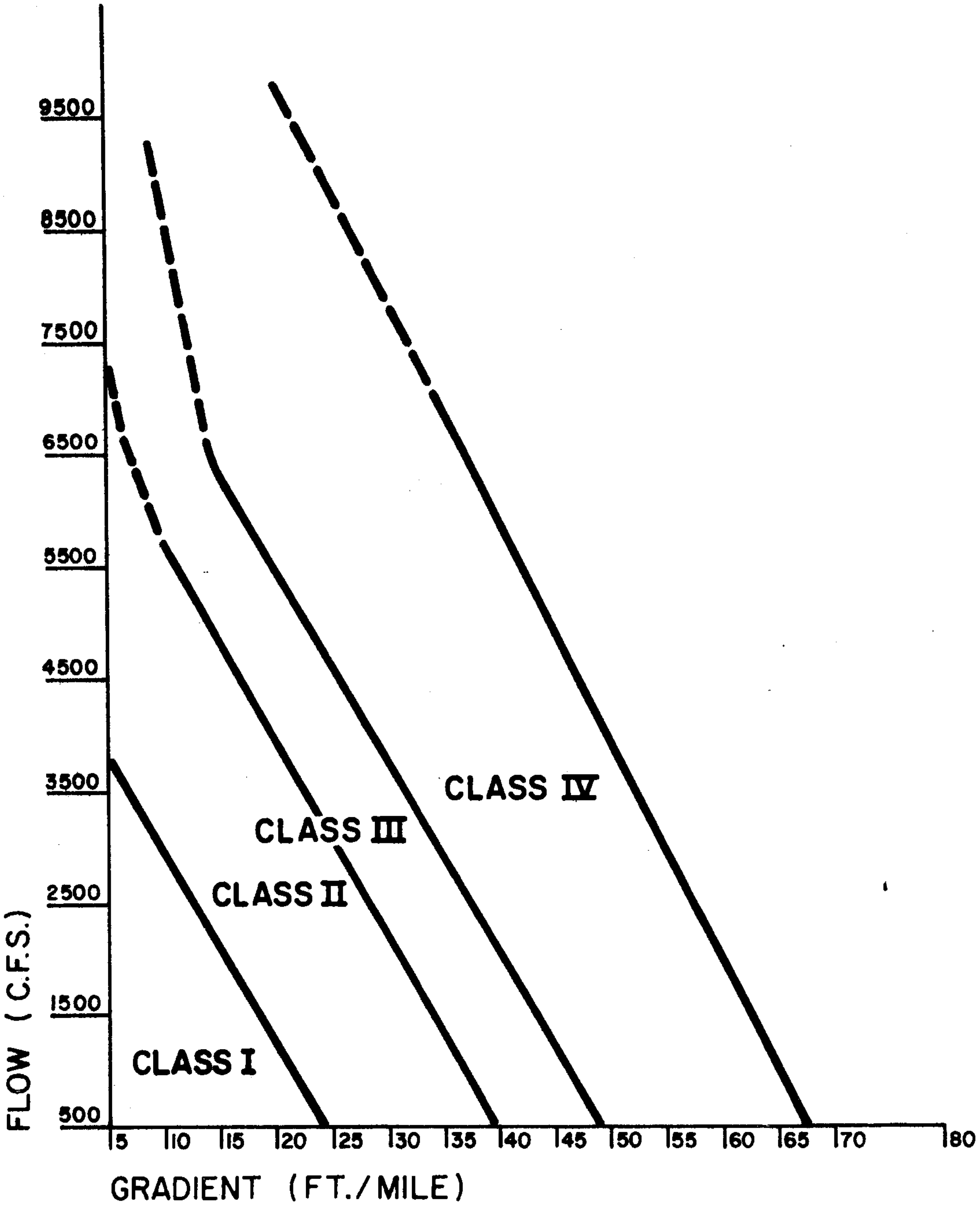
The Class of a stretch of river can be estimated roughly from information on gradient and flow. The following graph applies to stretches of uniform gradient quite well. It does not predict the class of short, steep stretches (See Figure 1).

More precise and less subjective Class determinations can be made if the river can be field inspected. The following chart (Table 3) can be used for this purpose. The stretch of interest is scored in all 11 categories and the scores summed. The total score indicates the International Classification of the stretch.

In addition to providing water of a suitable International Class, a stream must meet other requirements in order to provide a high quality white water experience. These are best described in terms of obstructions and time of travel.

Obstructions must be viewed as detractions from the white water experience. Portaging around a dam is not what is sought by most white water boaters. Thus, careful map, air photo, and field inpsection will be needed to find possible obstructions to boating and to determine if there is sufficient warning of these obstructions to insure against boater injury and suitable portaging areas to allow passage. This must be dealt with on a river-by-river basis, but in general, the more obstructions, the less desirable the water for white water boating.

Time of travel has two influences. First, it may determine the gear and supplies required for a river trip and, second, it may select for or against some forms of boating. The kayaker, for instance, may enjoy running and re-running a short, intense section of a stream with still water above and below. This might not be possible for a group in a drift boat, which is difficult to move upstream and heavy to portage. Thus, short sections of water may be ideal for "practice" and longer runs, of some hours or even days, may be more suitable for float trips or white water expeditions. Garren (1976) has provided some rules of thumb for determining the time of travel for various craft in various river situations. He notes that, if a kayak is assigned a drift time of 1.0, a canoe will require 1.1 times as long to traverse the same distance, a drift boat will require 1.3 times as long, and a rubber raft will require 1.6 times as long. He also presents a generic relationship between river discharge, in cfs, and river velocity in miles per hour. See Figure 2. This, much like the Class derived from the Arighi and Arighi chart, can be greatly refined by the hydrological studies, but the chart is useful for estimating time of travel directly for kayaks. This can be adjusted for other types of craft, if needed, using the multipliers.



ESTIMATING RIVER DIFFICULTY
(Assumes Fairly Even Gradient)

AFTER ARIGHI AND ARIGHI, 1974

Figure 1

Regardless of the approach taken to classification, upper and lower limits on river characteristics can be specified for the two groups of craft type, based on their characteristics.

2.1.2.1 Canoes and Kayaks

Canoes and kayaks are very maneuverable and draw very little water. They can pass over obstacles with as little as 3 inches of water and can be turned in their own length. With small margins for error and to prevent unnecessary bottom dragging, a minimum depth of 6 inches and a minimum width of 25 feet will allow passage. The minimum water velocity to yield Class I white water is about 5 feet per second.

Maxima for these craft are somewhat more difficult to establish. Very wide rivers, especially if they are Class IV or higher, adversely effect safety, but do not physically preclude the activity. Depths, too, cannot alone eliminate the activity, although at very high stage, most of the obstacles that create the white water experience may be so deeply covered as to be unnoticeable. Maximum velocity is in the vicinity of 15 feet per second. Above this speed, even an expert boater or team would be nearly unable to hold position or move upstream.

Optimum flow levels are completely river and boater skill specific. Generally, river conditions yielding Class II and III waters will be optimum for open canoes. The optimum for kayaks and decked canoes, especially for skilled boaters, may include Class IV waters. These optimum conditions will occur on many rivers at a depth of between 2 and 3 feet, with widths on the order of 75 to 100 feet, and velocities of about 10 feet per second.

Thus, the criteria for white water boating are as follows. Note that these are very general and, particularly for the optimum conditions, can only be accurately assessed at streamside or on the water.

Minimum Conditions -

> Width = 25 feet, Depth = 3 to 6 inches, Velocity = 5 feet per second. Conditions should yield Class I (and perhaps some Class II) water in the stream.

Maximum Conditions -

> No firm width and depth maxima can be established. Velocities in excess of 15 feet per second will preclude all but the most skilled and dedicated boaters. Conditions should yield Class IV or V waters over much of the stretch of interest.

Optimum Conditions -

Width = 75 to 100 feet, Depth = 2 to 3 feet, Velocity = 10 feet per second. Conditions should yield Class II and III waters in the stretch of interest (some Class IV might be desirable for kayakers.) The optimum conditions will require field checking, unless flow related classifications for the stream are available from reliable guidebooks or organizations.

2.1.2.2 Rafts and Drift Boats

The primary differences between these craft and canoes and kayaks are their lack of maneuverability and their ability to negotiate very heavy water. In terms of river characteristics, these craft require more space than do the smaller craft. A minimum width of 50 feet and a minimum depth of 1 foot should insure their passage. As before, a minimum velocity of 5 feet per second will often generate mild white water conditions. The implication of these minima is that rafts and drift boats require larger streams and more water to be used successfully.

Maximum and optimum conditions are very similar to those discussed for canoes and kayaks, except that these boats can sustain Class V waters more readily than can the smaller craft. Numerical maxima are as before, but these conditions can yield a higher Class water in the stream without eliminating the activity.

Minimum Conditions -

Width = 50 feet, Depth = 1 foot, Velocity = 5 feet per second. Class I or II waters should prevail.

Maximum Conditions -

No firm width or depth maxima can be established. Velocities greater than 15 feet per second may be limiting. River conditions yielding Class V and VI waters over long stretches will eliminate the activity.

Optimum Conditions -

Width = 100+ feet, Depth = 2 to 5 feet, Velocity = 10 feet per second. Conditions in the stream should yield Class II to IV waters in the stretch of interest. Some Class V will add to the enjoyment of skilled boaters, but may prove dangerous in the event of capsize.

2.1.3 Tranquil Water Boating

Five separate kinds of activity must be considered in tranquil water boating: canoeing, rowing, sailing, low power boating, and high power boating. These activities share many characteristics with non-tranquil water boating, but exhibit much more stringent limits on maximum conditions. The longitudinal suitability and time of travel considerations given above for white water boating apply in much the same fashion to flat-water boating, except that some short flat water reaches will see very heavy use if access is good. Obstructions to flat water boating include not only the dams and falls which obstruct white water activities, but rapids as well. Ideally, a flat water reach would include no dams, falls, or white water stretches. The flow would be uniform and progress could be made both downstream and upstream without severely taxing the participants. Failing of this, major portage areas should be considered as obstructions. A cut-off length of 1/4 mile for portaging may represent the upper end of desirability for users of light craft, such as canoes. Portaging of power boats is generally out of the question and any portage site must be considered as completely obstructing. Should a river reach prove generally suitable for flat water boating, there are specific criteria governing each of the forms of the activity, set by the nature of the craft.

2.1.3.1 Canoeing

Canoes, as discussed above, can negotiate waters as shallow as 3 to 6 inches, although poling will be more appropriate than paddling. Widths as narrow as the length of the boat can be acceptable, although a practical minimum is about 25 feet. The quality of canoeing improves markedly as depths become greater than 2 feet. At two feet, paddling without striking the bottom is possible. Safety considerations make a depth of 5 feet the upper bound of optimal canoeing; at this depth, most people can wade out in the event of capsize. There is no maximum width or depth which precludes canoeing, but velocities in excess of 5 feet per second impede upstream progress and mark the general lower limit of Class I white water conditions. Thus, the criteria are:

Minimum Conditions -

Width = 25 feet, Depth = 3 to 6 inches, Velocity = 0 feet per second.

Maximum Conditions -

There are no depth or width maxima. Velocities over 5 feet per second change the activity from tranquil water boating to low level white water.

Optimum Conditions -

Width greater than 75 feet, Depth = 2 to 5 feet, velocity less than 1.5 feet per second.

RIVER STUDIES PROGRAM

1.0 INTRODUCTION

The river studies program was based on a number of propositions. It was assumed that there is a set of physical parameters governing the potential for a specific kind of recreational activity in a riverine setting. These can be expressed in discrete terms, usually a range centered about an optimum. For any river these physical parameters will tend to vary with stream flow. The impact of flow variations on such parameters is to some extent predictable, since it is governed (at least in the gross) by well-known principles of hydrology. Accordingly, it is entirely feasible to develop a set of analytical techniques, based on map studies and analyses of hydrological data, which will permit one to predict what will happen to existing or potential recreation in a river if flow is modified by reduction or augmentation. Field observations may be necessary at known or potential recreation sites, but these will consist primarily of taking a set of simple physical measurements at the site. These measurements when correlated with flow at the time they are taken, will permit extrapolation to parameter changes that will follow from a modification of the observed flow. And, finally, these predicted changes in physical parameters can be related back to recreational potential.

In order to test these hypotheses, a total of seven rivers were studied between October of 1975 and August of 1976. These rivers, shown in Table A-1, were selected to provide a wide variety of test situations and to allow the interactive development of pre-field, field, and post-field analysis techniques of general applicability to the study of the relationships between flow and recreation.

TABLE A-1

RIVER STUDIES SCHEDULE

RIVER	DATES OF VISIT
Chattahoochee (Atlanta, GA)	10/21 - 10/25, 1975
Saco (Bartlett and Conway, NH)	4/22 - 4/26, 1976
Rio Grande (Alburquerque, NM)	5/16-5/19, 5/22-5/23, 1976
Huron (Ann Arbor, MI)	6/24 - 6/27, 1976
North Platte (North Platte, NE)	6/28 - 7/1, 1976
Boise (Boise, ID)	7/29 - 8/2, 1976
Russian (Cloverdale, CA)	8/5 - 8/8, 1976

2.0 RIVER SELECTION

2.1 Criteria

A number of criteria were established to use in screening candidate rivers for inclusion in the field study experimental program.

Recreation: There are a number of kinds of riverine recreation which may be affected by flow. These include: boating in tranquil waters; water contact activities; fishing; water-enhanced activities; and wetland-related activities. A variety of recreational situations was sought.

Location: A distribution over the mainland, contiguous States was desired.

Size: The experimental program required consideration of a range of river sizes.

Physical Characteristics: The field study program needed to encompass a range of river types.

Urban/Rural Location: A variety of settings were sought for the rivers to be studied.

Regulation: The presence of regulating structures was considered desirable.

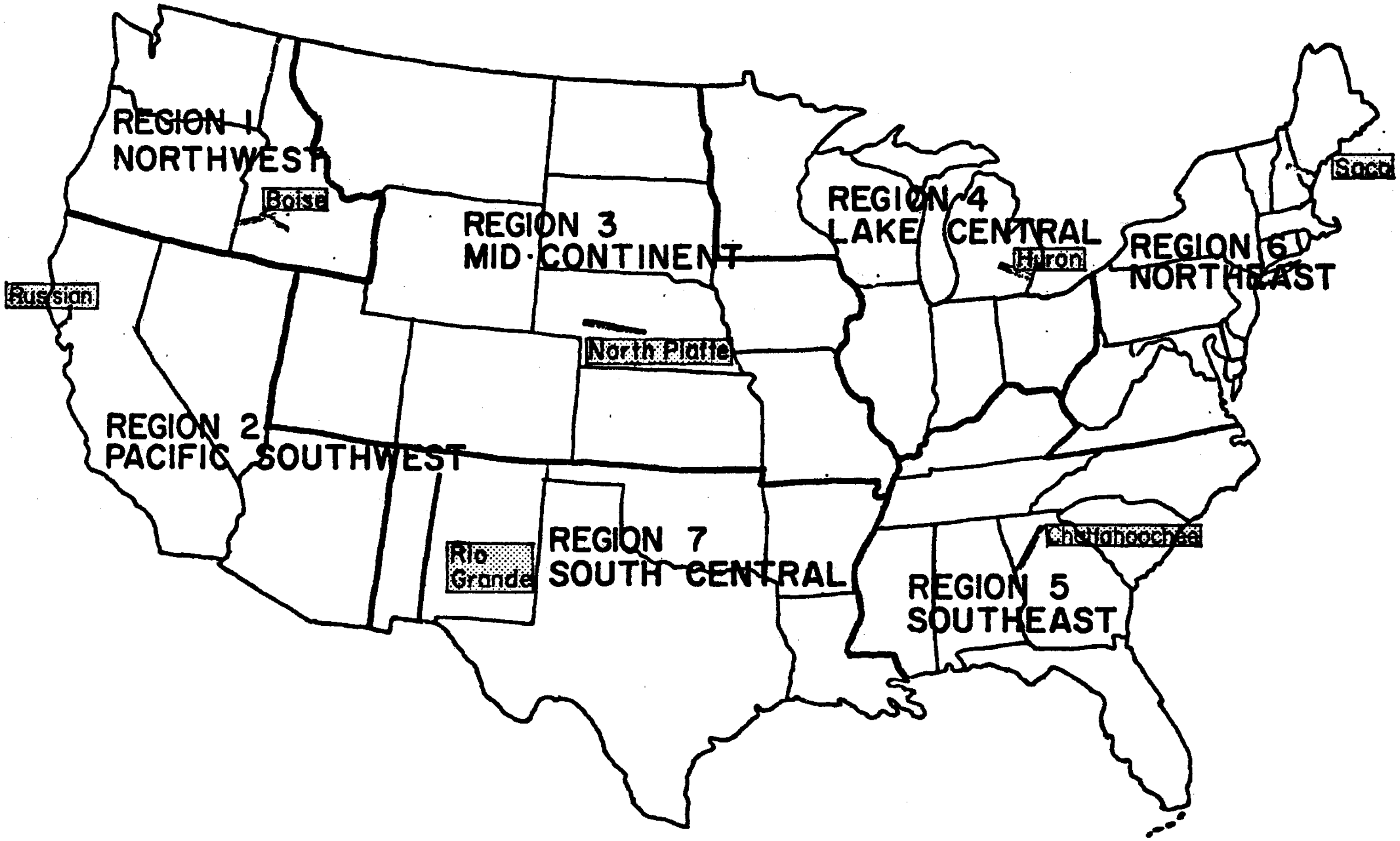
Wild or Scenic River Designation: While such designation was not a bar to selection, it was felt important not to have all test program rivers in this category.

Federal Power Commission Jurisdiction: Relicensing procedures of the Federal Power Commission offer an opportunity to modify future releases to support recreation.

Accessibility: Given limited budgets, easy access to the rivers to be studied was deemed desirable.

2.2 Selection

The seven rivers selected for field study provided a range of types which met the selection criteria. A total of 16 rivers was investigated for possible inclusion in the program. Geographic variability was assured by focussing the selection process on one river in each of the Bureau of Outdoor Recreation Regions (See Figure A-1).



RIVER STUDY LOCATIONS

Figure A-1

2.2.1 Chattahoochee River - Southwest Region

The Chattahoochee River between Buford Dam and Atlanta, Georgia offered a number of attractive characteristics for a study. It was, in fact, chosen as the pilot river, the first river to be studied.

There were a number of special considerations which made the Chattahoochee particularly attractive as a candidate for the pilot river study.

> Time of Year: The logic of the program design and the desires of the sponsoring agency dictated a preliminary field study in 1975. The required "start-up" time precluded any field work during the summer. This indicated a southern river. The weather in October was sufficiently warm to permit efficient conduct of a field program near Atlanta.
>
> Observation of Recreational Activities: Although activity on this part of the Chattahoochee is greater during the summer months, it was still possible to observe active recreation as late as mid-October.
>
> Recreation Potential: Studies by the Atlanta Regional Commission and the Georgia Department of Natural Resources indicated that the full recreational potential of this part of the Chattahoochee was not being used.
>
> Data Base: Access to a good data base on such key factors as flow and recreational use, as well as good mapping, was considered extremely important for the pilot river study. This was available for the Chattahoochee.
>
> Flow Variation: Study of the hydrological data base indicated that it would be possible to observe the effects of wide variations in flow on the river's characteristics within a short period of time. Unannounced changes in release schedules proved to be a disadvantage, however.
>
> Proximity to Regional BOR Office: It was felt that this would be a vital element in the first river study. The Southeast Regional Office of the Bureau of Outdoor Recreation is located in Atlanta. It was able to provide invaluable assistance in pre-trip planning, in effecting coordination with local public and private agencies, and by providing logistic support.

Considering all of these factors, both general and specific, the Chattahoochee was an obvious choice for the pilot river study.

2.2.2 Saco River - Northeast Region

The Saco rises as a white water stream in the White Mountains of New Hampshire and passes through Maine to the coast. Within a distance of 130 miles it undergoes transitions through all river types, from steep mountain rivulet to tidal estuary, through mostly rural areas. There is regulation of some reaches by dam. These are well downstream of the study reach. The river receives very heavy recreational use including white water canoeing, fishing, and water enhanced recreation such as picnicking, hiking, and camping. An intensive field study was planned on the upper reaches during the white water season. The Saco is not under consideration for designation as a wild or scenic river.

2.2.3 Rio Grande River - South Central Region

It was planned to study portions of the Rio Grande in New Mexico between Cochiti Dam north of Alburquerque and Isleta. Between these points the river passes through rural areas dedicated to agriculture, through Indian lands, and through a city. The river is regulated, and water is diverted for irrigation purposes. There are wide variations in flow (and in channel width and depth) on a seasonal basis, with lows occurring during the summer months. There is some canoeing and floating during the spring months, but recreational usage is not high at present. This is attributable to better quality canoeing and related opportunities in mountain streams as well as to poor aesthetic attributes of the river, especially during periods of low flow. Because of the low water temperatures, attributable to bottom flow from Cochiti Dam, there is a trout and bass fishery in the upper portions of the stretch studied, and in irrigation canals fed by the river. The fishery is said to be good in the latter.

2.2.4 Huron River - Lake Central Region

The Huron River rises to the northwest of Detroit, Michigan and passes through Livingston, Washtenaw, and Wayne Counties to enter Lake Erie south of the city. The stretch of interest is about 11 miles long, between Hudson Mills and Delhi Mills in Washtenaw County. The metropolitan area location and the presence of two river oriented parks on this part of the river contribute to heavy use. The area studied is mostly agricultural in nature. There are rapids in Delhi at the Delhi Metropark and at Hudson Mills; these represent an opportunity for canoeists when the water is high and an obstacle when it is not. The river is used for canoeing and some swimming. Water enhanced activities occur at the two parks. There is some opportunity for fishing (panfish) and for wildlife development, including some game as well as nongame animals. Regulation of the river is provided upstream by Portage Lake, the level of which is controlled to provide recreation on the lake. Currently there are no provisions for releases to maintain minimum stream flow, and this has been a matter of controversy in the past. Downstream recreational opportunities can be definitely adversely affected by low flow (impacts on fisheries, impossibility of passage of Delhi rapids, possible impacts on water quality).

2.2.5 North Platte River - Mid Continent Region

The North Platte is an excellent example of a Great Plains river, wide and flat with a braided channel. The reach chosen was that between Hershey Bridge and the diversion dam at North Platte, Nebraska. The river is controlled to provide water for irrigation so extensively that it sometimes nearly dries up in the summer. Riverine recreation is affected adversely by these extreme flow variations and by difficulty of access because of private property holdings along the banks. There is some float-boating and canoeing during spring high water, but participants often encounter fences across the bed which necessitates portage. A Nebraska statute enacted in 1967 does, however, allow persons "in the process of navigating or attempting to navigate with non-powered vessels in any stream or river in this state" to portage or otherwise transport their vessels around obstructions in the stream. During the summer months flows are highly variable; however, when downstream demands for irrigation water are heavy, the releases from the dam at Lake McConaughy allow the river to be used for boating. While Nebraska is primarily an "appropriation law" State, it does recognize certain attributes of "riparian" water law. In the case of the North Platte, both appropriation and riparian doctrines impact unfavorably in riverine recreation. There is some opportunity for hunting of small game and birds in wooded areas and wetlands along the river, although again private property rights tend to limit access. Though not in strong current use for recreation, the North Platte does offer opportunities that are curtailed because of legal and institutional considerations. This factor made it attractive for the purposes of this study.

2.2.6 Boise River - Northwest Region

The Boise River is a prime example of a small, regulated, western river which passes through an urban center and serves as a focus of recreation for metropolitan Boise, Idaho. The stretches of interest were Barber Dam to Boise and from Boise to Caldwell. Upstream, the Lucky Peak Dam, along with 2 other reservoirs, regulates water releases for irrigation and flood control. The river is used for fishing, swimming, tubing, and bankside activities such as hunting in the more rural areas and water-enhanced activities in adjacent urban parklands. Recreational use is highly dependent upon release from Lucky Peak Dam, which is in turn dependent upon needs for irrigation.

During periods of extreme low flows, water quality has deteriorated to the extent that it has been necessary to close the river to use for water contact recreation. There have been a number of studies on this part of the river by other agencies, providing a good ready-made data base against which field techniques and observations could be tested.

2.2.7 Russian River - Pacific Southwest Region

This river, regulated by Coyote Dam, flows through rural areas north of San Francisco. The reach of interest extends 94 miles from Ukiah, California,to the Pacific Ocean. It was planned to concentrate the field studies in the area from Cloverdale to Healdsburg. The upper river is widely used for recreation, including float trips and canoe trips extending over several days. North of Healdsburg there is a great deal of organized commercial recreation as well as public access for boating and swimming. One of the largest canoe rental operations in the entire State of California is maintained on this river with about a thousand craft available for hire during the summer recreation season. The river regulation combines upstream flood control with provision of water for diversion (irrigation). To meet the latter needs, the flow of the river has been augmented by diversion from a power dam on the Eel River, so that augmented flows now existant are considered better than the river's natural historic flows. The river is used for swimming as well as for streamside activities such as picnicking. Some preliminary studies of recreational potential had been carried out by the Southwest Regional Office of BOR.

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Recreation and Instream Flow. Volume 2. River Evaluation Manual

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Prepared for

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1.0 INTRODUCTION

1.1 Background

The demand for water-based recreation has grown substantially in the past several decades. It has, in fact, grown faster than population. Generically, this has to do with the increase, since the turn of the century, in the amount of leisure time and disposable income available to individuals. Additionally, many water related activities, such as white water canoeing, have undergone growth of boom proportions. This growth has affected both lake and stream-based activities. There are, however, inherent differences between the two types of activities which must be recognized.

Lake activities may be viewed as activity oriented. That is to say that the activity may be successfully and pleasureably carried out on virtually any relatively large body of water. More to the point, lake environments can, and have been, provided by human works (dams). Thus, it is not a supply-limited resource in any immediate sense.

Stream-based activities, on the other hand, are resource oriented. The availability of the activity and its quality may depend on the particular stream in which it occurs. Additionally, free-flowing water is seldom created by human works; indeed the dam that creates a new lake almost always inundates a stretch of free-flowing stream. Thus, instream recreation depends upon a supply-limited, and shrinking, resource. To compound this difficulty, there is intense competition for the waters in a free-flowing stream.

The assessment of such a set of activities is necessary if they are to be preserved. In the past, water has been viewed as a consumable resource with little or no supply limit. This is no longer the case. The need now arises to treat instream water and instream recreation as a nonrenewable resource and to enter into the competition for what free-flowing water remains.

However, before trade-off analysis can begin, the range of possible activities must be determined. Different riverine recreational activities impose different physical requirements.

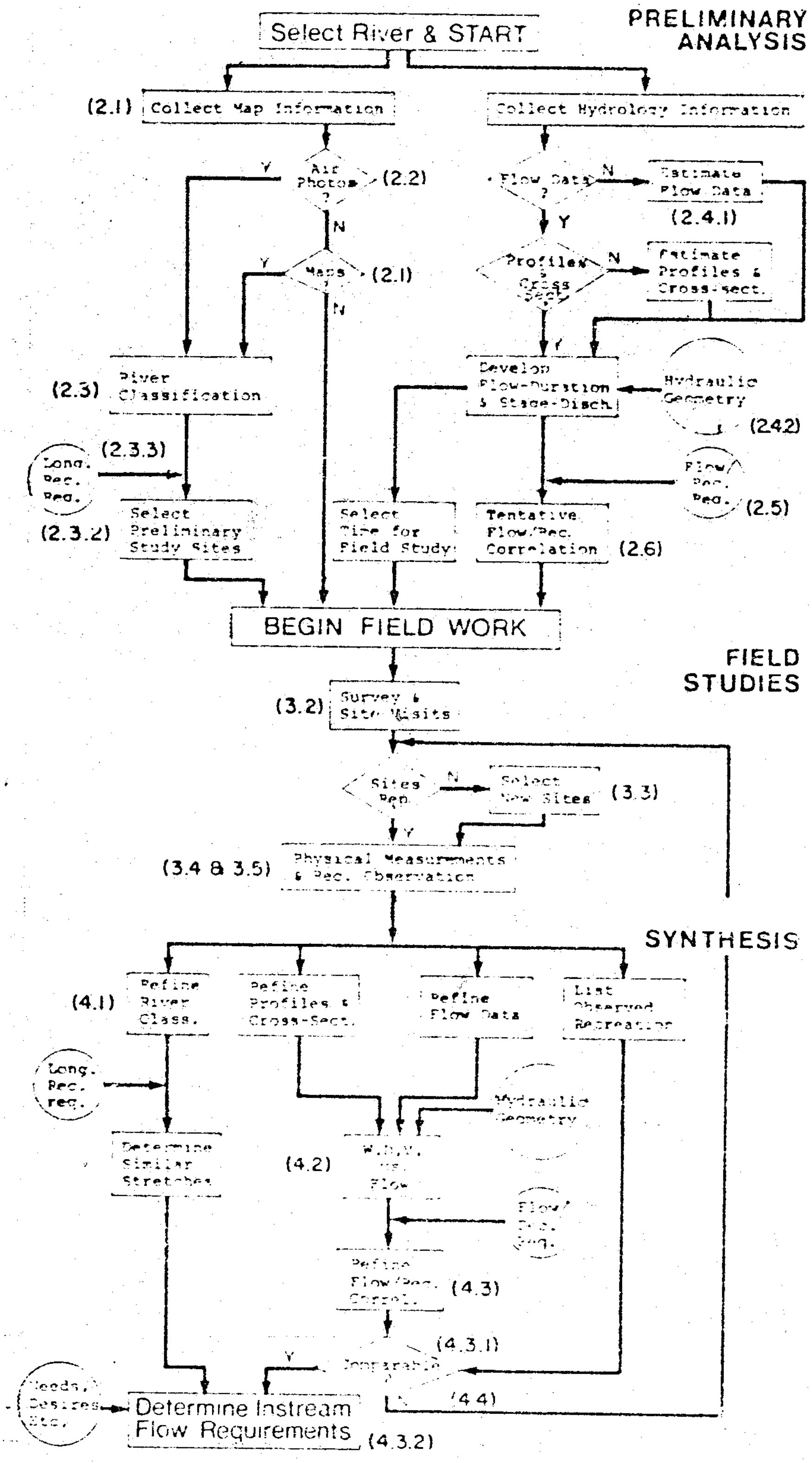
1.2 Scope of the Manual

This Manual serves as a practical guide to the evaluation of the physical relationships between recreational potential and flow level (discharge) on a river. While numerous factors impact on recreational potential, those most closely affected by variations in flow at a given place on a river are width, depth, and velocity. The method presented here concentrates upon relating changes in these parameters, whether observed or predicted, to recreational potential. Figure 1 is a flow chart of this procedure. The basic approach is synthetic in nature to the extent possible. That is, it relies upon preliminary analysis of data, on limited field studies, and on post-field analysis to yield predictions about conditions on the river, in relation to their effect on recreational opportunities. It does not require access to data on or observation of actual recreational experiences, though these can be helpful when they can be provided. It will probably in many cases require field measurements at more than a single flow, but it does not depend upon the availability of controlled releases from a dam or on measurements at a large number of discrete flows. Should an investigator feel, however, that controlled release experiments would be of value, Appendix A provides guidance on carrying them out. These approaches might be of particular use on remote, controlled streams where a second field visit is not feasible.

Section 2, Preliminary Analysis, describes the steps to be taken at the outset of the study of a specified river. This includes: the acquisition and use of maps and aerial photographs; the classification of the reaches of interest according to basic morphological form; the collection and analysis of hydrological data; the specification of criteria governing various types of flow-related riverine recreation; the correlation of the above data to permit tentative predictions as to discharge-recreation relationships on specific stretches or at specific sites on the river; and, finally, the applicability of available data on actual recreational usage of the area. The output of this entire process of preliminary analysis is the preliminary selection of sites for field study and the identification of the optimum expected flow under which to conduct the field study part of the effort.

Section 3, Field Studies, presents the tasks to be accomplished in conducting direct analysis of actual conditions on the river. Topics covered include: selection of dates for the visit, in relation to the previously identified desired flow; reconnaissance of the reach of interest to check stretch and site locations against those derived from map and photo studies; final selection of observation site; physical measurements; and observation of on-going recreation, if any. The field study process provides specific physical information on sites of interest at a given flow and provides the basis for later predictions as to changes in site conditions with variations in discharge.

Section 4, Synthesis, involves the development of predictions as to recreational potential as a function of discharge. The steps required to accomplish this include: analysis of data gathered during the field studies, correlation of the physical measurements and observations with hydrological data; development of rough predictions of changes in physical parameters such as width, depth, or velocity with a variation in flow; pre-



Note: Bracketed Figures Refer to

Flow Chart
RIVER STUDY PROCEDURE

diction of recreation potential at non-observed flow; and the checking of these predictions by a limited set of observations at flows different from that observed at the time of the primary field study. At the conclusion of this portion of the effort it should be possible to relate recreation potential to flow in the portions of the river that have been studied and, thus, to permit specification of flows for different recreational pursuits. This information, in conjunction with analysis of the recreational "market" or demand, of the available supply, and of the value associated with various recreational activities, will provide the basis for developing recommendations about the preservation or provision of instream flows for recreation.

1.3 Considerations for Planners and Policymakers

The following situations cover a broad range of possiblities. They share one common and important element, however. In each case, future recreational potential at some recommended flow may be more important than existing recreational activity on the river. This is as true for the non-regulated as for the regulated cases. While ultimate judgments and decisions must rest on a full evaluation of the social and economic benefits attributable to provision of flow-dependent and recreational opportunities, the initial determination of the requisite discharge depends upon an evaluation of the physical capacity of the river to support recreation and to meet the necessary flow related recreation criteria at specified flow.

1.3.1 Preservation

In some cases, the question may be one of preserving an existing natural flow. This would be important in considering the designation of a river under the provisions of the Wild and Scenic Rivers Act, for example. It could also be important in evaluating the long term impact of a proposed impoundment or large diversion which would radically affect natural flow conditions.

1.3.2 New or Proposed Designs

It may be possible to use a proposed new structure to provide instream recreational benefits greater than those found under existing conditions. This can be accomplished by releases to support recreation which would not be possible lacking regulation of the stream. The Duck River and Bear Creek projects of the Tennessee Valley Authority have such capabilities built in. The additional benefits from augmented instream flow (canoeing and fishery improvement, for example) serve the dual function of helping to justify the project economically and of mitigating unfavorable environmental effects of an impoundment.

1.3.3 Retention and Timed Release

Recreational oportunities on a stream may be enhanced by temporary retention and timed release of water from flood control structures. This is sometimes done on flood control dams which were initially designed to operate in a pass-through mode, with retention only to prevent imminent flood hazard. Modified scheduling of retention and release at such installations can provide an extended white water season and can improve fish habitat and, thereby, fishing opportunity.

1.3.4 Recapture

Even where existing flows are highly regulated and discharges governed by other needs, such as power generation and irrigation, it may be possible to recapture some flow for recreational purposes. This could take the form of acquisition of storage rights behind an irrigation dam as has been done by the Idaho Fish and Game Department at Lucky Peak Dam on the Boise River. It might take the form of acquisition of water rights by State agencies through the appropriation process to maintain instream values. A start was made in this direction by the State of Idaho at Malad Canyon where a flow was "appropriated", not for the normal diversion and consumptive use, but to maintain the aesthetic qualities of a river inside a state park. It could take the form of an alteration of generating schedules and resultant discharges at power dams. Licensing or relicensing of power projects operated under Federal Power Commission regulations may afford an opportunity to insure that impacts on instream recreation below the structure be provided for in release requirements.

The only method for dealing with these effects is a radical departure from the criteria approach used for all of the in-the-water activities. Careful map study and limited field reconnaissance will allow the identification of wetland resources along and near the stream of interest and of the possibility of adverse effects from flow variation.

Water-enhanced activities are also not amenable to simple criteria setting. The aesthetic attraction of water operates at all flows from a trickle to a torrent. Even dry stream beds may be favored hiking places, both for ease of passage and for the water-carved forms sometimes seen.

Thus, these two groups of activities are not included in the criteria system developed above for the on-the-water activities. The recreation planner must be sensitive to these uses, but only the terrestrial ecologist and the aesthetic analyst can make meaningful determination of the influence of absolute flow or flow regime on these resources in specific situations.

2.6 Tentative Flow-Recreation Correlation

A preliminary estimate of the possibility, extent, and quality of available recreation resources on the study stream can be made by comparing the hydraulic geometry information developed in Section 2.4 with the recreation requirements presented in Section 2.5 The planner should assemble the following data elements.

1. Study area map with stretch classifications marked
2. Typical cross-sections for the stretches of interest
3. Stage-discharge, stage-width, and stage-velocity curves for those typical cross sections,
4. Annual and monthly average flow data for the stretches, with maxima and minima, if available,
5. The tabulated width, depth, and velocity criteria for recreation activities (from Section 2.5).

2.6.1 Hydraulic Geometry Correlations

A first level correlation is made in three steps. First, the AAF, monthly average flow, and monthly minimum and maximum flows are tabulated. These are compared to the stage-discharge, stage-width, and stage-velocity curves to determine the average annual width, depth, and velocity; the average monthly width, depth, and velocity; the maximum monthly width, depth, and velocity; and the minimum monthly width, depth and velocity. Finally, these are compared to the recreation criteria to determine possible recreation activities. Of particular importance at this level will be comparison to minimum and maximum recreation criteria. This yields a multiplicity of lists of possible recreation activities under different flow conditions, by month.

Another approach to this first level correlation can be made by simply noting the range of flows with a reasonable chance of occurrence. Several points within this range can then be selected and widths, depths, and velocities determined for these. Then, at each of the selected flows, a list of possible recreation activities can be prepared. This format has a useful side benefit. If the lists are compared in order of increasing flow, several observations can be made.

First, there will be a limited suite of activities available at very low flows. These might include swimming, wading, canoeing (flat water), rowing, and bank fishing in many streams. Second, at some level of flow above this minimum, a larger number of activities will become available. Depth and velocity increases might make possible tubing, sailing, and low power boating without eliminating any of the previous suite of activities. At some flow above this value, tradeoffs will occur. Some activities will be added and others will be deleted. For example, in many streams, the flow necessary to permit high power boating might violate depth and velocity maxima for swimming or wading. At a somewhat higher flow still, entire suites of activities will be replaced by others. The clearest example of this is the 5 foot per second velocity. When this level is reached, the non-power tranquil water boating activities will generally be replaced by the non-tranquil water boating activities and all of the water contact activities except tubing may be lost. At even higher flows, velocities in excess of 10 feet per second will limit low-power boats and tubing, leaving only the white water boaters and bank fishermen. Finally, velocities over 15 feet per second may eliminate even the white water boaters.

2.6.2 Map Correlations

The second level of recreation correlation is solely map dependent. Even though the analysis at typical cross-sections may show that a large number of activities are possible in terms of width, depth, and velocity, many activities are also governed by longitudinal considerations. This is where the earlier classification and air-photo interpretation comes into play.

Let us suppose that a stretch is found to be suitable for any of the various boating activities. This stretch should then be checked on the maps. If it is very short, its desirability for boating activities will be seriously reduced. For example, a short stretch of flat water bounded by two major rapids may not be suitable for tranquil water boating activities. On the other hand, a longer stretch, including both of the rapids and the quiet stretch may make a very desirable tubing area or non-tranquil water boating area.

2.6.3 Auxiliary Requirements

Site-specific considerations come into play in dealing with the water contact activities. For most of these, a sandy bottom and some beach area is preferable to a muddy or gravelly bottom and "fall-in" banks. If these latter conditions are found, the activity may not be practical, even though it is technically feasible.

Guidance in these types of auxiliary considerations is given in Section 2.4, where site-specific and reach specific requirements are determined from air photos, and in Section 2.5, where auxiliary conditions for the various suites of activities are discussed.

The final result of this task will be a listing of possible recreation activities at various flow levels, amended to reflect longitudinal and site-specific requirements.

2.7 Use of Available Recreation Data

Often there will be available to the planner reports, studies, user surveys, or like information on the numbers of people engaging in specific recreational activities at sites or along stretches of the river to be evaluated. Where such information is available, especially when it is keyed to specific dates, the usage can be correlated to hydrological records. This will permit at least a rough estimate of recreation potential, at specific places, at specific flows. Since such data rarely include much information of an hydrological nature, they rarely will provide much insight on specific river conditions such as width, depth, or velocity. That recreation is taking place implies that these parameters are within acceptable limits, but often little more.

2.7.1 White Water User Data

One possible exception to this general rule relates to boating, especially on white water. In some instances recreational information is available tieing recreationists' evaluation of their experience to flow, using home made staff gages or painted gage

3.0 FIELD STUDIES

Preliminary analysis only begins the river evaluation process. Field visits are necessary to test preliminary hypotheses. Several important steps are required for the field studies aspect of river evaluation.

3.1 Timing

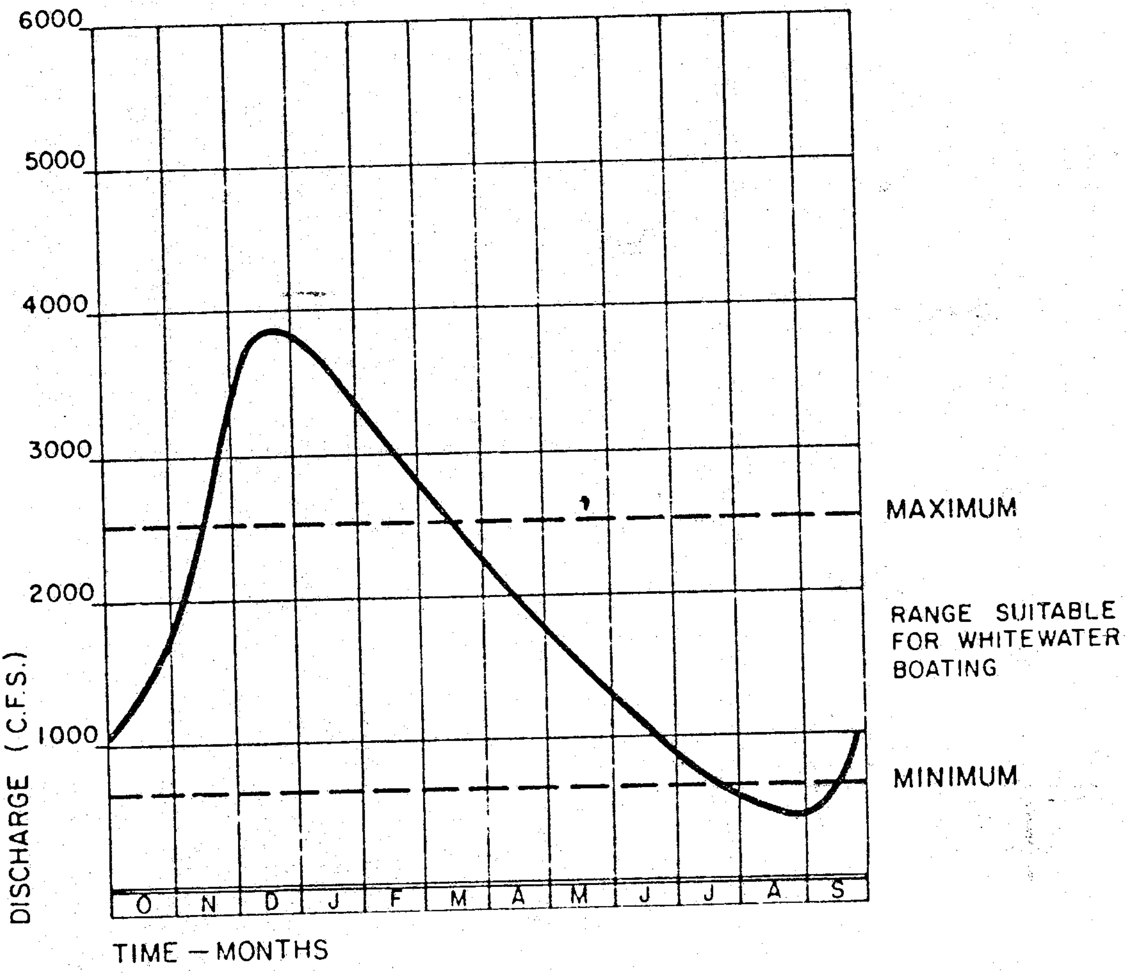
Timing of the field work is an important consideration. This should generally be chosen to provide a flow on the river which is considered to be at or below optimum for the kinds of recreational activity which appear from preliminary analysis to be of prime interest.

Where winters are severe it is desirable to avoid periods of very low temperature. River flow may be affected by ice at such times. Perhaps more to the point, conduct of field work on rivers is uncomfortable and may be hazardous when both air and water temperatures are low. In addition, all other things being equal, it is desirable to select times for the field visit which are appropriate to recreational usage in terms of weather.

Where a river is actively in use for recreation, the best choice of date for the trip may lie in the active recreation season. This affords an opportunity to combine theoretical studies of relationships between flow and recreation with actual observation of on-going activity. However, it will not always be possible to observe the flow of chief interest at such times. Ultimately, the timing of the trip should be governed by the expectation of finding a discharge close to that identified as more or less optimum for some dominant recreational use or some set of recreational uses. Often such flows will not coincide with the peak recreation season. This is especially true for many regulated rivers where flows during the summer months reflect irrigation requirements rather than the needs of recreation.

3.1.1 Identification of Dates for Flow of Interest

In the case of white water rivers, outfitters and canoeing organizations are usually very knowledgeable about the relationship between recreation potential and river stage. Canoeing guides frequently publish such information in written descriptions, tables, or graphs for specific rivers. Figure 11 illustrates this kind of presentation. When it is desired to study a river which is regularly used by white water enthusiasts the best course is to establish and maintain contact with the experts on the state of the water. This usually will provide sufficient information to permit scheduling a trip to the area about a week in advance and still obtain a flow in the range of interest.



SUITABLE FLOWS BY SEASON

(AFTER GARREN, 1976)

Figure 11

For many other kinds of recreation, however, the field visits may or may not coincide with peak recreational use, for various reasons. This being so, the period of expected flow at the desired level should govern selection of field dates. The objective should be to look for a flow on the low side of the expected optimum for the activity or activities expected to be of greatest importance as a result of the preliminary analysis phase of the work. In general, the lower the stage of the river, the easier it is to conduct the measurement program, especially in the case of running cross-sections.

3.1.2 Flow Data Analysis

During the course of an average year, most rivers, even most regulated rivers, exhibit rather wide ranges of average daily flow. The difference from high to low flow may cover several orders of magnitude. Moreover, save for the rare event, discharge patterns tend to be more or less consistent on a seasonal basis from year to year. Thus, if one chose the proper dates one might be able to examine any flow from, say, 200 to 30,000 cfs on a given river in the course of a year.

In the case of the natural stream which is adequately gaged there are usually available long term records of average flow by day, by month, and by year. These data can be plotted to reveal seasonal patterns. Usually, monthly averages will be sufficient for this purpose. However, in some cases where seasonal variation trends are sharp, it may be desirable to plot the pattern of daily averages for that season.

Most regulated streams will not exhibit ranges in flow as wide as those on a natural river. However, such streams are almost always gaged, which makes it possible to obtain and plot the patterns of flow distribution.

If the stream is ungaged, it is possible to approximate the discharge by calculating run-off from the watershed on the basis of meterological records of precipitation. The data can be plotted to some degree of accuracy in terms of seasonal or monthly averages. However, this method is usually not amenable to the determination of average daily flow, except perhaps on very small watersheds.

The analysis of flow data should permit identification of the best likely period in which to conduct the field trip within a matter of a few weeks, unless the year is atypical. The final selection of field trip dates should be made after consultation with USGS personnel or others who visit the reach of interest and are aware of the river stage and its relation to discharge. Where such information is lacking completely, it may be necessary to compare weather patterns (temperature and precipitation) with the norms for the average year and try to pick a period which should provide something approaching the desired flow under average conditions, modified if necessary to account for deviations from the norm in the weather.

3.1.3 Potential Conflicts with Active Recreation

An important consideration on some rivers may be the avoidance of certain recreation periods. An example of this would be the weekend of a white water race. Under these circumstances, cross-section measurements might range from impolitic to impossible. Basically, any event or condition which draws an unusual number of users to a river makes the actual field work difficult. One method of avoiding such conflicts and taking advantage of the circumstance is to plan the field effort for the week days just before the preclusive event or condition and to remain for the weekend to observe the activity and interview the participants.

3.2 Reconnaissance

Once in the field, the general reach of concern having been determined, a reconnaissance survey is the first step. Where the reach is long or access difficult, this is sometimes best accomplished from the air. Windscreen observations from an automobile provide a fairly rapid means for covering a reach of reasonable length if access is good. In some cases, actual transit of the river by canoe or other water craft may be desirable. The purpose of the reconnaissance is to develop a better "feel" for the river than can be obtained from simple analysis of maps, photos, and hydrological data. It permits the final selection of specific reaches and sites to be examined in detail.

3.2.1 Aerial Survey

In cases where the study reach is very long or where roadway access is difficult, aerial survey offers a large information return for little time investment. Aerial survey is best carried out by helicopter or in small, top-winged, low-speed aircraft. This allows slow, low flying and provides for unobstructed photography. Air reconnaissance gives the survey team an opportunity to see the entire reach in a short period of time, to take oblique aerial photographs, and to examine the reach for obstacles and opportunities which might have been missed in the map and aerial photo studies prior to field trip. This can be particularly useful in finding access routes to remote rivers. The routes may often take the form of small dirt roads or logging roads not visible on maps or high altitude air photos.

3.2.2 Windscreen Survey

An alternate to or supplement to air reconnaissance is a windscreen survey where roadway access to the river is good. This has the advantage of not requiring an aircraft, but it will seldom allow a view of all of the study reach. The intent is the same as aerial survey - to find obstacles and opportunities overlooked in remote studies. Additionally, site visits can be made part of the windscreen survey when preliminary sites are readily accessible from roads. A limited amount of bank side hiking can extend the coverage of a windscreen tour considerably.

3.2.3 On-the-Water Survey

If time will allow, an on-the-water survey can be a useful adjunct to an air or windscreen survey and may be required on rivers with little or no roadway access. In this case, on-the-water survey will be the most feasible method of visiting the preliminary study sites to gather information for final site selection. On truly inaccessible streams, it may be necessary to perform physical measurements on too many rather than too few of the preliminary sites to avoid the necessity of repeating the trip. In any event, the on-the-water survey is the most complete and accurate form of survey, since all of the photo stretch classifications can be field verified and amended, if required, before detailed studies are undertaken. The craft of choice for this task is usually an open canoe, either with or without a small outboard motor. Such a craft can negotiate very shallow water and, well handled, can be used in moderate (Class II or II-1/2) white water.

3.2.4 Initial Site Visits

Regardless of the method of reconnaissance chosen, visits to all preliminary study sites must be made. At each site, a field data sheet (see 3.4) can be used to record estimated and measured physical characteristics of selected sites and to record photos of the rejected sites. It is also possible that the preliminary reconnaissance will have revealed some sites of strong potential for study which were not discovered in the pre-field map and air photo studies. These should also be visited so that the final site selection will yield the most representative and useful set of field study sites.

3.3 Site Selection

3.3.1 Recreational Criteria Affecting Site Selection

Some categories of sites at which detailed measurements and observations are to be taken should be pre-selected prior to start of the field study. These might include sites which are representative of similarly classified stretches and sites which are expected to provide unusually suitable conditions for one or more recreation activities. Further subdivision of potential sites is often necessary to ensure adequate documentation of flow conditions along a river reach.

Instream recreational activities can be categorized generally as those centered about a suitable site and those requiring longitudinal suitability. In the one case, minimum flow requirements must be met at the specific location; in the other, minimum flows must prevail throughout the stretch. It is not always possible to identify all areas along a stretch which may present physically limiting factors from remote data alone; however, using a combination of air photos and field checking should make it possible to locate at least the critical areas. These would include such features as: dams, falls and rapids, very wide sections where depths are uniformly below the average for the rest of the stretch, and areas where extensive instream vegetation may interfere with passage. Failure to locate such areas, and to take account of the limiting conditions they present, may lead to error in recommendations based on remote information alone.

Complete width, depth, and velocity measurements at such areas may not always be feasible. For example, in a large riffle area with an average depth of less than six to eight inches it is easy to measure width and depth. But it is extremely difficult to take accurate velocity measurements because of the shallow water. For such a site, discharge information may be imputed by comparison with a site more amenable to measurement in the vicinity, either downstream or upstream.

3.3.2 Physical Site Criteria

The preselection process should have narrowed the areas to be considered for final site selection. However, field checking is often essential to complete the site selection process. Some conditions may not be found if remote data are relied on solely.

For activities, such as most non-tranquil water boating, where minimum depths are extremely critical, the location of physically limiting areas must be accomplished in the field.

When small dams or diversions have been emplaced since the most recent aerial photography, these must be identified either through a field check or through communication with people having knowledge of local conditions.

If no aerial photography is available, sites selected on the basis of map study alone must be verified by field investigation as a rule.

If extraordinary runoff events have occurred since the most recent aerial photographs were taken, major channel shifting may have occurred. While such changes may not require reclassification of the stretch, it may be necessary to shift field study sites to new locations at some distance from places identified during the preselection process.

When two sites appear on the basis of remote data to be similar in terms of classification it is wise to field check them to determine whether or not both must be studied. While no two sites are exactly alike, if the two are sufficiently similar that it appears that recreational activities will be affected in essentially the same manner by changes in flow, then a single site may be chosen for detailed study. If doubt exists, however, both sites may be studied.

Alternative sites may be required if access is difficult or land ownership is unclear. However, when a particular site is deemed necessary for a complete analysis, permission to enter should be obtained prior to departure for the field.

3.3.3 Number of Field Sites Required

The number of sites to be investigated may be influenced by many factors. These include the length and heterogeneity of the river reach, the difficulty of running sections because of river conditions, problems of access, the season of the year, available manpower, and budget. Because there are so many variables, it is not possible to stipulate precisely the number of sites which should be studied in detail.

If one assumes that about a week (5-7 days) is available for field work on a river reach, some rough estimates of the work can be made. If access is possible from roads or by hiking from a road, reconnaissance should take no more than a day for most investigations. If access must be by water, reconnaissance and field surveys are combined. Two people can run a cross-section on a wadeable river 300 feet wide in no more than 1.5 to 2 hours; this time includes completion of the field analysis form and establishing photo points. However, access time must be added. If one assumes no equipment failures, moderate to easy access, and depth and current conditions amenable to wading, a crew can study five sites per day.

If a river is essentially homogeneous in channel pattern, a small number of sites will provide adequate coverage of stretches of interest. However, consider a reach which is classified as 80% braided and 20% straight. This does not imply a like distribution of field investigation sites. If many of the braided stretches are quite similar in nature, it may not be necessary to sample each of them. On the other hand, if the straight stretches offer a number of potentially limiting or hazardous areas, they may require intensive sampling. As a rule, however, the number of sites will tend to be larger in those stretches representing the greater length of the total reach; but the site distribution will not necessarily follow the relative length distributions exactly.

Finally, it should be noted that the number of sites to be studied varies with the purposes of the river investigation as well as with the river conditions and other factors considered above. In some cases a "rough cut" may be all that is required; in others, a rather precise determination of flows may be called for. The latter will entail a much more extensive field program than will the former case. Accordingly, the number of sites to be studied must be determined by the study team after due account is taken of all the variables which must be considered.

3.4 Physical Measurements

When study sites have been definitely established, a suite of physical measurements are taken, including the development of cross-sections and velocity profiles. Along with measurements of width, depth, and velocity, observations of special conditions affecting recreation potential should be recorded. Liberal use of a camera provides a permanent record which can be of invaluable assistance later in analysis of field data. When a tour of the river is chosen as the means for conducting the reconnaissance, the measurements may be taken at appropriate places during the tour.

3.4.1 Equipment

The following items are necessary to carry out field measurements on wadeable streams or rivers. In the case of rivers which are not wadeable, provisions to carry out measurements from boats, bridges, or cableways must be made.

1. Data Forms:
   a. Field Survey Forms,
   b. Cross-section tabulation forms (on Field Survey Form).

2. Maps - preferably mounted on cardboard strips.

3. Air Photos - black line prints of originals joined together and mounted on cardboard, with a plastic or acetate overlay case.

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FEDERAL PARTICIPATION IN WATERWAYS DEVELOPMENT

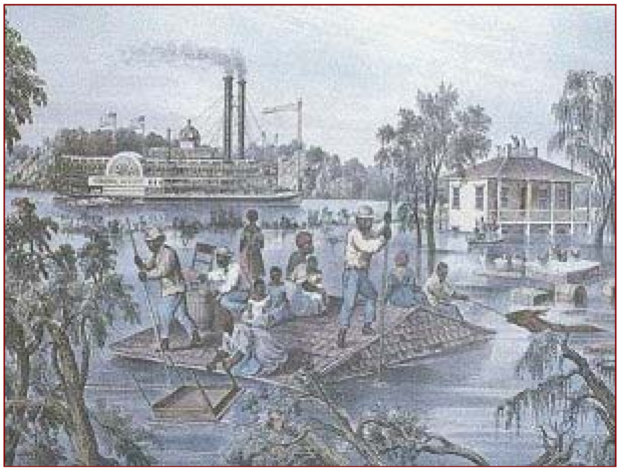
In 1820, Congress began addressing the navigational needs of the nation's interior by authorizing a reconnaissance of the Mississippi and Ohio rivers. It was made by Captains H. Young and W. T. Poussin, and Lt. S. Tuttle of the Engineer Corps of the Army. Fieldwork, begun in 1821, extended from Louisville to the mouth of the Ohio River and from St. Louis to New Orleans on the Mississippi. Also, in 1821, two Engineer officers, Brig. Gen. Simon Barnard and Maj. Joseph G. Totten, were detailed to make a thorough investigation of the Mississippi and Ohio Rivers. Their report, submitted the following year, contained observations on the physical characteristics of the rivers and gave considerable attention to the formation and removal of snags. Legislation was enacted in 1824 directing the removal of snags and other obstructions from the channels of the rivers.

In 1831, a bold attempt was made to improve navigation conditions at the mouth of the Red River by an artificial cutoff, proposed by Capt. Henry M. Shreve. A second cutoff was made at Raccourci Bend, several miles below, by Louisiana in 1848.

Improvements of the Mouth

Improvement of the mouth of the Mississippi River for seagoing navigation was first undertaken by Congress in 1837, with an appropriation made for an accurate survey of the passes and bars at the river's mouth. This survey was conducted by Capt. A. Talcott, Corps of Engineers, and finished in 1838. He recommended a plan for deepening the bars by dredging, but a lack of necessary funds prevented substantial progress on his channel & project.

By 1850, the growing river commerce, together with increasing destruction caused by floods, was creating demand for Federal participation in navigation improvements and flood protection.



A painting of the destruction caused by the floods.

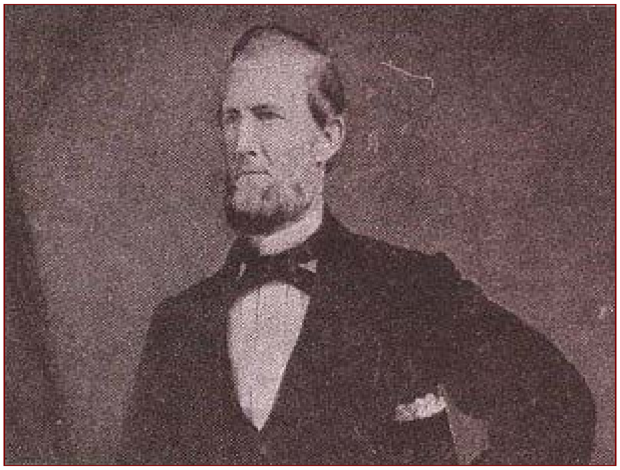
In 1850, the Secretary of War, conforming to an Act of Congress, directed Charles Ellet Jr., an engineer, to make surveys and reports on the Mississippi and Ohio Rivers with a view to the preparation of adequate plans for flood prevention and navigation improvement. His report was most complete, and it exercised considerable influence on later thought.

Also in 1850, Congress appropriated $50,000 for the preparation of a topographic and hydrographic survey of the delta of the Mississippi and for investigations to determine the most practicable plans for flood control and navigation improvements at the mouth of the river. But it was not until 1861 that Capt. A. A. Humphreys and Henry L. Abbott, of the Corps of Engineers, were able to complete their field investigations and submit their now-famous "Report Upon the Physics and Hydraulics of the Mississippi

River; Upon the Protection of the Alluvial Region Against Overflow; and Upon the Deepening of the Mouths." While this report dealt primarily with flood control, it did consider the navigation problem in considerable detail and was a great step forward in the development of river engineering in the United States.

Jetty System

Meanwhile, the problem of keeping the river's mouth open to oceangoing traffic was one of serious growing concern to the Nation. Congress appropriated $75,000 In 1852 for improving the channel at the mouth of the river by contract.



A photograph of Capt. James B. Eads.

It was not until 1867 that dredging operations were resumed at the mouth of the Mississippi River, but still the vexing problem was not solved. No significant progress had been made by 1873 when Capt. James B. Eads, a famous construction engineer, advocated a system of parallel jetties. He offered to open the mouth of the river by making a jetty-guaranteed channel 28 feet deep between Southwest Pass and the Gulf at his own risk. If he succeeded, his fee would be $10,000,000.

After much debate, in 1875 Eads was directed to begin his work, in South rather than Southwest Pass. He faced a difficult task, complicated by the existence of yellow fever and unfavorable financial arrangements; however, he pushed the project to completion. On July 8, 1879, a 30-foot channel was officially declared to exist at the mouth of the Mississippi.

Levee System Advocated

The importance of the Mississippi River to the Nation had, by now, become firmly established. Congress had shown an increasing interest in flood control and navigation problems on the Mississippi, and legislation designed to improve this mighty stream for the use of the Nation was rapidly taking form. In 1874, Congress had authorized certain surveys of transportation routes to the seaboard. Among these was reconnaissance of the Mississippi River from Cairo to New Orleans, made under the direction of Maj. Charles R. Suter, an officer of the Corps of Engineers.

A painting of surveying the Mississippi River.

Five years later, a board of Engineer officers concluded that a complete levee system would aid commerce during periods of high water only. Their conclusion is noteworthy for considering flood control and navigation improvements as part of the same problem.

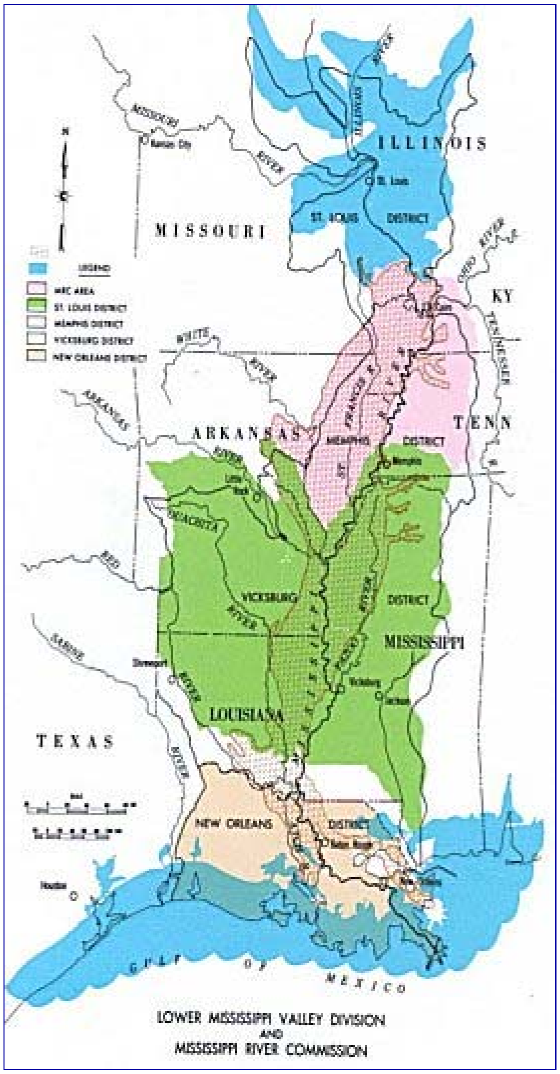
Mississippi River Commission

In that same year, 1879, on June 28, the Mississippi River Commission was created by Act of Congress as an executive body reporting to the Secretary of War. The Commission is composed of seven men nominated by the President of the United States and confirmed by the Senate.

Since the enactment of the Flood Control Act of May 15, 1928, the Commission has served as an advisory and consulting - rather than executive - body responsible to the Chief of Engineers, U.S. Army. The general duties of the Commission include the recommendation of policy and work programs, the study of and reporting upon the necessity for modifications or additions to the flood control and navigation project, recommendation upon any matters authorized by law, making inspection trips, and holding public hearings. The work of the Commission is directed by the President of the Commission, acting as its executive officer, and carried out by U.S. Army Engineer Districts at St. Louis, Memphis, Vicksburg, and New Orleans.

Lower Mississippi Valley Division

The President of the Commission also serves as Division Engineer, U.S. Army Engineer Division, Lower Mississippi Valley, headquartered in Vicksburg. The jurisdiction of this Division extends from about Hannibal, Missouri, to the Gulf of Mexico. Work within the Division is carried out by the Engineer Districts listed above.

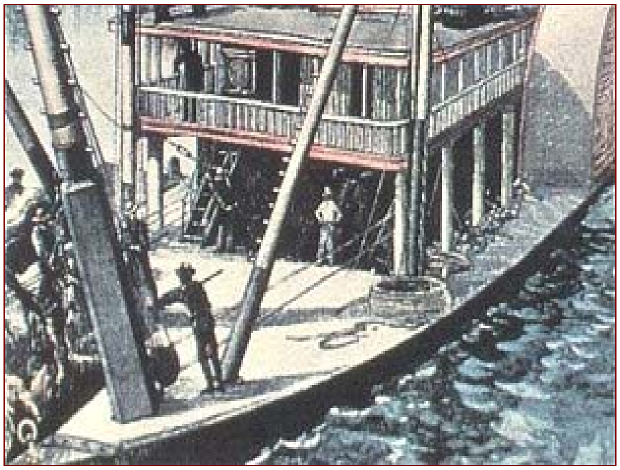


A map of the Lower Mississippi Valley Division
and Mississippi River Commission.
[Click to view larger map.]

Improvements for Navigation

In 1896, Congress authorized a navigation channel 9 feet deep and 250 feet wide at low water between Cairo and Head of Passes. In 1928, the width was increased to 300 feet, and in 1944, the authorized channel depth from Cairo to Baton Rouge was increased to 12 feet at low water, with the authorized width remaining at 300 feet. (The 12-foot channel is to be obtained by a program of bank stabilization and maintained by dredging. Progress is being made on developing this channel, and a 9-foot depth is now being maintained.)

Early improvements of the Mississippi River above Cairo consisted mostly of removal of snags and closure of sloughs to confine low-water flows to the main channel.



A painting of dredging the Mississippi River.

Then in 1907, Congress adopted a project depth of 6 feet between the Missouri River just above St. Louis and Minneapolis, to be obtained by dredging and the construction of wing dams to contract the low-water channel.

As development of inland navigation continued, it became apparent that a depth of 6 feet on the upper Mississippi would not allow it to keep pace with the growing traffic on the 9-foot channels of the lower Mississippi and the Ohio. In 1930, following a careful study of the merits of improvement of the river, Congress authorized construction of a 9-foot channel between Minneapolis and the mouth of the Illinois River, just above St. Louis, providing for the construction of locks and dams. The act was modified in 1932 to provide for some modifications to the improvement plan. Since that time, additional modifications have been made to the basic project.

Under the plan of improvement, 36 locks and 29 dams were constructed. There are no locks and dams below St. Louis.

After the mouths of the Mississippi River had been opened and maintained in a navigable state, Congress authorized in 1945 the development of a navigation channel for oceangoing traffic in the lower reaches of the river. The depths and widths of the channel between Baton Rouge and the Gulf of Mexico are:

- Baton Rouge to New Orleans - 40 by 500 feet
- Port of New Orleans - 35 by 1,500 feet, with portion 40 by 500 feet
- New Orleans to Head of Passes - 40 by 1,000 feet
- In Southwest Pass - 40 by 800 feet
- In Southwest Pass Bar Channel - 40 by 600 feet
- In South Pass - 30 by 450 feet
- In South Pass Bar Channel - 30 by 600 feet
- Mississippi River-Gulf Outlet - 36 by 500 feet
- Mississippi River-Gulf Outlet Bar Channel - 38 by 600 feet

[Continue to River Commerce]

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"SEDIMENT-MORPHOLOGY RELATIONS OF ALUVIAL CHANNELS"

WAITE R. OSTERKAMP

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SEDIMENT-MORPHOLOGY RELATIONS OF ALLUVIAL CHANNELS

By Waite R. Osterkamp[1,2]

ABSTRACT

The interpretation of numerous data collected from alluvial stream channels of the western United States suggests that discharge characteristics are the principal control of channel size, but that sediment characteristics largely determine channel shape. 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.

For the general power function

$$W = a\overline{Q}^b$$

relating width (W) to mean discharge $(\overline{Q})$, the value of the exponent (b) appears to vary 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 highly turbulent alpine streams that have very low sediment discharge.

BACKGROUND AND PURPOSE

During the last decade, personnel of the U.S. Geological Survey in Kansas have conducted a series of studies to develop empirical relations among discharge characteristics and geometry variables of alluvial stream channels. Data have been collected from hundreds of gage sites throughout the western United States. These data represent conditions ranging from highly ephemeral (discharge no more than 1 percent of the time) stream channels of the Southwest to large streams of the Midwest, such as the Missouri River. In recent years, attention has been concentrated on the formational processes of specific types of stream channels. Geometry-discharge relations have been studied to determine the effects of channel-sediment properties, discharge variability and regulation (in cooperation with the Kansas Water Resources Board), and channel modification (in cooperation with the U.S. Army Corps of Engineers). Reports describing limited parts of these investigations are in various stages of preparation or publication. This paper has been prepared to integrate information from these reports and to give an initial interpretation of the geomorphic dynamics of fluvial systems, with emphasis on the control of sediment properties on the shape and pattern of alluvial channels.

The generalizations presented in this paper are based on width-discharge and width-sediment-discharge relations developed for other studies. Data supporting the relations are given as cited, but several specific examples are described to justify the ideas proposed here. The purpose of this paper, therefore, is to suggest and support several principal generalizations concerning the morphology of natural alluvial stream channels. The generalizations that emphasize the effects of fluvial sediment on the size and shape of alluvial channels are summarized by the following:

1. A minimum channel width is defined by the amount and variability of the discharges conveyed, but it is modified by the availability and transport of specific sediment sizes that form and maintain stable alluvial banks.
2. For streams of similar discharge characteristics, a maximum bed or channel width is defined by the amount and percentage of medium- and coarse-grained sand in the total sediment load.
3. The manner in which the shape of an alluvial channel changes in the downstream direction largely is a function of discharge variability, availability of sediment for transport, and the particle-size distributions of the sediment transported.

MEASUREMENT OF CHANNEL VARIABLES

The study of fluvial processes has proven to be among the most complex and difficult topics of geomorphology because of the number of variables involved, the inconsistent or nonlinear interrelations among those variables, and the lack of suitable methods to quantify some of those variables. The effects of fluvial sediment can be recognized and quantified, although it is still unclear which variables of sediment discharge are the best descriptors.

It is reasonable to assume that only two independent variables determine the size and shape of natural stream channels--climate and geology. Divisions or results of these two primary variables pertinent to alluvial channels are the characteristics of precipitation, temperature, soils, topography, and vegetation. Except for temperature, which probably is of minor consequence, these secondary variables are nearly as difficult to quantify as the primary variables. Realistic quantification appears feasible only by a tertiary breakdown. Although tertiary variables can be treated as independent in the study of fluvial systems, it is obvious that they are not independent in nature but depend on both climate and geology. Pertinent tertiary variables include:

1. Total or mean discharge,
2. Variability of discharge,
3. Temporal distribution of discharge (particularly seasonal distribution and elapsed time since the last erosive flood event),
4. Amount of sediment discharge (mean concentration),
5. Size distribution of sediment,
6. Temporal changes in availability and size distribution of sediment,
7. Type of riparian vegetation, and
8. Maturity of the riparian community.

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[2] Non-member advisor of Task Committee on Relationship Between Morphology of Small Streams and Sediment Yield, Hydraulics Division, ASCE.

The variables of discharge (1-3) are primarily determinants of channel size or cross-sectional area. The sediment variables (4-6) are determinants of channel shape and are treated as complicating variables of geometry-discharge relations. The variables of riparian vegetation (7-8) help determine both channel size and shape. Suitable methods of quantifying the effects of riparian vegetation are not yet available, and they will be discussed only briefly. Other variables, such as temperature and water chemistry, no doubt influence geometry-discharge relations, but their effects appear to be minor relative to those of sediment.

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. The present paper considers relations of width with both mean discharge and various flood discharges of specified recurrence intervals.

The coefficients of power-function equations presented here are based on widths and discharges expressed in meters (m) and cubic meters per second (m^3/s). Particle-size diameters are given in millimeters (mm), and silt-clay percentages are the content, by weight, of bed or bank material with particle diameters of less than 0.062 mm.

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, therefore, are presented before a more detailed analysis of the effects of fluvial sediment is described. The variables are discussed in the order previously listed.

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, $\overline{Q}$ (Osterkamp, 1979b):

$$W \simeq a\overline{Q}^{0.50} \quad . \qquad (1)$$

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. The exponent value of this relation agrees with values given in numerous previous papers and appears accurate for the groups of relatively stable channels represented, but it is not accurate for channels of most sand-bed streams or ephemeral streams. In general, the widths of perennial stream channels having stable, accretionary banks, which are resistant to erosion by peak discharges, vary closely with the square root of mean discharge.

When channels are similar in all other respects, including mean discharge and sediment characteristics, variable or flashy discharge produces a broad width, and steady discharge is associated with a relatively narrow width. The peak discharges of the flashy streams winnow away fine material, cause bank erosion, and prevent the establishment of a mature, stabilizing growth of riparian vegetation. Channels with steady discharge, such as regulated streams and the spring-effluent channels of southern Missouri, generally have stable banks and are relatively narrow because erosive discharges are rarely conveyed. The effect of discharge variablity (for perennial streams) is illustrated by 96 sand-bed and sand-banks channels of the Missouri River basin. The ratio of the 10-year flood to mean discharge, $Q_{10}/\overline{Q}$, was computed for each, with 55 and 41 of the streams, respectively, having a ratio greater and less than or equal to 60. Power-function equations for the two groups of data were calculated as follows:

$$W = 9.6\ Q^{0.74} \quad (Q_{10}/\overline{Q} > 60)\ ; \qquad (2)$$

$$W = 8.0\ Q^{0.62} \quad (Q_{10}/\overline{Q} \leq 60)\ . \qquad (3)$$

Aside from the relatively large exponents, it is significant that, particularly for large streams, channels conveying steady discharge (equation 3) are generally narrower relative to discharge than are flashy streams.

Variation in the temporal distribution of discharge is distinguished in several manners, but the most significant effect on channel morphology appears to be the timing of flood events. Studies by Schumm and Lichty (1963), Burkham (1972), and Wolman and Gerson (1978) demonstrated the relation between large erosive floods and channel widths. Numerous data from different streams show that channel material is relatively coarse grained following the winnowing effects of an erosive flood. Limited channel-sediment data (unpublished) have been collected from various streams that have been widened by peak discharges, such as Plum Creek, south of Denver, Colorado, and the Cimarron River in southwestern Kansas. These data, with written descriptions and photographic evidence (Schumm and Lichty, 1963; Burkham, 1972), indicate the changes in bed- and bank-material particle sizes that occur during and following historic flooding.

Effect of Sediment on Width-Discharge Relations

Recent studies (Andrews, 1979; Richards, 1979) have suggested a direct relation between channel size and total sediment discharge. Results from numerous sites in the Missouri River basin (Osterkamp and Hedman, in review) further indicate that sediment concentrations for streams of similar water discharges have a marked effect on width-discharge relations only if a significant portion of the sediment load is moved by traction. Extensive data show that, during normal discharge rates (below flood stage), most sediment coarser than about 0.5 mm is moved primarily by traction (Visher, 1969; Middleton, 1976). When the sediment is suspended and distributed through the entire water depth, variations in load have minimal effect on channel width. Variations in the tractive load that is transported through a portion of water depth (generally not more than about

0.2 m) largely determine a required channel width to maintain movement.

The effect, as indicated by bed and bank material, that the size distribution of fluvial sediment exerts on channel morphology is illustrated by the linear relations of figure 1. The relations are based on data from nearly 300 gage sites, mostly in the Missouri River basin (Osterkamp and Hedman, 1977; in review), that have been separated into groups according to particle-size distributions of bed and bank material. The bed material is assumed representative of the tractive load of the stream. Bank material is formed primarily of sediment from suspension and by coarse sizes deposited on recession of peak discharges. The equations show that narrowest channels and lowest exponents occur when bed material is mostly (greater than 60 percent) silt and clay (fig. 1, line 1). If no sand and coarser sizes are available for transport, all sediment is carried in suspension. The bed and bank materials are nearly homogeneous, and the channel tends to be narrow, deep, and U-shaped.

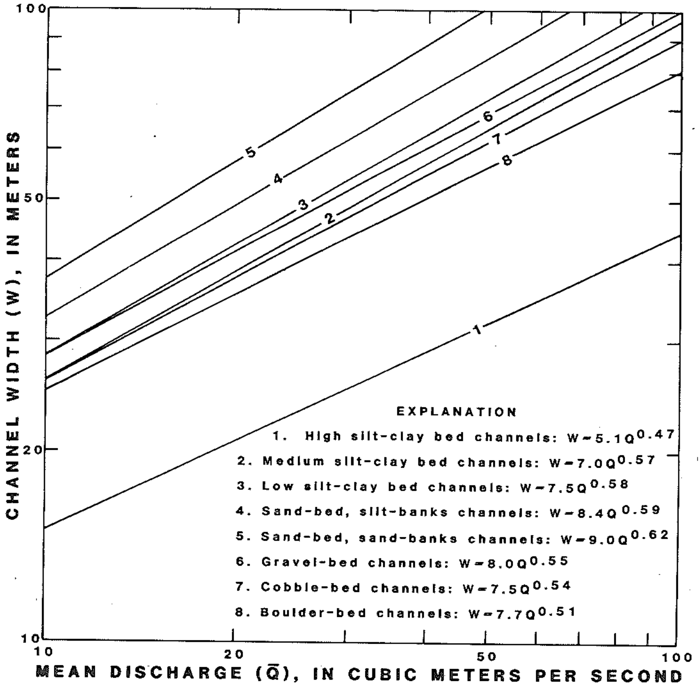

FIG. 1.--Relations of width to mean discharge for channels of specified sediment characteristics

Lines 2 and 3 (fig. 1) relate widths to mean discharges of channels with bed material containing 31 to 60 and 11 to 30 percent silt and clay, respectively. Although these channels consist predominantly of fine particle sizes and tend to have stable, cohesive banks, the increased widths result from the tractive movement of small to moderate amounts of sand. Fluvial-sorting processes, which enrich the bed material with sand and the bank material with silt and clay (Osterkamp and Wiseman, 1980), form a channel section with sloping sides and a nearly horizontal sand bed. Line 1 (fig. 1) suggests that nearly all of the sediment conveyed by the channel consists of fine particle sizes, and lines 2 and 3 suggest that the sediment supply includes both fine sizes and sand. Lines 4 and 5 (fig. 1) relate width to discharge data of stream channels where the bed material is dominated by sand sizes (less than 11 percent silt-clay content and a median-particle size of less than 2.0 mm). The sand-bed, silt-banks channels (line 4) are formed when a sediment supply has significant portions of both sand and finer sizes. Sand-bed, sand-banks channels (bank material with less than 70 percent silt and clay) are formed when the suspended load of fine sizes is small relative to the coarser sizes moved by traction (line 5). Owing to the sand, these channels maintain wide, horizontal beds and have poorly cohesive banks that are susceptible to erosion by peak discharges.

The narrowest and deepest channels occur when sand is not available for transport. Conversely, the widest and shallowest, and often braided, channels occur when the entire sediment supply is of sand size. Similarly, the smallest exponent or slope is associated with channels having high silt and clay in the bed and banks, and the largest exponent is related to channels with the most sand in bed and banks (fig. 1).

To show an extreme condition suggested but not illustrated by figure 1, width and mean-discharge data were collected from various braided streams of similar sediment conditions in the Sand Hills area of Nebraska (Osterkamp and Hedman, in review). The data yield the relation:

$$W \simeq 3.0\bar{Q}^{1.0} , \qquad (4)$$

which suggests that downstream changes in discharge for these streams are accommodated totally by adjustments in channel width, not by changes in mean channel depth or water velocity. This observation is consistent with bank-material data (Osterkamp and Wiseman, 1980), which suggest that water velocities near the wetted perimeter and processes of bank sorting do not change significantly in the downstream direction. In other words, increases in discharge for braided streams 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. Considering the extremes of tractive movement--narrow channels formed entirely of silt and clay (fig. 1, line 1) or highly braided channels formed entirely of sand--it is inferred that the exponents of the width-mean discharge relations range from roughly 0.45 to 1.0.

Lines 6, 7, and 8 are power-function relations for (nonglacial) channels with median-particle sizes of bed material corresponding to gravel, cobbles, and boulders, respectively. Abundant sand in bed material commonly is available for transport in gravel-bed channels, whereas sand ordinarily is protected in cobble-bed channels and, particularly, in boulder-lined channels. Generally, the banks of these channels are armored by the same coarse sizes that armor the beds (Osterkamp and Wiseman, 1980). The lines and equations (fig. 1) show decreasing channel widths and power-function exponents with increasing bed-material sizes. Implicit in these trends are increases of channel gradient, channel roughness and armoring, and decreasing tractive sediment movement at normal discharge rates. For highly turbulent, well-armored alpine streams, only moderate channel widths are required because minimal amounts of sand and coarser sizes are moved during low to medium flow. At high discharge rates, bed and bank sorting processes occur, and large sizes are moved tractively. Hence, greater widths occur in channels having coarse sizes than in the silt-clay bed channels (fig. 1, line 1), although both types of channels are regarded here as highly stable.

Summarizing the power functions of figure 1, lines 1 through 5 refer to progressive increases in channel sandiness and in width relative to discharge. Increasing sandiness suggests decreasing channel stability because of the corresponding reduction in cohesiveness afforded by the silt and clay of the channel material. As the median-particle size of the bed material increases beyond the sand range, the coarsest, normally immobile sizes cause increased armoring, or protection of available sand, and reduced tractive sediment movement. Lines 5 through 8, therefore, indicate decreasing widths relative to mean discharge and thus increasing channel stability. The exponents of the power function equations (fig. 1), which appear to vary directly with the amount of tractive sediment movement, can be likened loosely to channel instability as used here.

The size distribution of fluvial sediment also helps control channel morphology through sorting processes. Extensive particle-size analyses of bed and bank samples from perennial streams of the Missouri River basin (Osterkamp and Wiseman, 1980) suggest that the formation of stable alluvial banks is dependent on the availability and sorting of specific size ranges of sediment. The bank-material analyses (fig. 2), which represent wide ranges of geologic, topographic, and climatic conditions, show a pronounced tendency toward bimodal distributions. Based on logarithmic-probability analysis of bank samples, the fine-grained subpopulation includes particle sizes up to about 0.35 mm, whereas a coarse-grained subpopulation has sizes greater than about 1.3 mm. Sand sizes in the range between the two subpopulations are generally absent. Analyses of bed samples from the same channel sections give unimodal distributions, do not show deficient sand sizes, and show a size "break" at 0.5 mm (fig. 2).

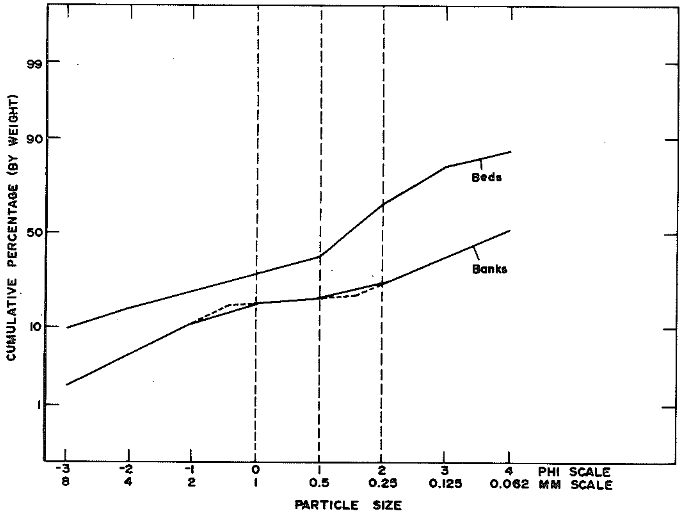

FIG. 2.--Particle sizes of bed and bank material from perennial stream channels of the Missouri River basin. The cumulative size analyses for the beds is the average of 239 samples; that for the banks is the average of 471 samples. Dashed lines are straight-line projections from data points, yielding an inferred range of deficient sand sizes in bank material.

Based on previous studies (Middleton, 1976; Visher, 1969), comparisons of the data with analyses of the suspended-sediment loads, and comparisons of coarsest sizes found in the bed and banks of specific channels, it is inferred that the fine subpopulations of both bed and banks are associated with the suspended loads. The coarse subpopulations of both probably are associated with tractive movement. Sand sizes of 0.35 to 1.3 mm do not occur in the bank material because these sizes are not in suspension at normal discharge rates. At flood discharges, the sand sizes apparently are washed from the bank slopes and coarser sizes probably remain as a lag deposit.

Relatively stable banks are deficient in 0.35 to 1.3 mm sand regardless of channel gradient or basin characteristics. Bank-sorting processes, therefore, appear to be essentially constant in the downstream direction, which suggests that stream velocities at and near the channel perimeter do not change in the downstream direction. If the total-sediment load of a stream is predominantly medium- to coarse-grained sand, wide, unstable channels will result because the fine (less than 0.35 mm) and coarse (greater than 1.3 mm) sizes required for bank stability are not available. Braided channels, such as those of the Sand Hills area in Nebraska, are likely to occur regardless of discharge variability, when virtually all sediment in transport is between 0.35 and 1.3 mm in size.

Short-term to seasonal changes in the availability and size distribution of sediment probably occur in most streams that have a supply of well-graded sediment. Whether the changes are natural or induced, the processes of bank erosion and accretion (release from storage and storage of fluvial sediment) are generally too slow to reflect those changes. Hence, short-term changes are not considered by the equations presented here. Short-term changes in sediment supply represent a stress, or independent variable, affecting the width-discharge-sediment relations. A long-term change in the sediment load and distribution, however, often accompanies the progressive changes by a stream channel to attain stability after a destructive flood (Schumm and Lichty, 1963; Burkham, 1972; Osterkamp, 1979a). As used here, the virtually instantaneous coarsening of bed material due to the winnowing effects of a highly erosive flood is associated with long-term change because years or decades may be required for new storage of fine sediment and a return to pre-flood conditions. Long-term sediment changes, therefore, are a dependent-to-interrelated variable of the width-discharge-sediment relations and are reflected by the equations presented and referenced here.

Flood Relations

Power-function equations that include flood discharges of specified recurrence interval have been developed for the Missouri River basin (Hedman and Kastner, 1977; Osterkamp and Hedman, in review) by using the same techniques as those used for relating channel characteristics to mean discharge at gaged sites. Relations of channel width with flood discharges generally are not as well defined as those relations which include mean discharge because (1) the frequencies of flood discharges generally are not as well defined at gaged streams as is mean discharge and (2) flood discharges generally are conveyed through channel sections of which only a small part of the perimeter is the result of recent fluvial processes.

Nevertheless, the width-discharge equations for specified flood frequencies vary with the channel-sediment characteristics and reflect the influence of fluvial sediment (Osterkamp and Hedman, in review).

The width-discharge relations of the various channel types for the 10-year flood, as an example, show variations similar to those for mean discharge (fig. 1). Flood relations for the various channel types are not provided, but examples are given for channels with sand beds and silty banks (fig. 3). The exponents of the equations increase with recurrence interval, but probably not as a result of increasing tractive sediment movement. Rather, the inferred causes of the increasing exponents are (1) the tendency for attenuation of flood discharges in the downstream direction with increase in recurrence interval and (2) peak rates of precipitation and runoff, per unit area of a drainage basin, tend to decrease with increasing basin size.

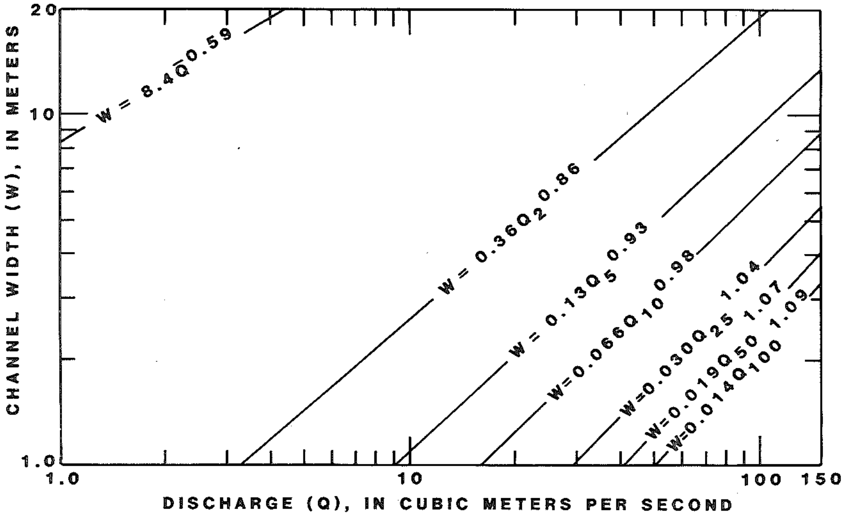

FIG. 3.--Power-function relations of width to discharge characteristics for channels with sand beds and dominantly silt-clay banks. $\bar{Q}$ is mean discharge; Q_2 through Q_{100} are discharges of floods with recurrence intervals of 2 through 100 years.

EXAMPLES

To better characterize the generalizations previously made, figure 4 provides interpretations of how four types of stream channels are altered by floods and then adjusted during subsequent periods of normal discharge rates. Although the relations are hypothetical and are based on a mean discharge of about 1.0 m^3/s, they refer to actual channels and mostly are represented by the general relations of figure 1. The graphs (fig. 4), reading from bottom to top, represent a channel formed of silt and clay in eastern Kansas (fig. 1, line 1), a highly armored alpine stream in Wyoming (fig. 1, line 8), a sand-bed, sand-banks channel in Nebraska (fig. 1, line 5), and a sandy, highly ephemeral stream channel (flow less than 1 percent of the time) in southern Arizona (not represented in fig. 1). Because the ephemeral stream channel is formed by infrequent flow events, discharge rates during periods of flow generally are much greater than 1.0 m^3/s, and the channel is very wide relative to mean discharge (fig. 4).

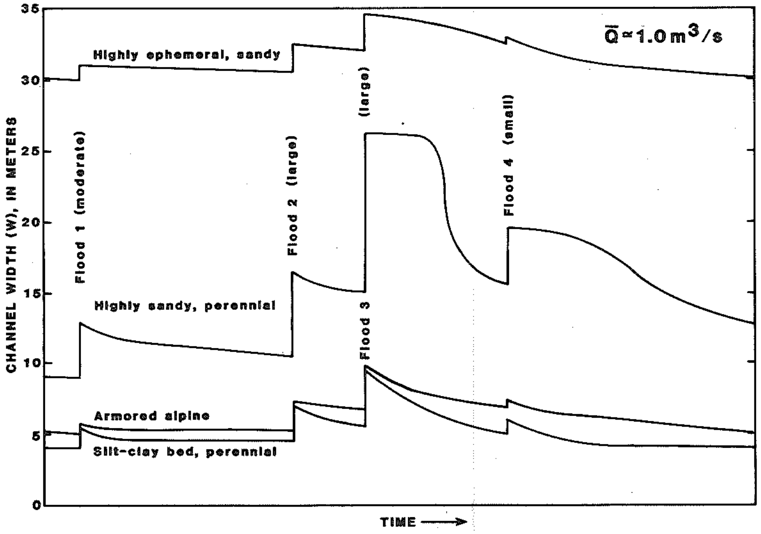

FIG. 4.--Schematic width-time relations for different types of stream channels.

A moderate flood (fig. 4, flood 1) widens all four channels. The alpine stream is widened least owing to the armor of cobbles and boulders. Widening is substantial in the sandy, perennial stream channel because the poorly cohesive banks are readily eroded. The ephemeral stream channel is not widened significantly because the channel was previously shaped by similar flow events and little or no healing was possible during the extended no-flow periods. Following flood 1, bank accretion and channel narrowing occurs in all four cases but is most pronounced for the sand channel that had been widened most. Succeeding floods (fig. 4, floods 2, 3, and 4) alter the various channels according to the timing and magnitude of the floods, the typical discharge characteristics of the streams, and the channel-sediment properties. Flood 2 widens the channels and destroys some flood-plain vegetation, thereby making the channels vulnerable to bank erosion by flood 3. Flood 4 represents an interruption of the healing or narrowing process after flood 3.

The silt-clay bed channel shows significant widening by erosive floods because the banks are poorly protected. Following the various floods, however, narrowing is rapid because abundant silt and clay in suspension is available for bank accretion. The armored channel is not easily widened by peak discharges, but subsequent narrowing is slow owing to the difficulty of replacing either fine or coarse sizes to the banks. The sandy, perennial stream channel is easily widened by the floods, but sufficient fine sediment in transport is available for recovery to occur readily.

The widths of the highly ephemeral stream channel always reflect 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 flood 1, therefore, the sandy, perennial stream channel (fig. 4) 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 equation 4 of figure 1. Following flood 3, the channel was more than doubled in width (at the expense of flood-plain area), straightened, and modified to a braided pattern. Most silt and fine sand had been washed from the bed material, and coarse-sand to gravel sizes had been added by destruction and reworking of flood-plain deposits. Whereas equation 5 of figure 1 might have described the width-mean discharge relation prior to flood 2, the braided, highly unstable conditions of this channel following flood 3 are not represented in figure 1.

In all cases, the relations of figure 4 suggest that channel narrowing (bank accretion) is accompanied by (1) a general reduction of bed-material sizes and tractive sediment movement, (2) storage of fine sizes in bank material, and (3) reduction of channel gradient (increased sinuosity). Although supporting data are not available, it is inferred that the rates of channel narrowing generally decrease as stable conditions are approached (Osterkamp, 1979a). An exception is represented by the sandy, perennial stream channel (fig. 4). Following the extensive flood-plain destruction of flood 3, an extended period was required for re-storage of fine sediment sizes in the channel alluvium before significant narrowing could occur. With storage of fines, a change from a braided pattern to a defined channel could proceed rapidly. Channel changes of this sort have been documented for the Cimarron River in Kansas (Schumm and Lichty, 1963), the Gila River in Arizona (Burkham, 1972), and Plum Creek in Colorado (unpublished).

CONCLUSIONS

Regardless of the discharge characteristics in alluvial streams, 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.

If a stream having steady discharge transports only fine-grained sediment in suspension, the channel will assume a narrow (relative to water discharge) and highly stable condition. An opposing, or widening, tendency for a channel section is caused by sand and coarser sediment that moves by traction and requires a width proportional to the effect of the tractive load. If the variability of discharge and sediment characteristics at two sites on a stream are similar, the channel shape at both sites will be similar; however, the channel size will vary with the amount of discharge. If the sediment characteristics differ, both size and shape of the channel will change between the sites.

The equations of figure 1 indicate that the largest exponents for the width-discharge relations should be associated with large rates of tractive sediment movement. However, the equations were developed from data collected at relatively stable sites and do not represent braided conditions. Data from braided streams of the Sand Hills area of Nebraska, however, give an exponent of 1.0 (Osterkamp and Hedman, in review).

As indicated by figure 4, the width-discharge relations of a stream are not constant through time. Temporal changes of the relations, however, are accompanied by changes in the channel-sediment characteristics, roughness, and channel gradient. If little or no net aggradation or degradation is occurring during a suitably defined period, any channel reach can be defined by power-function relations that assume approximate equilibrium.

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Statistical Summaries of Streamflow Data and Characteristics of Drainage Basins for Selected Streamflow-Gaging Stations in Arizona Through Water Year 1996

By G.L. POPE, P.D. RIGAS, *and* C.F. SMITH

Water-Resources Investigations Report 98–4225

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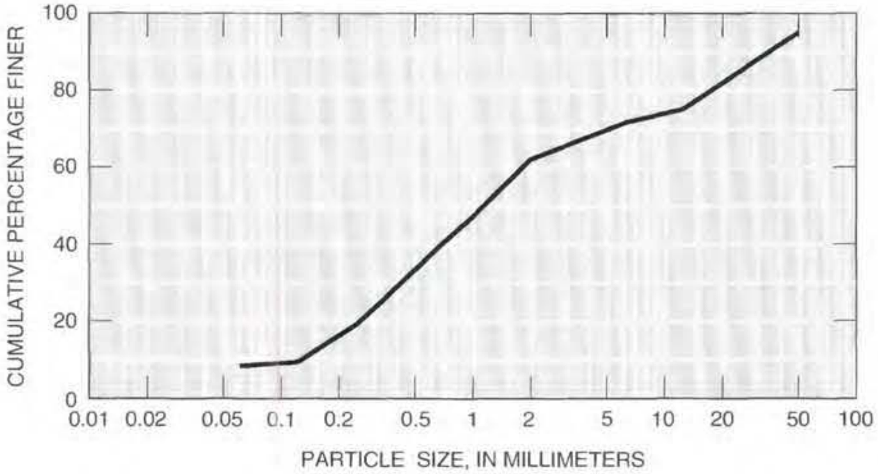
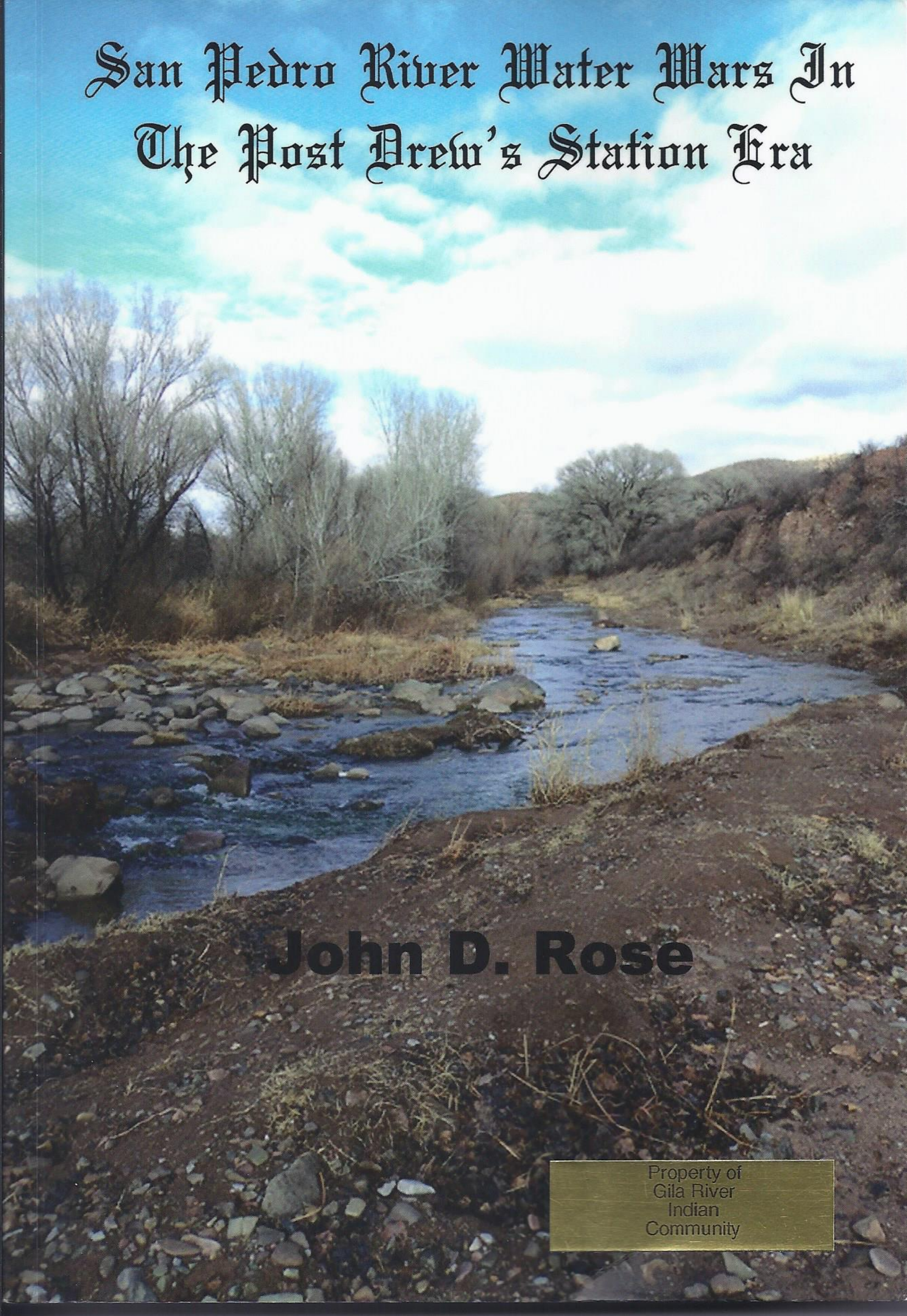


Figure 14*C*. Particle-size distribution for bed material, San Pedro River near Charleston.

Figure 14*D*. View from left bank looking downstream toward right bank of cross-section 1, October 8, 1964, San Pedro River near Charleston.

San Pedro River Water Wars In The Post Drew's Station Era



John D. Rose

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John Rose is also the author of *Charleston & Millville A.T. Hell on the San Pedro* and *On the Road to Tombstone: Drew's Station, Contention City and Fairbank.*

For articles written by John D. Rose visit his website, *WyattEarpExplorers.com*, the most popular Tombstone/Earp related site in the world.

Photo on reverse is of the San Pedro River just south of Contention City and cover photo of the San Pedro River near Charleston by John D. Rose. Photo on the back cover by Aubrey Summer Rose.

INTRODUCTION

Recorded impressions of the San Pedro River occur only intermittently in the periods prior to and after the major settlement and development of the mill towns connected to the Tombstone mining boom. Some notices appear in the Weekly Arizonian which offer insights, and accounts exist by others who came through the area, even if only for a brief time. James Bell was such an example, bringing a herd of cattle through Arizona on the way to California in the summer of 1854. "The valley through which the San Pedro passes is a desirable location for ranches. The hills on either side are covered with timber…and a good quality of grass; some portions of these hills are verry [sic] pretty…Upon the whole this is the most habitable place seen since I left San Antonio." [1]

I too am enchanted by this area. Its rugged aesthetic still appeals to me, and it challenged me to learn more than just locations of the sites that settlers left behind. I wanted to know who they were, and learn as much as possible about their lives while living there. It led me to many discoveries and many publishing breakthroughs. I was honored to be the first to publish excerpts from Cora Drew's account of her life at Drew's Station, as well as unknown photos generously shared with me by the Drew family. Their generosity has contributed to my greater understanding of the river, which has been a focus for me of decades of travel and research. It has been a privilege and a thrill to work with them. I find writing about towns and settlements along the San Pedro River a unique challenge, wondering if enough information can be found even for short articles. Persistence rewarded me with the research that comprised my first book, *Charleston and Millville, A.T.: Hell on the San Pedro*.

After searching through the Charleston area, I began to look at the area north of Contention City. I was in search of the stage road that completed the final leg of the journey from Tombstone to Contention to Benson. I envisioned not only the remains of a dusty roadway that thousands once traversed, but also accompanying home wends its way north, both above and below the ground, till it reaches the Gila River near Winkelman, Arizona.

THE SAN PEDRO RIVER OF A DIFFERENT ERA

On any given day in the 1880's, a horseback ride along the San Pedro River would offer a visual experience that today is hard to imagine. In the spring and summer along the San Pedro one would still see acres of golden brown grasses turned to green, mesquite, willows, and other trees here and there having bloomed for the season, just as one would see today. But this is where the like comparisons would come quickly to an end.

Interspersed between large patches of grass and mesquites would be acres of corn, alfalfa, orchards and garden crops with rows of melons and potatoes in production up and down the San Pedro, often on both sides of this overburdened water way. One would see a steady traffic of wagons filled with vegetables headed for market, farmers and their helpers toiling in the fields, and smoke rising from wood stoves inside the small and often primitive cabins that many along the river called home. Earthen dams and connecting irrigation ditches would guide water flow to distant crop fields. It was a dynamic population that often traveled north and south along the river, heading easterly to Tombstone for banking, shopping, and entertainment only when such errands were required. These farmers often qualified as ranchers as well, tending to stock. The stereotype that ranchers were one group of people, and on the other side farmers were an opposing group, is overplayed. Rather, the portrait of such entrepreneurs shows those who are eager to earn for their families in whatever way the land would allow.

These small settlements would see children playing along the river and attending school. Those folks located in the rural settings also rubbed shoulders with mill men and saloon keepers at river centers such as Contention City and Charleston. Jobs were fluid as mill men became ditch diggers and farm workers and repair men.

Indian sightings were common at this time; Parsons was hoping to dodge any chance meetings with Apaches and Geronimo. On June 15th, he "lunched at St. David" noting that "The Mormons treated us well…I left others here and went to Benson for promised military escort." On Thursday, June 17th, a jumpy Parsons needed a bath and his horse was in need of a rest. "Good bath in [the] San Pedro River this afternoon. Water didn't quite cover me lying down, but had a good wash meantime keeping lookout for Indian." [3] It is noteworthy that prior to the summer rainy season, water flow in the river was scant, barely able to cover someone lying down in it.

NO WATER AT THE SAN PEDRO STAGE STATION

The Weekly Arizonian would also record in 1859 which stations, along what is now commonly referred to as the Butterfield Stage route, had water and which did not, for the benefit of travelers. They reported that the San Pedro Station, which was built so close to the river that the waterway later consumed the site, was without water in 1859, long before Tombstone was even discovered and major settlements sprang up along this key, but very limited, water way. But travelers arriving in Tombstone sometimes told of having to wait to cross the river during its flooding, which only occurs after a substantial rainfall. [4]

River Variability and Complexity

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Chapter 1

Introduction

Upon having some astronomical phenomena explained to him, Alfonso X, King of Castile and Leon (1252–84) exclaimed,

> If the Lord Almighty had consulted me before embarking upon creation, I should have recommended something simpler
>
> (Mackay, 1991)

River engineers and geomorphologists might well have a similar opinion especially when it is recognized how variable a river can be through time and from reach to reach. However, when Leopold and Maddock published US Geological Survey Professional Paper 252 it was a landmark occasion. Geologists and geomorphologists suddenly became aware of order in rivers, although engineers with their regime equations had anticipated these hydraulic geometry relations. The hydraulic geometry relations of width, depth, and velocity were immediately of value in prediction of river characteristics. However, some of us neglected to recognize how variable the relations were and how significant was the scatter about the regression lines. This should have warned us that, yes, in a general sense channel width increased downstream as the 0.5 power of discharge, but a prediction of what the width was around the next bend could be in gross error, and, therefore recognizing this variability could be of considerable practical significance.

River characteristics vary sometimes little and sometimes greatly. Reaches are singular because of the numerous variables acting that prevent a single variable, discharge, from dominating river morphology and behavior. The question to be answered is why is one reach of a river connected to a different type of reach? That is, why can reaches be so different? For example, why does a straight river become meandering and a meandering river braid or anabranch? An understanding is critical to the practical application of river data.

Recently, books dealing with this fluvial variability have been edited (Gregory, 1977; Schumm and Winkley, 1994; Gurnell and Petts, 1995; Miller and Gupta, 1999). Most of the literature dealing with river variability and change has involved what have been referred to as alluvial rivers or alluvial adjustable rivers, and these have been grouped into braided, meandering, and straight. However, more recently considerable attention has been devoted to the study of steep mountain streams and the effects of bedrock (Tinkler and Wohl, 1998).

A modern alluvial river is one that flows on and in sediments transported by the river during the present hydrologic regime, but it is associated with an older sediment complex at depth. Alluvial rivers have always played an important role in human affairs. All of the early great civilizations rose on the banks of large alluvial rivers such as the Nile, Indus, Yellow, Tigris, and Euphrates. River engineering began in those early times to minimize the effects of floods and channel changes. Today, engineers face the same problems, and they have been successful in developing flood control, navigation, and channel stabilization programs but often at great cost and with the need to continually maintain and repair structures and channels.

In order to manage alluvial rivers, an understanding of their complexity in space and through time is necessary. They differ in three ways:

1. there is a spectrum of river types that is dependent upon hydrology, sediment loads, and geologic history (in other words, rivers differ among themselves);
2. rivers change naturally through time as a result of climate and hydrologic change;
3. there can be considerable variability of channel morphology along any one river, as a result of geologic and geomorphic controls (Schumm and Winkley, 1994).

Information on these differences, especially the last two, will aid in predicting future river behavior and their response to human activities.

An important consideration in predicting future river behavior and response is the sensitivity of the channel. That is, how readily will it respond to change or how close is it to undergoing a change without an external influence? For example, individual meanders frequently develop progressively to an unstable form, and a chute or neck cutoff results, which leads to local and short-term channel adjustments. The cutting off of numerous meanders along the Mississippi River caused dramatic changes, as a result of steepening of gradient, which led to serious bank erosion and scour (Winkley, 1977).

Because of this complexity the stratigrapher-sedimentologist, who must interpret ancient valley-fill and alluvial plain deposits, faces a great challenge. For example, many fluvial successions will display characteristics of more than one type of river. This is not "sedimentological anarchy," as suggested by Walker (1990), but it is a recognition of the complexity and variability of fluvial systems in space and time (Miall, 1996, p. 202).

If the sedimentologist-stratigrapher is concerned with the vertical third dimension of an alluvial deposit, the river engineer and geomorphologist is essentially concerned with the two-dimensional surface of the valley fill.

Chapter 2

Types of rivers

Before considering the variability of a single river, it is necessary to consider the different types of rivers that exist (Table 2.1). Once a topic is sufficiently comprehended, it appears logical to develop a classification of its components. A classification can provide a direction for future research, and there have been many attempts to classify rivers (e.g., Schumm, 1963; Mollard, 1973; Kellerhals *et al.*, 1976; Brice, 1981; Mosley, 1987; Rosgen, 1994; Thorne, 1997; Vandenberghe, 2001). Indeed, Goodwin (1999) thinks that there is an atavistic compulsion to classify, and indeed, an individual's survival may depend on an ability to distinguish different river types (deep versus shallow).

Depending upon the perspective of the investigator, a classification of rivers will depend upon the variable of most significance. For example, the classic braided, meandering and straight tripart division of rivers (Leopold and Wolman, 1957) is based upon pattern with boundaries among the three patterns based upon discharge and gradient. Brice (1982, 1983) added an anabranched or anastomosing channel pattern (Figure 2.1) to the triad and distinguished between two types of meandering channels (Table 2.1). The passive equiwidth meandering channel is very stable as compared to the wide-bend point-bar meandering channel (Figure 2.2). This is a very important practical distinction between active and passive meandering channels (Thorne, 1997, p. 188). A highly sinuous equiwidth channel gives the impression of great activity whereas, in fact, it can be relatively stable (Figure 2.3). Brice also indicates how width, gradient, and sinuosity, as well as type of sediment load and bank stability varies with pattern (Figure 2.2).

Based upon examination of sand-bed streams of the Great Plains (Kansas, Nebraska, Wyoming, Colorado), USA, and the Murrumbidgee River, Australia, Schumm (1968) proposed a three-part division of rivers based upon type of sediment load and channel stability (Table 2.2). The bed sediment in these channels did not vary significantly; therefore, grain size was not related to channel morphology, but type of load (suspended, mixed, or bed-material) was.

There are five basic bed-load channel patterns (Figure 2.4) that have been recognized during experimental studies. These five basic

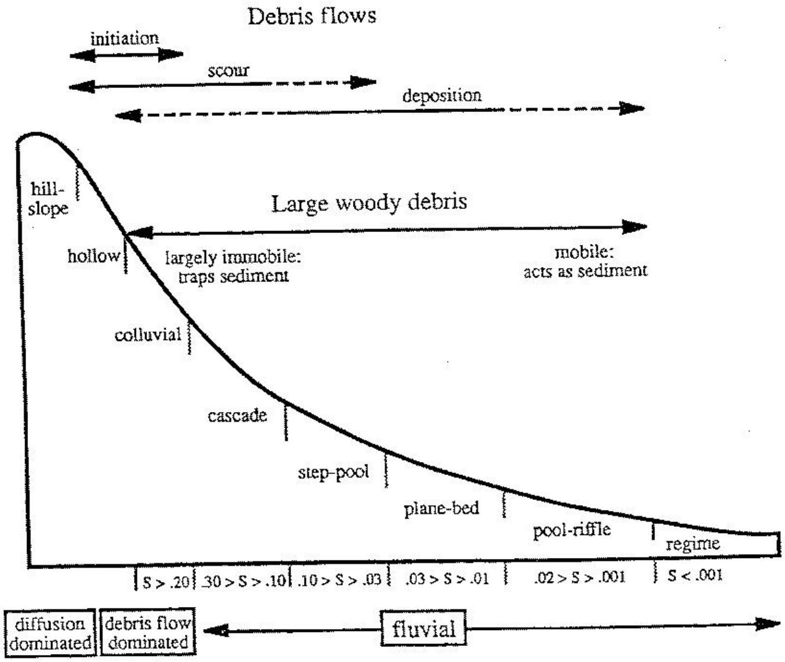


Figure 2.6 Idealized long profile from hillslopes and unchanneled hollows downslope through the channel network showing the general distribution of channel types and controls on channel processes in mountain drainage basins (from Montgomery and Buffington, 1997).

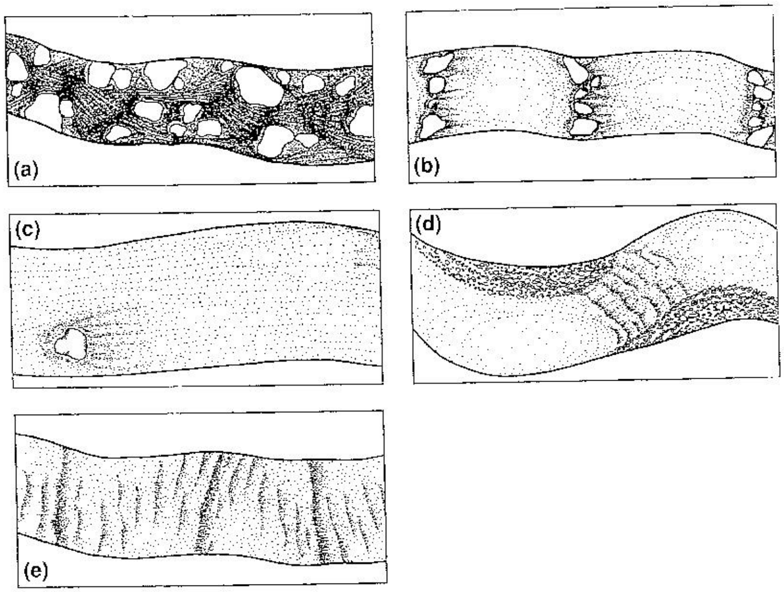


Figure 2.7 Schematic planform illustration of channel morphologies at low flow: (a) cascade channel (Figure 2.6) showing nearly continuous, highly turbulent flow around cobbles and boulders; (b) step-pool channel showing sequential highly turbulent flow over steps and more tranquil flow through intervening pools; (c) plane-bed channel showing single boulder protruding through otherwise uniform flow; (d) pool-riffle channel showing exposed bars, highly turbulent flow through riffles, and more tranquil flow through pools; and (e) dune-ripple channel showing dune and ripple forms as viewed through the flow (from Montgomery and Buffington, 1997).

Although Figure 3.3 was developed independently of Figures 3.1 and 3.2, they can be related. For example, the pre-incision channel of Figure 3.1(a) is associated with Time a (Figure 3.3), whereas the newly incised channel of Figure 3.1(a) occurs between Times a and b (Figure 3.3). The still deepening channel of Figure 3.1(b) occurs between Times b and c of Figure 3.3. The widening and commencement of sediment storage of Figure 3.1(c) occurs between Times d and e of Figure 3.3. The relatively mature channel of Figure 3.1(e) develops between Times d and e, and is complete at Time f (Figure 3.3). This sequence can take about 40 to 50 years in channelized streams of the southeastern (Figure 3.1) USA and over 100 years in the arroyos of the southwestern (Figure 3.2) USA.

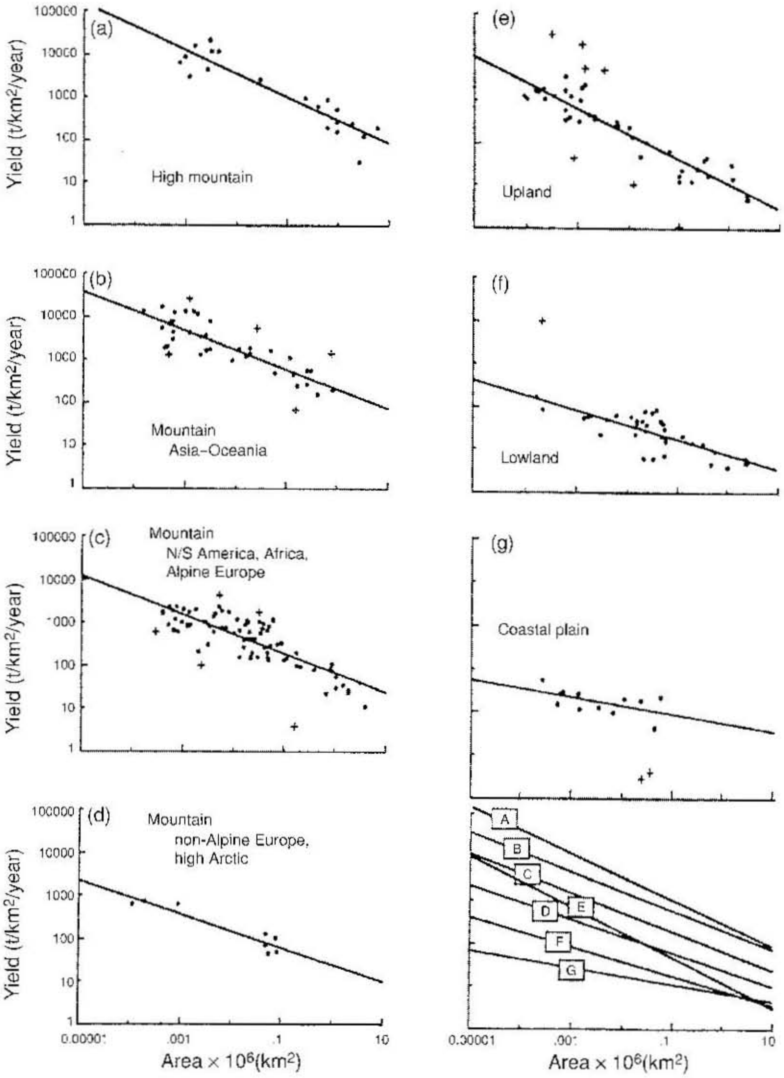
In summary, there are many causes of channel incision (Table 3.1), therefore, each incised channel must be evaluated separately. However, in many cases the incision process destroys evidence for its cause. An understanding of the cause of incised channels is important for their prevention, but it is probably less so for their control following incision. In many cases, more than one cause combines to induce incision. For example, a large flood (D2) may trigger incision, but it is the buildup of sediment in the valley (B7) that sets the stage for incision, and the impact of animals or humans may also be significant.

Although all of the causes listed on Table 3.1 can cause channel incision, they may not. Depending upon the magnitude of the impact and the sensitivity of the channel or valley floor, incision does not always result. Therefore, it is important to recognize that in a given region, channel behavior may not be in phase. That is, some channels may be incised, whereas others are aggrading or are relatively stable. Observation of some incised channels should not cause an investigator to ignore other apparently stable valley floors. Finally, timing is important regarding control of incised channels, and the results of human impacts can vary greatly depending upon the stage of incised-channel evolution (Figure 3.3).

Other responses

The other erosional responses listed on Table 3.1 are obvious. For example, nickpoint migration is the upstream shift of an inflection in the longitudinal profile of the stream (Figure 3.4). This break in the smooth curve of the stream gradient results from rejuvenation and incision of the stream. A nickpoint in alluvium moves upstream, especially during floods. Above the profile break the river is stable; below the break there is erosion. As the nickpoint migrates past a point, a dramatic change in channel morphology and stability occurs (Schumm *et al.*, 1987). Nickpoints are of two types: first is a sharp break in profile which forms an in-channel scarp called a headcut (Figure 3.4a), and second is a steeper reach of the channel, a nickzone over which the elevation change is distributed (Figure 3.4b). It is important to recognize that through time a stable reach of river may become suddenly very unstable as a result of passage of a nickpoint.

Figure 5.2 Variation of sediment load with drainage basin area for seven topographic categories of river basins. Note the marked difference between high mountains (a, b, c, d), upland (e), and lowland and coastal plain basins (f, g) (from Milliman and Meade, 1983).



boundary between the Pacific and Indian tectonic plates, that is, they are related ultimately to rates of tectonic uplift and relief creation.

Rivers often follow structural lows or major geofracture systems. Melton (1959) estimated that between 25 percent and 75 percent of all continental drainage in unglaciated regions has been tectonically influenced or controlled, while Potter (1978) concluded that some large rivers have persisted in essentially their present locations for hundreds of millions of years, because they occupy major tectonic zones. Tectonic deformation by altering channel gradient can have a significant impact on the behavior and form of a particular reach of river.

Earthquakes that occur a considerable distance upstream may affect the downstream river channels. For example, the 1950 earthquake in Bangladesh caused massive landslides in the Himalayas

Chapter 13

Floods

Floods (Figure 1.2) normally affect almost all of the length of a river but, of course, there are exceptions. For example, the flood may only impact the downstream reaches of a channel or an upstream flood may have its effects dissipated downstream. However, except for extreme events that not only modify the channel, but also the valley, the impacts are ephemeral, being lost as the channel readjusts during floods of lesser magnitude.

Floods produced by local events such as the failure of landslide dams will be discussed in Chapter 15. Here are considered hydrologic events caused by climatic conditions. Wohl (2000b, p. 167) states these conditions as: "A flood may cause dramatic changes along some reaches of a channel and have relatively little effect on other reaches. Similarly, a flood that occurs once every hundred years may create erosional and depositional forms that are completely reworked within 10 years along one channel, but that persists for decades along a neighboring channel."

Stream channels in eastern Australia decrease in size downstream contrary to hydraulic geometry rules (Nanson and Young, 1981a, b). The reason is that the floods go overbank downstream and the channels convey only part of a flood. Also in Australia, Warner (1987a, b) identified periods of higher and periods of lower average rainfall and flooding. These flood-dominated regimes (FDR) and drought-dominated regimes (DDR) tend to persist from 30 to 50 years. The FDR have mean annual discharges from two to four times greater than DDR. During FDR, channel width increases and depth decreases but the greatest effect is along sandy reaches (Pickup, 1986) or where all of the flow is confined to a channel. For example, Mullet Creek (Nanson and Hean, 1985) sustained up to 340 percent widening in confined reaches whereas widening was about 20 percent downstream where the floods were overbank and gradients were gentler. Also, cutoffs were more likely to occur during FDR (Erskine, 1986a, b).

During floods, erosion dominates where velocity and stream power are greatest. For example, during the Big Thompson flood of 1976 in Colorado, channel reaches less than 40 m wide and with gradients of 0.02–0.04 had major scour, whereas reaches greater than

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Alluvial chronologies and archaeology of the Gila River drainage basin, Arizona

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ABSTRACT

Late Quaternary alluvial chronologies are established for five streams (Gila River, Salt River, Tonto Creek, Santa Cruz River, and San Pedro River) in the Gila basin of southern Arizona. Each streams has a complex history of deposition, erosion, and landscape stability that structured and fragmented the archaeological record over the last 15,000 years. The limitations that geologic processes imposed on the archaeological record of these alluvial environments must be recognized before meaningful interpretations of prehistory can be made. These stratigraphic sequences also provide the basis for reconstructing changes to the alluvial landscape of each valley over time. All five streams were intensively utilized during the Late Prehistoric period (A.D. 300–1450) by the Hohokam. The Hohokam were irrigation agriculturalists who were dependent upon these streams for survival. Thus, the regional stability and instability of the floodplain environments of southern Arizona influenced the expansion, contraction, reorganization, and collapse of the Hohokam.

1. Introduction

The drainage basin of the Gila River encompasses most of southern Arizona. This land of broad valleys and high mountains lies in the heart of the semi-arid Sonoran Desert. The streams flowing through this region were the focal point for human activities from the Paleoindian through the Historic time periods. Thus, understanding the landscape history of the Gila River and its tributaries is important to interpreting the archaeological record and to understanding the history of human utilization of the region.

The Gila River drains 150,732 km^2 and flows into the Colorado River (Fig. 1). Major tributaries include the Verde, Salt, San Simon, San Francisco, San Pedro, and Santa Cruz Rivers. Very little stratigraphic work has been conducted on the Verde, San Francisco, Salt, and San Simon Rivers, though stratigraphic records exist for the middle Gila River (Huckleberry, 1993, 1995; Waters and Ravesloot, 2000), Santa Cruz River (Haynes and Huckell, 1986; Waters, 1988; Freeman, 1997; Waters and Haynes, 2001; Haynes and Huckell, 2007), upper San Pedro River (Haynes, 1981, 1982, 1987; Waters and Haynes, 2001), and segments of the Salt River particularly in its headwater areas in the Tonto Basin (Waters, 1998).

In this paper, the alluvial records and landscape histories of the middle Gila River, Santa Cruz River, upper San Pedro River, and Tonto Basin are reviewed. This is followed by a discussion of the ways in which the archaeological record of the Gila River drainage basin has been shaped by geological processes during the late Quaternary and how landscape changes along these rivers affected prehistoric people.

2. The Gila River drainage basin alluvial stratigraphy

The stratigraphic records for the middle Gila River, Santa Cruz River, upper San Pedro River, and Tonto Basin were compiled through the examination of numerous cut-bank exposures and exposures made by mechanical trenching. Chronological control for these stratigraphic sequences is provided by radiocarbon dates (primarily on wood and charcoal) and the stratigraphic position of diagnostic artifacts. The sequences were largely created in the late twentieth century and represent the work of many scholars.

2.1. Middle Gila River

The middle Gila River extends from its junction with the Salt River to the bedrock gorge 26 km east of Florence (Fig. 1). This segment of the Gila River has a watershed of about 50,000 km^2. The channel of the Gila River is entrenched and flanked by three terraces (Huckleberry, 1993, 1995; Waters and Ravesloot, 2000). Adjacent to the streambed is a low terrace, Terrace 1 (T-1), that is inundated during large floods. Above Terrace 1 is a prominent terrace, Terrace 2 (T-2), which is underlain by sediments dating from 15,000 ^{14}C yr B.P. to present (Fig. 2). Still higher is a single Pleistocene terrace, Terrace 3 (T-3). Late Pleistocene and Holocene sediments underlie T-1 and T-2. These sediments are divided into six units, labeled I to VI, from oldest to youngest (Fig. 3). Temporal control for this sequence is provided by 27 radiocarbon dates (Table 1) and diagnostic artifacts (Waters and Ravesloot, 2000).

Prior to 15,000 ^{14}C yr B.P., the Gila River abandoned its floodplain and downcut into its alluvium creating T-3. By at least 15,000 ^{14}C yr B.P., and probably earlier, alluvium began to fill the channel with sand and gravel (unit I) and this continued until 4500 ^{14}C yr B.P. During this

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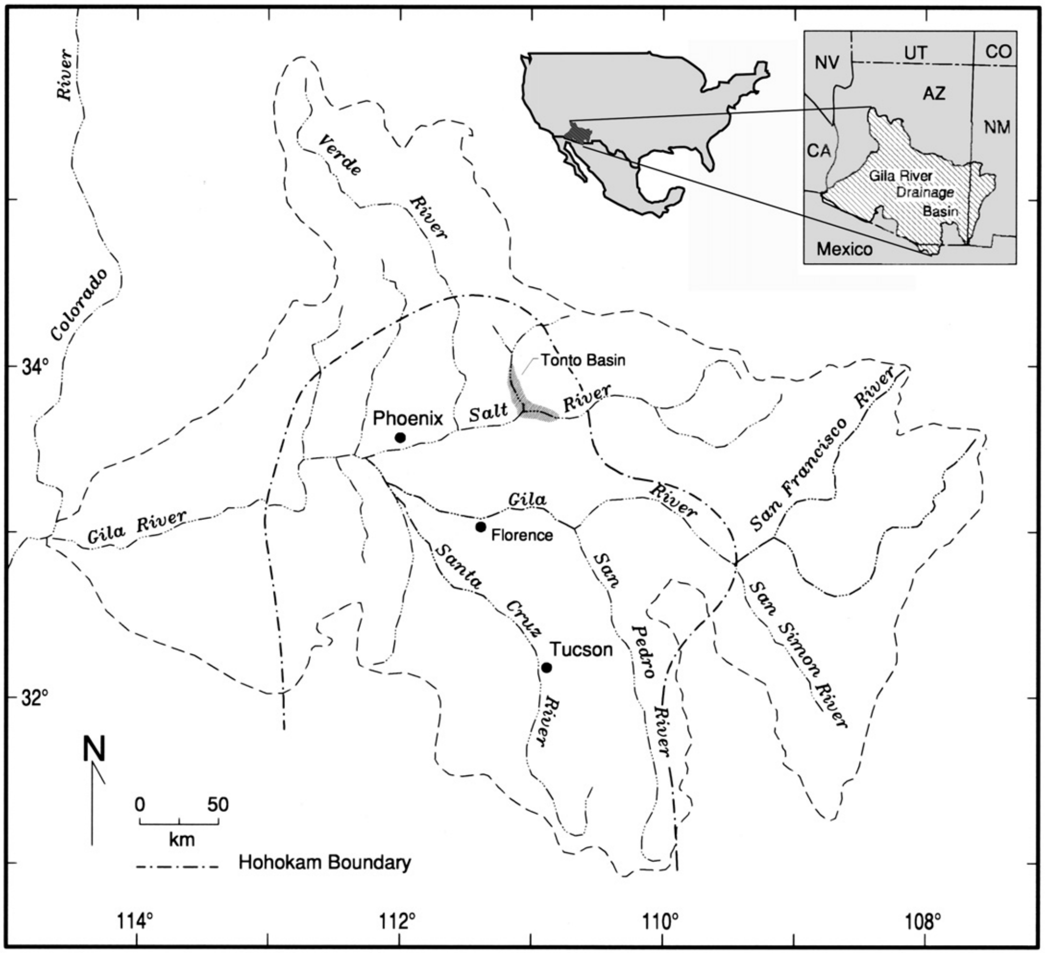

Fig. 1. Gila River drainage basin, Arizona, with the Gila River and its major tributaries. The Hohokam cultural boundary is shown.

11,000 years period, the channel of the Gila River became narrow. From about 4500 to 500 ^{14}C yr B.P., overbank fine sands, silts, and clays (units II and III) accumulated on the floodplain adjacent to the channel. Concurrent with the later phases of deposition of unit III (ca. 1000 ^{14}C yr B.P.) was a period of channel downcutting and widening followed by aggradation of unit IV. On the floodplain, the Orchard soil, with its distinctive prismatic and blocky structure and weak calcic horizon, formed on unit III from about 500 ^{14}C yr B.P. until about 200 ^{14}C yr B.P. Channel deposition continued until about 200 ^{14}C yr B.P. (A.D. 1713–1885) and overbank silts buried the Orchard paleosol (unit V). Finally in the late nineteenth century, the Gila River downcuts, and creates T-2, T-1, and widens its channel.

2.2. Santa Cruz River

The Santa Cruz River extends more than 350 km in length and drains an area of more than 8000 km^2 (Fig. 1). The alluvial stratigraphy of the middle reach of the Santa Cruz River in the Tucson Basin has been extensively studied. Floodplain alluvium along this river segment is divided into seven major stratigraphic units (Figs. 3 and 4). Chronologic control is provided from over 100 radiocarbon dates (Table 2) (Haynes and Huckell, 1986; Waters, 1988; Freeman, 1997, 2000). Late Pleistocene deposition took place in a wide channel in which coarse alluvium (gravel and sand, unit I) was deposited. The post-8000 ^{14}C yr B.P. sequence, however, is dominated by the cutting and filling of arroyos, with the first erosional event occurring sometime between 8000 and 5600 ^{14}C yr B.P., followed by channel filling from 5600 to 4000 ^{14}C yr B.P. (unit II). Additional arroyo cutting-and-filling events occurred between 4000–2500 (unit III), 2500–2000 (unit IV), 2000–1000 (unit V), 1000–500 (unit VI), and 500–200 ^{14}C yr B.P. (unit VII). Arroyo incision during the late nineteenth and early twentieth centuries created the modern channel (Fig. 3).

2.3. Upper San Pedro River

The San Pedro River is about 240 km long and drains roughly 11,500 km^2 from its head near Cananea, Mexico to its confluence with the Gila River (Fig. 1). Within the low-order tributaries of the upper San Pedro

Fig. 2. Looking across the dry streambed of the Gila River at T-2. The sediments underlying T-2 date to the late Quaternary.

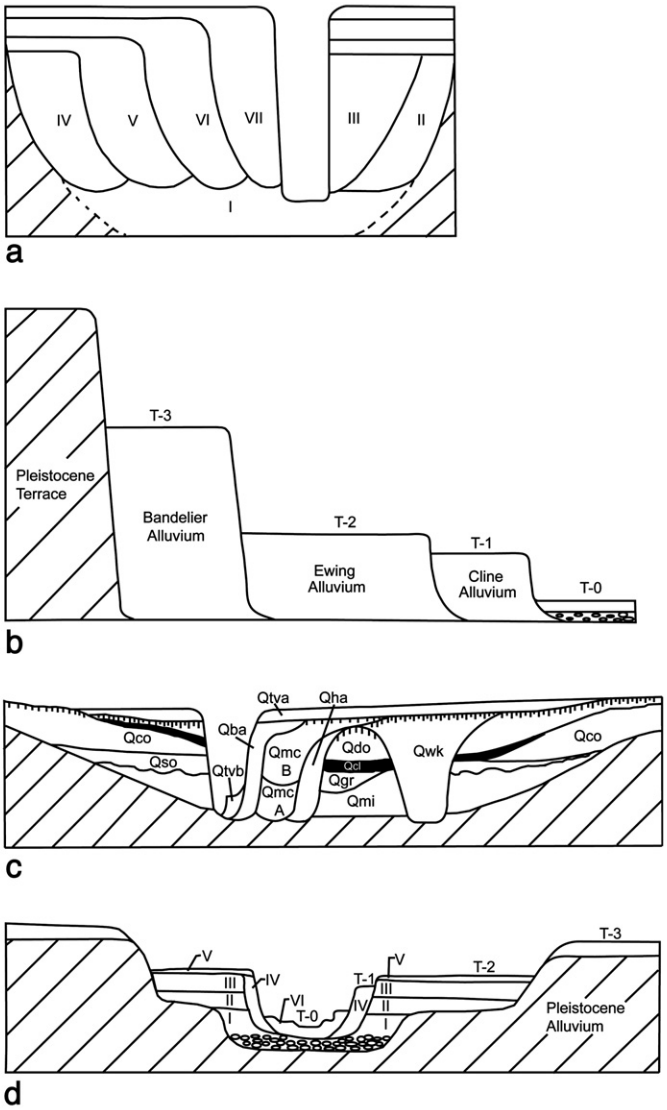

Fig. 3. Late Quaternary alluvial stratigraphy of the Santa Cruz River (a), Salt River and Tonto Creek, Tonto Basin (b), Lower San Pedro Valley (c), and middle Gila River (d).

River is a stratigraphic record that spans the past 40,000 years (Haynes, 1981, 1982, 1987; Waters and Haynes, 2001; Haynes and Huckell, 2007; Fig. 3). The most thoroughly studied stratigraphy is within Curry Draw (Fig. 5; 13.7 km long; drainage basin 13.4 km^2), with additional data coming from the Lehner Ranch Arroyo (12.4 km long; drainage basin 17.6 km^2) and other tributaries. Temporal control is provided by radiocarbon dates (Table 3) from the sequences at Curry Draw ($n=112$), Lehner Ranch Arroyo ($n=75$), and the main channel of the San Pedro River ($n=64$). Based on a synthesis of all sections the stratigraphic and geological data show that from 14,000 to 9600 ^{14}C yr B.P., deposition occurred in spring-fed ponds and shallow channels (units Qmi, Qso, Qco, Qgr, and Qcl; Fig. 3). From ca. 9600 to 7500 ^{14}C yr B.P. deposition was characterized by slopewash aggradation (unit Qdo). After 7500 ^{14}C yr B.P., the fluvial erosional and depositional regime changed to one dominated by arroyo channel cutting-and-filling. Initial arroyo cutting occurred ca. 7500 ^{14}C yr B.P. (channel filled with unit Qwk by 4000 ^{14}C yr B.P.), followed by arroyo cutting-and-filling events at 4000–2600 (unit Qha), 2600–1900 (unit QmcA), 1900–1000 (unit QmcB), 1000–600 (unit Qba), and 600–200 (unit Qbb) ^{14}C yr B.P., and again during the late nineteenth and early twentieth centuries creating the modern channel and its associated alluvium (units Qtva and Qtvb).

Table 1
Radiocarbon ages from the middle Gila River (Waters and Ravesloot, 2000)

Geological unit	Radiocarbon age (^{14}C yr B.P.)	Laboratory number	Material dated
Unit IV	175±40	AA-27112	Charcoal
	400±70	A-9791	Charcoal
	945±45	AA-27108	Charcoal
	965±40	AA-27118	Charcoal
Unit III	<185	A-9795	Charcoal
	470±40	AA-27109	Charcoal
	475±60	A-9790	Charcoal
	565±60	AA-27114	Charcoal
	570±40	AA-27110	Charcoal
	1255±55	A-9796	Charcoal
	1630±45	AA-27105	Charcoal
	1765±60	AA-27116	Charcoal
	2070±80	A-9789	Charcoal
Unit II	2235±65	A-9792	Charcoal
	2460±60	Beta-93419	Charcoal
	2490±45	AA-27113	Charcoal
	2660±50	AA-27107	Charcoal
	2665±50	A-9794	Charcoal
	3430±50	AA-27121	Charcoal
	4200±55	AA-27119	Charcoal
	4460±50	AA-27111	Charcoal
	4485±55	AA-27106	Charcoal
Unit I	3920±50	AA-27115	Charcoal
	4580±50	AA-27117	Charcoal
	8915±105	AA-27120	Charcoal
	14,770±200	AA-27104	Charcoal

All radiocarbon ages are corrected for carbon-isotope fractionation and standard deviations are given at one sigma.

2.4. Tonto Basin

The Tonto Basin is part of the upper watershed of the Salt River (Fig. 1). Near the terminus of the basin, the Salt River is joined by Tonto Creek. Along the Salt River and Tonto Creek, three terraces are defined (Waters, 1998, Fig. 3). These are labeled Terrace 3 to Terrace 1, from oldest (highest) to youngest (lowest). All are fill terraces created by vertical aggradation of the floodplain and later downcutting of the channel. Eight radiocarbon dates (Table 4) provide chronological control.

Sometime before 3500 ^{14}C yr B.P., Tonto Creek and the Salt River eroded any previously deposited Holocene sediments that may have existed from these valleys. Around 3500 ^{14}C yr B.P., alluvium began to accumulate in the scoured channels. Aggradation in the channels

Fig. 4. View showing the late Holocene stratigraphy of the Santa Cruz River floodplain in the Tucson Basin and the modern arroyo channel in the background. The people are excavating a Hohokam pithouse within the alluvial fill.

Table 2
Selected radiocarbon ages from the Santa Cruz River (Waters and Haynes, 2001)

Geological unit	Radiocarbon age (^{14}C yr B.P.)	Laboratory number	Material dated
Historic erosion			
Unit VII			
Lower	480 ± 50	A-4667	Charcoal
	490 ± 180	A-2444	Charcoal
Erosion 500 yr B.P.			
Unit VI			
Upper	610 ± 90	A-1890	Charcoal
	630 ± 80	A-1885	Charcoal
	650 ± 125	Beta-13710	Charcoal
	660 ± 80	Beta-13703	Charcoal
Lower	730 ± 90	AA-721	Charcoal
	960 ± 120	AA-720	Charcoal
Erosion 1000 yr B.P.			
Unit V			
Upper	1020 ± 200	A-3140	Charcoal
	1310 ± 75	Beta-13705	Charcoal
Lower	1620 ± 180	A-2814	Charcoal
	1790 ± 120	A-2813	Charcoal
	1840 ± 80	Beta-14822	Charcoal
	1890 ± 70	Beta-13706	Charcoal
	1920 ± 85	Beta-14823	Charcoal
	1950 ± 120	A-2812	Charcoal
Erosion 2000 yr B.P.			
Unit IV			
Upper	1960 ± 80	A-1887	Charcoal
	2190 ± 105	Beta-14820	Charcoal
	2030 ± 230	A-1883	Charcoal
Lower	2290 ± 80	A-1782	Charcoal
	2300 ± 110	A-1781	Charcoal
	2420 ± 70	A-4080	Charcoal
	2450 ± 220	AA-887	Charcoal
Erosion 2500 yr B.P.			
Unit III			
Upper	2520 ± 105	Beta-13707	Charcoal
	2520 ± 130	A-2817	Charcoal
	2520 ± 140	A-1857	Charcoal
	2530 ± 80	Beta-14715	Charcoal
	2630 ± 100	A-1892	Charcoal
	2650 ± 120	A-3627	Charcoal
Lower	3650 ± 60	Beta-85537	Charcoal
	3650 ± 100	A-2816	Charcoal
	3810 ± 60	CAMS-33965	Charcoal
	3990 ± 60	CAMS-33961	Charcoal
Erosion 4000 yr B.P.			
Unit II			
Upper	3980 ± 100	A-1783	Charcoal
	4380 ± 60	Beta-81048	Charcoal
	4400 ± 220	A-1858	Charcoal
	4850 ± 90	A-1854	Charcoal
Lower	5105 ± 55	AA-3855	Charcoal
	5540 ± 95	AA-3861	Charcoal
Erosion 5600–8000 yr B.P.			
Unit I			
Upper	7970 ± 130	Beta-14537	Sediment

All radiocarbon ages are corrected for carbon-isotope fractionation and standard deviations are given at one sigma.

continued until sometime around 2400 ^{14}C yr B.P. By this time, about 10 m of alluvium (Bandelier alluvium) had accumulated in the channel of Tonto Creek, the Salt River, and their tributaries.

Shortly thereafter, both streams downcut through the floodplains, creating Terrace 3. This erosion removed much of the Bandelier alluvium and scouring was nearly complete before the next episode of aggradation. From around 2400 to around 1000 ^{14}C yr B.P., 4–4.5 m of alluvium accreted in the floodplains of both streams (Ewing alluvium). Deposition ceased around 1000 ^{14}C yr B.P., and the Tonto Creek and Salt River downcut into the floodplains, creating Terrace 2. Scouring associated with channel downcutting and widening during this event removed much of the previously deposited Ewing alluvium.

Aggradation began again sometime before 800 ^{14}C yr B.P. and continued until at least 200 ^{14}C yr B.P. Approximately 3.5–4 m of alluvium (Cline alluvium) accumulated. It appears, based on historic records, that sometime in the late 1800s both streams downcut into the Cline alluvium, thus creating Terrace 1 and the modern channel.

3. Inferred causes of landscape change

The alluvial stratigraphic sequences studied in the Gila River drainage basin, come from three different geomorphic settings. The stratigraphic sequence for the Tonto Basin represents deposition and erosion along headwater streams of the upper drainage basin, the middle Gila River sequence represents aggradation and degradation along a major (trunk) stream, and the stratigraphic sequences for the Santa Cruz River and San Pedro tributaries record the dynamics of erosion and deposition in arroyos. The stratigraphic sequences for these streams show that erosion and deposition was largely synchronous and this suggests that regardless of geomorphic location, streams were responding similarly to climate change during the late Quaternary. Arroyos, however, record more cut-and-fill cycles during the late Quaternary than other stream types, suggesting that arroyos are more sensitive to climate variations.

3.1. Aggradation and degradation along the middle Gila River and its watershed

The floodplain of the middle Gila River is characterized by aggradation from 15,000 ^{14}C yr B.P. to present, with a major sedimentological change at 4500 ^{14}C yr B.P., and two episodes of degradation at 1000 ^{14}C yr B.P. and in the late nineteenth century. The Gila River floodplain appears to have been responding to changes in climate, sediment yields from the upstream reaches of the drainage basin, magnitude and frequency of floods, and human impacts (Waters and Ravesloot, 2000).

Aggradation of coarse-grained channel sediments, with no obvious break in deposition, characterized the middle Gila River from 15,000 to 4500 ^{14}C yr B.P. During the cooler and wetter climatic conditions of the late Pleistocene (Hall, 1985; Van Devender et al., 1987), the Gila River appears to have been a more competent stream capable of carrying coarse sediment loads. During the early and middle Holocene, when temperatures rose and peaked (Hall, 1985; Van Devender et al., 1987), sand and gravel continued to be deposited in the channel even though the paleodischarge of the Gila River

Fig. 5. Late Quaternary stratigraphy exposed in the cut-bank of Curry Draw at the Murray Springs Clovis site in the upper San Pedro Valley.

Table 3
Selected radiocarbon ages from the San Pedro River (Waters and Haynes, 2001)

Geological unit	Radiocarbon age (^{14}C yr B.P.)	Laboratory number	Material dated
Teviston-B alluvium (Qtvb; inset fill terrace)	None (post-A.D. 1958 based on aerial photography at Curry Draw)		
Teviston-A alluvium (Qtva)	None (arroyo channel cutting ca. A.D. 1916 based on oral history for Curry Draw)		
Historic erosion			
Backrich-B alluvium (Qbb)	500±80	SMU-39	Charcoal
Erosion 600 yr B.P.			
Backrich-A alluvium (Qba)	860±60	SMU-289	Charcoal
	900±120	A-891	Charcoal
Erosion 1000 yr B.P.			
McCool-B alluvium (QmcB)			
Upper	>840±60	TX-937	Charcoal
	1040±40	SMU-323	Wood
	1090±70	TX-1041	Charcoal
	1150±50	SMU-46	Charcoal
	1290±50	SMU-334	Wood
	1370±120	SMU-26	Charcoal
Lower	1430±160	A-479A	Wood
	1550±90	A-617	Charcoal
	1680±50	SMU-271	Charcoal
Erosion 1900 yr B.P.			
McCool-A alluvium (QmcA)			
Upper	2050±90	TX-1194	Charcoal
Lower	2550±160	A-450	Charcoal
Erosion 2600 yr B.P.			
Hargis alluvium (Qha)			
Upper	2550±500	A-633	Organic clay
	3190±80	SMU-40	Charcoal
	3350±150	A-903	Charcoal
Lower	3890±270	AA-1140	Charcoal
	3950±180	A-480	Charcoal
	4000±130	SMU-15	Carbonized plants
Erosion 4000 yr B.P.			
Weik alluvium (Qwk)			
Upper	4230±290	A-697B	Humates
	5630±130	TX-936	Humates
	5750±250	A-905A	Charcoal
	5890±270	A-696B	Humates
Lower	6400±100	SMU-139	Humates
Erosion 7500 yr B.P.			
Donnet Ranch alluvium (Qdo)			
Upper	7890±420	A-715B3	Humates
	8620±160	TX-1046	Humates
Lower	9530±100	SMU-175	Humates
Clanton Ranch clay (Qcl)			
Upper	9640±180	TX-1183	Organic clay
	9900±80	SMU-204	Humates
Lower	10,630±60	AA-26212	Humates
	10,680±140	SMU-109	Organic clay

All radiocarbon ages are corrected for carbon-isotope fractionation and standard deviations are given at one sigma.

undoubtedly declined. This period of deposition appears to be the result of the continued shedding of sediments from the upstream watersheds. During the early and middle Holocene, sediments that had been created and stored on the hillslopes of upland watersheds during the late Pleistocene were eroded, transported, and eventually deposited along the middle Gila River.

The upper watershed of the Gila River lacks a documented alluvial chronology necessary to confirm this interpretation. A well documented stratigraphic record, however, is available for the upper drainage basin of the Salt River (a major tributary of the Gila River) in the Tonto Basin (Waters, 1998). This record is used as a proxy for events associated with the upper watershed of the Gila River. In the Tonto Basin, Tonto Creek and the upper Salt River lack preserved alluvial sediments older than about 3500 ^{14}C yr B.P. (Waters, 1998). This indicates that prior to this time, the upstream areas of the Salt River and Tonto Creek were being stripped of sediment and this sediment was transported to the main trunk channel. The high sediment yields were likely triggered by changes in vegetation at the end of the Pleistocene and during the arid Altithermal (Hall, 1985; Bull, 1991), which made sediment stored on the hillslopes and in upper drainage basin streams vulnerable to erosion.

The regime of the middle Gila River changed greatly around 4500 ^{14}C yr B.P. By this time the channel of the Gila River was choked with coarse sediments and the channel had narrowed and stabilized. Around this time, overbank floods began to occur on a regular basis and vertical floodplain aggradation continued until 500 ^{14}C yr B.P. which resulted in the formation of units II and III which are composed of silt and clay. Overbank deposition and soil formation on the floodplain along the Gila River coincided with the establishment of modern desert vegetation in the study area (Van Devender et al., 1987), periods of frequent and infrequent large floods (Ely, 1997), and the end of the arid Altithermal and the establishment of cooler and wetter conditions (Mehringer, 1967; Mehringer et al., 1967; Hall, 1985).

This long period of floodplain aggradation was interrupted around 1000 ^{14}C yr B.P, when the channel of the Gila River downcut and widened. This cutting event correlates with a wet climatic episode documented in Arizona (Van Devender et al., 1987; Davis, 1994; Ely, 1997). This was also a period of intense high-magnitude flooding (Ely, 1997). This channel began to fill with sediment shortly after it formed. This filling event coincides with the latter part of the Medieval Warm period (A.D. 1100 to 1300) and a major decrease in flooding (Ely, 1997).

In the late nineteenth century, the Gila River downcut, created T-2, beveled T-2 and created T-1, and widened its channel. These changes are attributed to the large floods that occurred in the late 1800s (Huckleberry, 1993), coupled with the human impacts that occurred along the Gila River prior to this time—especially, wood cutting on the banks and floodplain of the river, modification of the land for agriculture, and reductions in streamflow and a drop in the water table as a result of agricultural expansion (Wilson, 1999). These human impacts along the river weakened the resistance of the channel to erosion and, therefore, enhanced the destructive potential of the floods of the late nineteenth century.

3.2.. Aggradation and degradation in the Santa Cruz and Upper San Pedro valleys

Arroyo formation and cutting-and-filling cycles are linked to changing climate and vegetation during the late Quaternary (Waters and Haynes, 2001). The stratigraphic records of the low-order tributaries of the upper San Pedro River (Haynes, 1987) and the larger Santa Cruz River (Haynes and Huckell, 1986; Waters, 1988; Freeman,

Table 4
Radiocarbon ages from the Tonto Basin, Arizona (Waters, 1998)

Geological unit	Radiocarbon age (^{14}C yr B.P.)	Laboratory number	Material dated
Terrace 1	225±60	Beta-36791	Dispersed charcoal
(Cline alluvium)	765±65	Beta-36792	Dispersed charcoal
Terrace 2	1060±60	Beta-45506	Canal bulk sediment
(Ewing alluvium)	1440±70	Beta-45505	House dispersed charcoal
	1805±55	Beta-44707	Dispersed charcoal
	2295±95	Beta-36789	Dispersed charcoal
	2440±60	Beta-36790	Dispersed charcoal
Terrace 3	2390±70	Beta-44706	Roasting pit charcoal
(Bandelier alluvium)	3485±70	Beta-35343	Dispersed charcoal

All radiocarbon ages are corrected for carbon-isotope fractionation and standard deviations are given at one sigma.

1997, 2000) are correlated with paleoenvironmental records for the Sonoran Desert that were established by the study of pack rat middens (Spaulding et al., 1983; Van Devender et al., 1987; Van Devender, 1990), pollen sequences (Mehringer, 1967; Mehringer et al., 1967; Hall, 1985; Davis and Shafer, 1992), and climatic proxy data from geologic records (Waters, 1989; Anderson, 1993; Hasbargen, 1994; Ely, 1997; Rodbell et al., 1999; Moy et al., 2002).

From 15,000 to 8000 ^{14}C yr B.P., evidence of arroyo cutting-and-filling is absent from the alluvial records of the San Pedro Valley and Santa Cruz Valleys. During this time woodlands covered the floors of desert basins (Spaulding et al., 1983; Van Devender et al., 1987; Van Devender, 1990) and water tables were high (Haynes, 1968;Waters, 1988; Karlstrom, 1988). These conditions were not conducive for arroyo formation.

Arroyos cutting first appears sometime between 5600 and 8000 ^{14}C yr B.P. on the floodplain of the Santa Cruz River, and at ca. 7500 ^{14}C yr B.P. along the San Pedro River. Arroyo cutting coincides with climatic and biotic changes that took place in the Sonoran Desert. Around 8000 ^{14}C yr B.P., the cooler temperatures and greater effective moisture of the late Pleistocene and early Holocene were replaced by the higher temperatures and less effective moisture conditions that characterized the Altithermal (Hall, 1985; Waters, 1989; Davis and Shafer, 1992; Ely, 1997). The first appearance of arroyos also coincides with the onset of significant El Niño activity (Rodbell et al., 1999; Moy et al., 2002), which had been insignificant during the early Holocene. During this period, water tables dropped (Haynes, 1968; Karlstrom, 1988) and the xeric juniper scrub that had previously covered the floors of desert basins was replaced by desert scrub (Spaulding et al., 1983; Van Devender et al., 1987; Van Devender, 1990). These changes made the valley floors susceptible to erosion.

Arroyo cutting-and-filling cycles increase dramatically after 4000 ^{14}C yr B.P. Six episodes of channel entrenchment occurred on the floodplain of the other low-order streams in the San Pedro Valley and six entrenchment episodes occurred on the floodplain of the Santa Cruz River. These arroyo-cutting events were synchronous between the two valleys, occurring around 4000, 2500, 2000, 1000, and 500 ^{14}C yr B.P. and again in the late nineteenth and early twentieth centuries.

The period of repeated arroyo cutting-and-filling that began at 4000 ^{14}C yr B.P. coincides with major changes in vegetation and climate. By 4000 ^{14}C yr B.P. a fully modern desert scrub vegetation community became established along the floors of desert valleys of the Sonoran Desert (Spaulding et al., 1983; Van Devender et al., 1987; Van Devender, 1990). At 4000 ^{14}C yr B.P., the modern climate regime, characterized by generally lower temperatures and greater effective moisture compared to the middle Holocene, and numerous wet and dry episodes (Mehringer, 1967; Mehringer et al., 1967; Waters, 1989; Davis and Shafer, 1992; Ely, 1997), developed.

Four of the six prehistoric arroyo-cutting events along the Santa Cruz River and the tributaries of the San Pedro Valley coincide with wet periods documented by pollen, pack rat middens, and geologic records at 4000, 1000, and 500 ^{14}C yr B.P., and during the late nineteenth and twentieth centuries (Mehringer, 1967; Mehringer et al., 1967; Spaulding et al., 1983; Hall, 1985; Van Devender et al., 1987; Waters, 1989; Van Devender, 1990; Davis and Shafer, 1992; Baker et al., 1995; Ely, 1997; McFadden and McAuliffe, 1997). Paleoenvironmental records for the period 2000–2500 ^{14}C yr B.P. are poorly documented and arroyo incision at these times cannot yet be correlated with a particular wet period.

The wet periods that triggered arroyo cutting during the late Holocene may be related to changes in the El Niño-Southern Oscillation pattern. Since 4000 ^{14}C yr B.P., El Niño events became more frequent, peaked around 2000–1000 ^{14}C yr B.P., and then decreased towards modern times, but still remained significant (Keefer et al., 1998; Rodbell et al., 1999; Moy et al., 2002). El Niños are known to produce periods of extended heavy rainfall that result in high-magnitude flooding within the watersheds in southern Arizona (Andrade and Sellers, 1988; Webb and Betancourt, 1992; Bull, 1997; Ely, 1997).

The six synchronous arroyo cutting events that began ca. 4000 ^{14}C yr B.P. appear to be the result of dry–wet climate cycles during the past 4000 years. Dry conditions led to a drop in water tables and a reduction in vegetation cover that protected the desert valleys from erosion (Schlesinger et al., 1990). Floods that resulted from a period of increased precipitation following a dry period would trigger arroyo cutting (Balling and Wells, 1990; McFadden and McAuliffe, 1997; Waters and Haynes, 2001).

In addition to changes in climate and vegetation, channel entrenchment during the late nineteenth and early twentieth centuries was enhanced by human impacts of the floodplains of the Sonoran Desert. The initial loci of historic arroyo cutting along the Santa Cruz River are traced to the excavation of drainage ditches on the floodplain (Cooke and Reeves, 1976; Waters, 1988) and to wagon ruts at Curry Draw (Cooke and Reeves, 1976; Haynes, 1987). Like prehistoric arroyo cutting, however, historic channel cutting is coincident with periods of El Niño activity, which generated frequent, large-scale flooding in southern Arizona (Andrade and Sellers, 1988; Ely, 1997).

4. The archaeological record of the Gila River drainage basin

The earliest inhabitants of the Gila River drainage basin were the Clovis people. These highly mobile hunter–gatherers hunted mammoth and camped in the basin from about 11,100 to 10,800 ^{14}C yr B.P. (Waters and Stafford, 2007; Haynes and Huckell, 2007). This Paleoindian period was followed by a long period known as the Archaic. Archaic peoples were primarily mobile hunters and gatherers that occupied defined territories. During the late Archaic period, people began to experiment with agriculture. Following a formative period, a more sedentary agricultural society, known as the Hohokam emerged and flourished in the basin from about A.D. 300 to 1450 (Doyel, 1991; Gregory, 1991). Little is known about the protohistoric period that followed. During the historic period, that begins A.D. 1540, groups such as the Pima, Papago, and Maricopa occupied the basin. The archaeological record of these prehistoric and historic cultures is buried within the alluvium of the Gila River drainage basin.

The nature and completeness of the archaeological record buried in alluvial sediments parallels the nature and completeness of the geological sequences of the drainages in the Gila River drainage basin. Meaningful archaeological interpretations of the archaeological record of the Gila River drainage basin are dependent upon an evaluation of site preservation. Archaeologists must consider whether the observed patterns of occupation within and between areas accurately reflect the distribution of human activities across the landscape or the biases of geological preservation (Butzer, 1982; Waters, 1992; Bettis, 1995; Mandel, 1995; Waters and Kuehn, 1996). The archaeological record of the Santa Cruz River, San Pedro River, Tonto Basin, and middle Gila River can be evaluated in the context of the respective geological records (Fig. 6).

In the upper San Pedro Valley, a number of undisturbed Clovis kill and camp sites are preserved within the alluvial sediments (Haury et al., 1953; Haury et al., 1959; Haynes, 1981, 1982; Haynes and Huckell, 2007). These sites include Lehner, Naco, Murray Springs, and others. These sites are preserved because of the favorable geological conditions that existed along small basin, piedmont streams in the upper San Pedro Valley during the late Pleistocene. Clovis sites were buried soon after abandonment beneath an organic-rich clay, the black mat (Haynes and Huckell, 2007), which was deposited in a low-energy cienega (wet marshland) environment (Fig. 7). Subsequent Holocene erosion did not remove the Clovis-age surface. On the other hand, Clovis sites have not been found in the alluvium of the Santa Cruz River, middle Gila River, or Tonto Basin (Fig. 6).

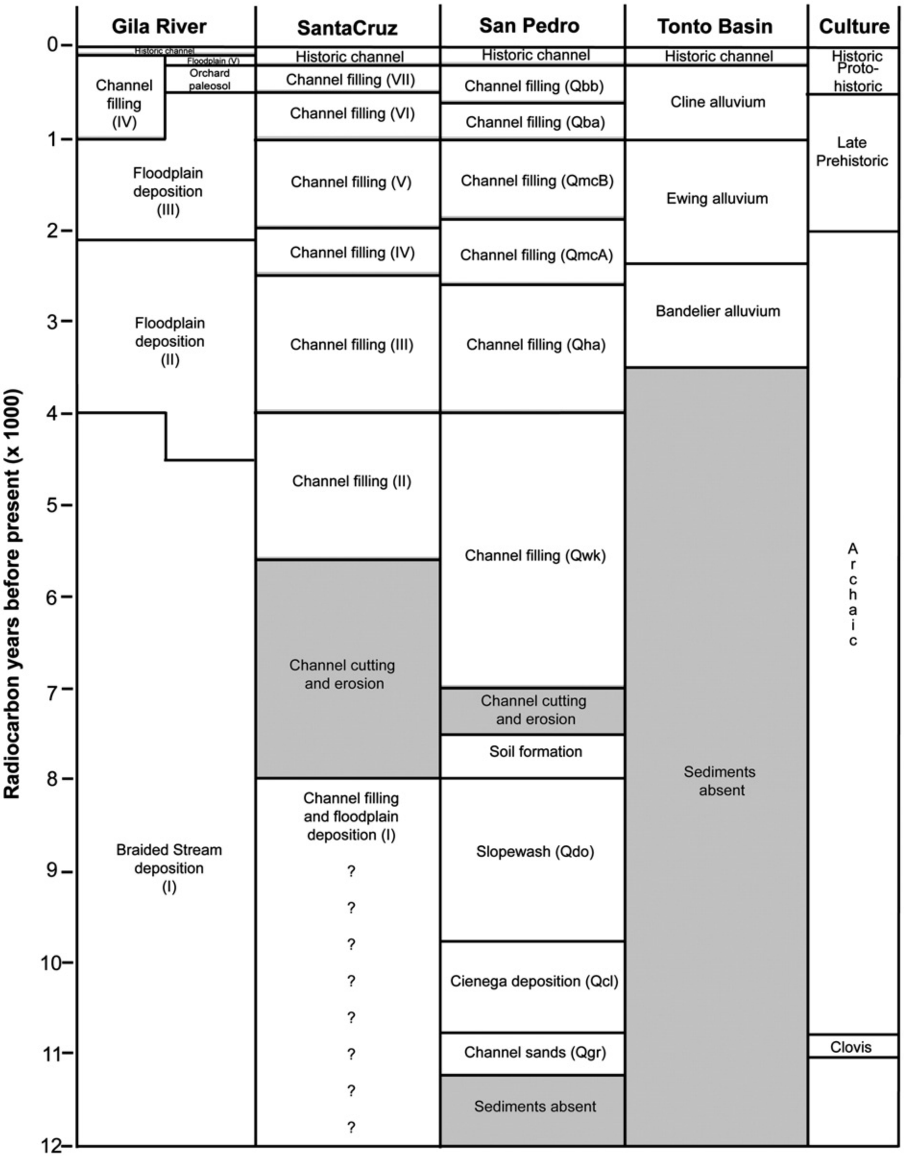

Fig. 6. Chart showing the late Quaternary alluvial records of the Gila River, Santa Cruz River, Upper San Pedro River, and Tonto Basin. Time in radiocarbon years B.P. and the cultural sequence for southern Arizona are indicated.

Along the middle Gila River, Clovis remains could potentially be found in unit I, but any artifacts would lie in a secondary context because the sands and gravels of unit I were deposited in a high-energy braided stream environment, which is not conducive to the preservation of behavioral contexts (Waters and Ravesloot, 2000). If Clovis sites do occur in a secondary context, they would likely be undetectable because the sparse artifact record typically found at Clovis sites would become lost within the enormous volume of sand and gravel comprising unit I.

Along the Salt River and Tonto Creek in the Tonto Basin, alluvial sediments older than 3500 ^{14}C yr B.P. are not preserved (Waters 1998). Erosion in both areas has removed the late Pleistocene sediment record and with it any traces of Clovis occupation. Similarly, Clovis-age alluvial sediments that once may have existed along the Santa Cruz River in the Tucson Basin have been removed by erosion (Waters, 1988). Thus, no Clovis sites occur in the alluvial sediments of the Santa Cruz River within the Tucson Basin. Clovis hunters were present, however, along the middle Gila River, Santa Cruz River, and in the Tonto Basin based on the discovery of isolated Clovis projectile points on the surface of the *bajadas* (alluvial piedmont) adjacent to the riverine areas (Huckell,

Fig. 7. The Black Mat (Clanton Clay, unit Qcl) at the Murray Springs site, Arizona. The Clovis occupation surface is preserved directly beneath the Black Mat.

1982). Clearly, Clovis people were using these regions, but the most likely locations of their activities have disappeared.

As a consequence, the intensity of Clovis utilization of the riverine environments of southern Arizona cannot be gauged. It cannot be determined whether the Clovis record of the upper San Pedro Valley represents a unique, intensive occupation of only this area during the late Pleistocene or whether this record instead reflects the biases imposed by different intervalley geological processes.

The Archaic record is also differentially preserved along the rivers and streams of southern Arizona (Fig. 6). For example, archaeological sites are absent within the alluvium of the middle Santa Cruz River until ca. 5000 ^{14}C yr B.P., when vertical accretion deposits are first preserved. Within the Tonto Basin, along the Salt River and Tonto Creek, the absence of alluvial sediments dating beyond 3500 ^{14}C yr B.P. precludes all but a Late Archaic record of utilization of these floodplains. Along the middle Gila River, the Archaic record could date back to 4800 ^{14}C yr B.P., the age of the oldest preserved, fine-textured overbank alluvium. Any earlier Archaic sites occur in a secondary context within unit I. The best preserved Archaic record is found in the San Pedro Valley. Early Archaic sites in the upper San Pedro Valley alluvium lie in a primary context because of the low-energy associated with deposition. Part of the Middle Archaic record is missing, however, because of erosion. After this, the archaeological record is again well preserved. Until ca. 3500 ^{14}C yr B.P., the Archaic record is fragmented and differentially preserved among the valleys of the Gila River drainage basin (Fig. 6). It is not until the Late Archaic (ca. 3500 ^{14}C yr B.P.) that sites have the potential to be equally preserved and reasonable intervalley correlations of human behavior can be made between the major valleys of the Gila River drainage basin. The observations concerning the Late Archaic also hold true for the Late Prehistoric record. Again, the alluvium of each valley dating to the past 2000 years is well preserved and has the potential to contain a more complete record of human activity of these riverine areas. Thus, Late Prehistoric intravalley and intervalley utilization and human interaction can be studied with confidence.

In summary, the archaeological record of the Gila River drainage basin does not accurately reflect the complete pattern of human sites that once existed in this region through time. Geomorphic processes associated with changing landscapes have significantly affected the temporal and spatial archaeological sample. Meaningful interpretations of prehistory depend on recognizing and understanding the limitations that geological processes have imposed on the archaeological record.

5. Late prehistoric Hohokam farmers in the Gila River drainage basin

Prehistoric agriculturalists, known as the Hohokam, occupied much of the Gila River drainage basin from ca. A.D. 300–1450 (Haury, 1976; Gregory, 1991; Doyel, 1991). Except for isolated springs, the streams of the Gila River drainage basin provided the Hohokam with the only reliable source of water in an otherwise arid environment. Along these perennial rivers of Arizona the Hohokam culture emerged, flourished, contracted, and collapsed.

The material traits that are recognized as Hohokam (i.e., red-on-buff ceramics, distinctive iconography, pithouse architecture, village layout, ballcourts, mortuary practices, and irrigation agriculture) began to develop around A.D. 300 in a core area around the lower Salt and middle Gila River valleys. Over the next seven centuries, the Hohokam sphere of influence expanded to include almost all of southern Arizona—including the upper San Pedro River, Santa Cruz River, and Tonto Basin (Fig. 1). This period of village growth, expansion of canals, and cultural elaboration is known as the Pre-Classic period. Between A.D. 1050 and 1150, the Hohokam experienced a period of major reorganization. Settlements that had been occupied for centuries were abandoned, the geographic range of the Hohokam cultural pattern decreased, and the regional system of over 125 ballcourts were gradually replaced by platform mounds as the predominant form of public architecture (Doyel, 1991; Gregory, 1991). This reorganization was felt across the entire Hohokam region. By A.D. 1150, the Hohokam had developed a new organizational system, villages with platform mounds were established, people aggregated into fewer but larger settlements, traditional pithouse villages centered around plazas were replaced with post-reinforced and adobe-walled structures surrounded by compound walls, canal systems were consolidated, and many other ritual and material aspects of the culture changed (Haury, 1976; Doyel, 1991). These new traits characterize the Hohokam Classic period. This new organization sustained itself until around A.D. 1400 to 1450, when the Hohokam culture collapsed; sites and canal systems were abandoned and people appear to have dispersed into smaller groups across southern Arizona.

Human cultures, such as the Hohokam, are adapted to high-frequency environmental processes, those that operate over short periodicities (annual or seasonal variability), because people perceive this as stability (Dean, 1988). For a culture to sustain itself over time, its adaptation must be flexible enough to handle expected, but unpredictable, high-frequency variations in environmental variables (e.g., floods and droughts). Low-frequency variations that occur infrequently, such as channel cutting, with periodicities greater than one human generation, may have more severe consequences for people (Dean, 1988). The human response to low- and high-frequency environmental changes depends on a number of variables. Two of the most important are prehistoric subsistence patterns and how close the population is to the carrying capacity of the land (Dean, 1988). To societies that are at or near the carrying capacity of the land and dependent on an intensive agricultural subsistence, low- and high-frequency changes to the landscape become critical threats to survival.

High-frequency reconstructions of late Holocene annual and seasonal stream discharge, based on dendrochronological extrapolations, are available for the Salt and Gila Rivers (Graybill, 1989; Graybill et al., 2006). These streamflow reconstructions are very useful in understanding floodplain dynamics because they document high, average, and low flow periods along these two streams. Low-frequency floodplain events (e.g., channel downcutting, floodplain aggradation, and floodplain stability) are documented in the stratigraphic record. This discussion focuses on low-frequency floodplain changes that are documented in the geological record. To fully understand the floodplain dynamics of the Hohokam region, these two records must be integrated in the future (Ravesloot et al., in press).

The emergence and expansion of the Hohokam pattern during the Pre-Classic period occurred during a time when geomorphic conditions were excellent for the establishment of canal systems and farming (Waters and Ravesloot, 2001; Ravesloot et al., in press). The Gila River was characterized by a narrow channel and a broad floodplain. Flow was perennial and confined to the channel except during floods when the water would overtop its banks and inundate the adjacent lowlands. This flooding resulted in overbank deposition and vertical aggradation of the floodplain. Channel configurations were stable and floodplain aggradation was also taking place along the Santa Cruz River, San Pedro River, Tonto Creek, and Salt River at this time (Waters and Ravesloot, 2001).

Coinciding with the major reorganization of the Hohokam culture that occurred between A.D. 1050 and 1150 (ca. 1000 ^{14}C yr B.P.) were major changes on the floodplains of the streams making up the middle Gila River drainage basin. Along the middle Gila River, the channel downcut and significantly widened between A.D. 1020 and 1150 (Waters and Ravesloot, 2001; Fig. 6). The new channel was wider than the modern channel of the Gila River (modern channel width ranges from 0.5 to 2.3 km, but is typically at least 1 km). This disrupted channel and floodplain stability that had existed for over 700 years. This wide channel had a braided streambed and the main flow channel shifted over the streambed with each large flow. This would have made it difficult for the Hohokam to get water into their canals as the position of the channel relative to established canal headgates changed. Every year Hohokam engineers would have to cope with the problem of diverting streamflow across the porous streambed. At times, the channel would have been close to the headgates and at other times on the opposite side of the streambed. Any temporary diversion dams constructed to get water into the headgates would have been vulnerable to being washed out within such a channel environment. This problem would have required considerable labor and organization to keep the canal systems operating (Waters and Ravesloot, 2001).

Between A.D. 1050 and 1150 a deep channel was cut into the floodplain of the Santa Cruz River (Fig. 6). Arroyo cutting would have disrupted centuries of floodplain stability and would have created stress on the agriculturally dependent population in the Tucson Basin. Entrenchment would have left canal headgates high above the channel floor, making it virtually impossible to restore the previously existing canal system. Correlative channel downcutting is documented in the upper San Pedro stratigraphic sequences at this time and would have led to similar agricultural problems.

Alluvial stratigraphy of the Salt River and Tonto Creek in the Tonto Basin shows that just prior to A.D. 1050, the Salt River and Tonto Creek cut into the respective floodplains (Fig. 6). Filling of the channel began before A.D. 1215–1280, with channel cutting coinciding with the abrupt end of Hohokam influence in the Tonto Basin.

While little work has been done on the main stem of the Salt River traversing the Phoenix basin, preliminary research has been conducted just upstream of the confluence of the river with the Gila River (Onken et al., 2004). The stratigraphy in this research of the Salt River suggests possible channel downcutting around A.D. 1050–1150.

Channel downcutting and widening seen in the Gila River drainage basin, corresponds to a period of intensified high-magnitude floods in southern Arizona (Ely, 1997). Synchronous regional channel cutting between A.D. 1050 and 1150 must have had a significant negative impact on Hohokam agriculture and was likely a major factor contributing to the reorganization that followed (Waters and Ravesloot, 2001).

Regional channel entrenchment would have disrupted centuries of floodplain stability and agricultural pursuits on the floodplain. The physical changes to the floodplain environments along the streams of the Gila River drainage basin would have threatened the Hohokam lifeway, forcing a major change in irrigation and agricultural strategies. The Classic period Hohokam appear to have responded to fluvial instability by re-engineering and consolidating their canals, placing canal headgates in locations on the floodplain where they were protected from floods, pooling resources and organizing labor to maintain and repair the canal systems, consolidating communities, and increasing and diversifying their food production by vigorously pursuing dry and floodwater farming (Waters and Ravesloot, 2001). The dramatic reorganization in Hohokam villages and canal systems appear to be a response to the changes to the floodplain environments along the streams of the Gila River drainage basin.

At the end of the Classic period, the Santa Cruz River and the upper San Pedro River entrenched floodplains and created problems for the inhabitants of these two regions similar to those created during the Pre-Classic to Classic period transition (Waters and Ravesloot, 2001). No stratigraphic evidence exists, however, for changes to the channel of the Gila River or Salt River (the Classic period core area), or along the streams in the Tonto Basin at this time (Waters and Ravesloot, 2001). Uneven changes to floodplain environments in the Gila River drainage basin was likely a factor, but not the decisive factor, speeding cultural change at the end of the Classic period. It appears that other factors, perhaps internal political and social problems were more important in this transition (Waters and Ravesloot, 2000, 2001).

6. Conclusions

Alluvial stratigraphic studies along the streams making up the Gila River drainage basin provide critical information for interpreting the archaeological record. Stratigraphic data provides the framework to evaluate the completeness of the archaeological record. This record has been shaped by the geologic history of these streams, and this has severely influenced the preservation of archaeological sites through time which limits archaeological interpretations.

Landscape changes along riverine systems can be destabilizing events to irrigation agriculturalists. Changes to floodplain environments may create stress that triggers or accelerates social changes as shown in the Gila River drainage basin. In the Hohokam core area along the middle Gila River and most likely along the Salt River, and in the outlying areas of the Tucson Basin, upper San Pedro Valley, and Tonto Basin, landscape change in the form of channel entrenchment and widening coincides with the abrupt changes that took place between the Pre-Classic and Classic periods. This seems to be more than a mere coincidence. Channel cutting-and-erosion would have resulted in crop failures, loss of farmland, and the need to abandon older canal systems and construct new ones. This would have created severe stress on the Hohokam agriculturalists. These changes to the landscape may have triggered the changes seen in the Hohokam culture area or may have accelerated cultural changes that were already underway. Landscape changes around A.D. 1450 occurred in only some drainages of the Gila River basin and, thus, may have only been a local factor driving the cultural changes seen at this time.

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