Computation and Analysis of the Instantaneous Discharge Record for the Colorado River at Lees Ferry, Arizona - May 8, 1921, through September 30, 2000

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U.S. Department of the Interior
U.S. Geological Survey

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PROFESSIONAL PAPER 1677

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Data downloadable from the temporary site:

ftp://ftpext.usgs.gov/pub/wr/az/flagstaff/GCMRC-water/

Objectives

- Evaluation of the natural hydrologic variability in the Upper Basin as measured in the discharge of the Colorado River at Lees Ferry (42-year period from May 1921 to March 1963; only 10-15% virgin flow depleted prior to 1963, mostly before 1921)
- Evaluation of the effects of the operation of Glen Canyon Dam on the discharge of the Colorado River in Grand Canyon National Park (37-year period from March 1963 through September 2000)
- Implications for sediment transport and storage in the reach between Lees Ferry and the Grand Canyon gaging station

Chief analyses

- Flow duration (with sediment transport implications)
- Sub-daily discharge variability
- Flood frequency

Main problem to overcome

Data were of differing precision during different time periods

- May 8, 1921 through June 12, 1921
  not published
- June 13, 1921, through September 30, 1986
  mean daily
- October 1, 1986, through May 31, 1998
  30 minutes
- After June 1, 1998
  15 minutes

Retrieve and compile digitally all raw data collected by the USGS at the Lees Ferry and Grand Canyon gaging stations

4 years of work

Lees Ferry - May 1921 through September 1986

35 boxes of data in the Federal Records Center

Grand Canyon - November 1922 through September 1986

-Construct a continuous record of instantaneous stage

-Enter staff gage data from May 8, 1921, through January 18, 1923

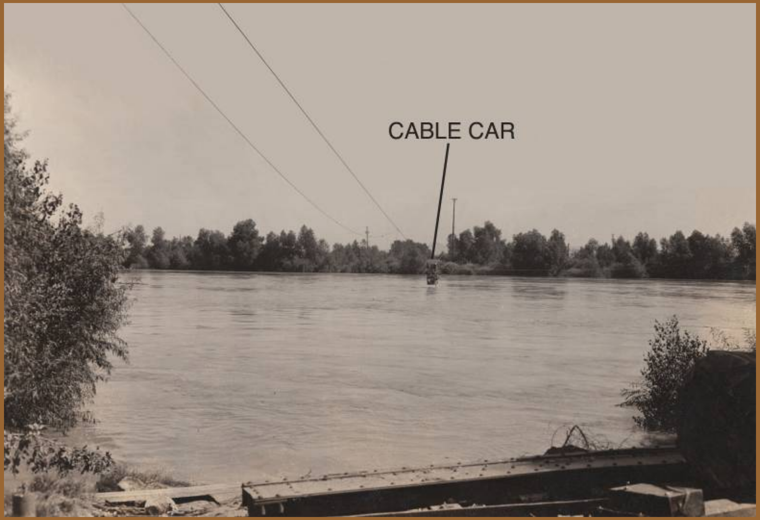
-Digitize strip-chart data from January 19, 1923, through September 30, 1986

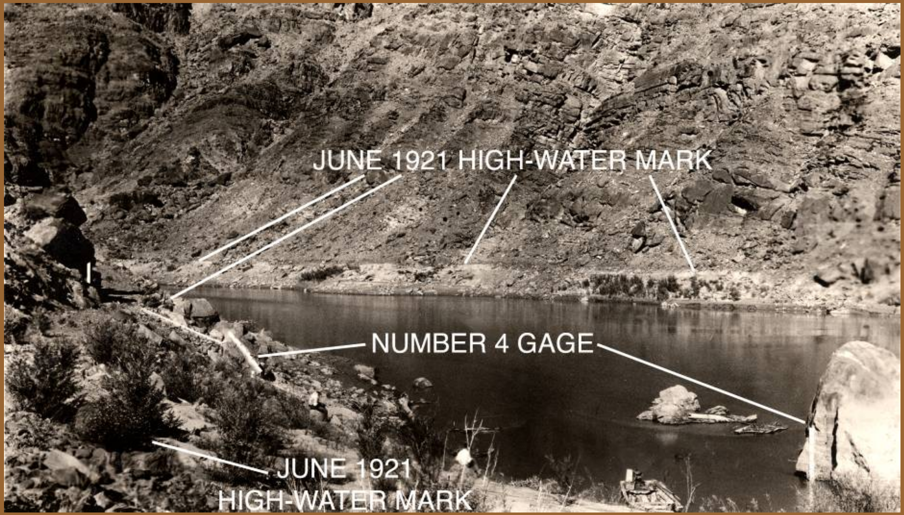
-Enter digital-recorder data from February 2, 1967, through September 30, 1986

-Compute a continuous record of instantaneous discharge using the appropriate rating curves and shifts

-Quality control

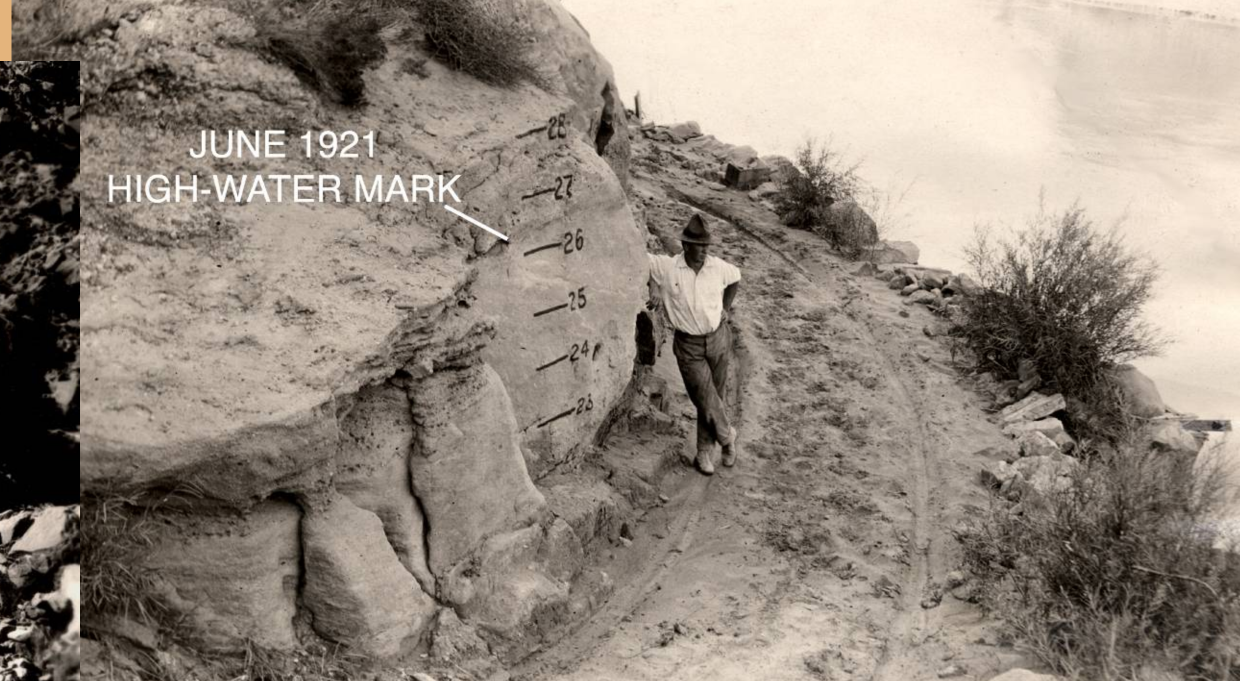
Check and, if necessary, revise peak discharges of the largest pre-dam floods

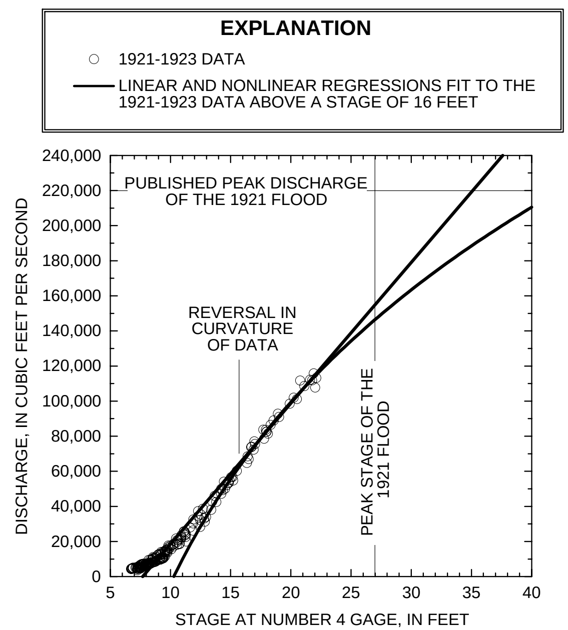


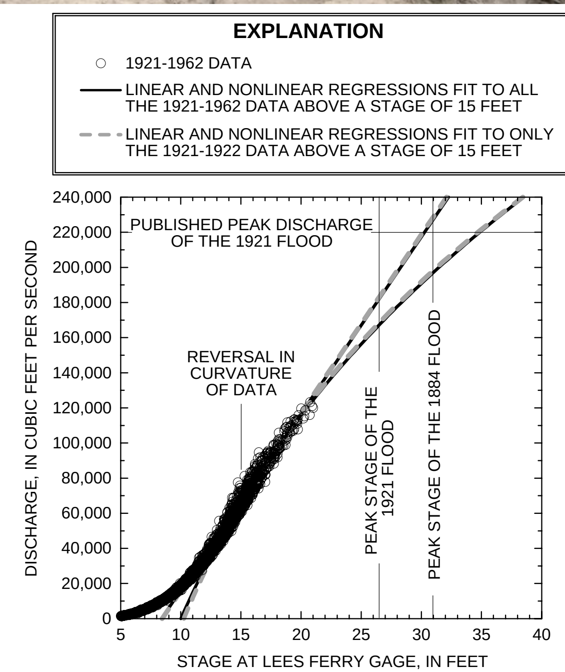


	Original value	1939 revision	This study
1921	174,000 ft^3/s	220,000 ft^3/s	170,000$\pm$20,000 ft^3/s
1884	210,000-250,000 ft^3/s	300,000 ft^3/s	210,000$\pm$30,000 ft^3/s

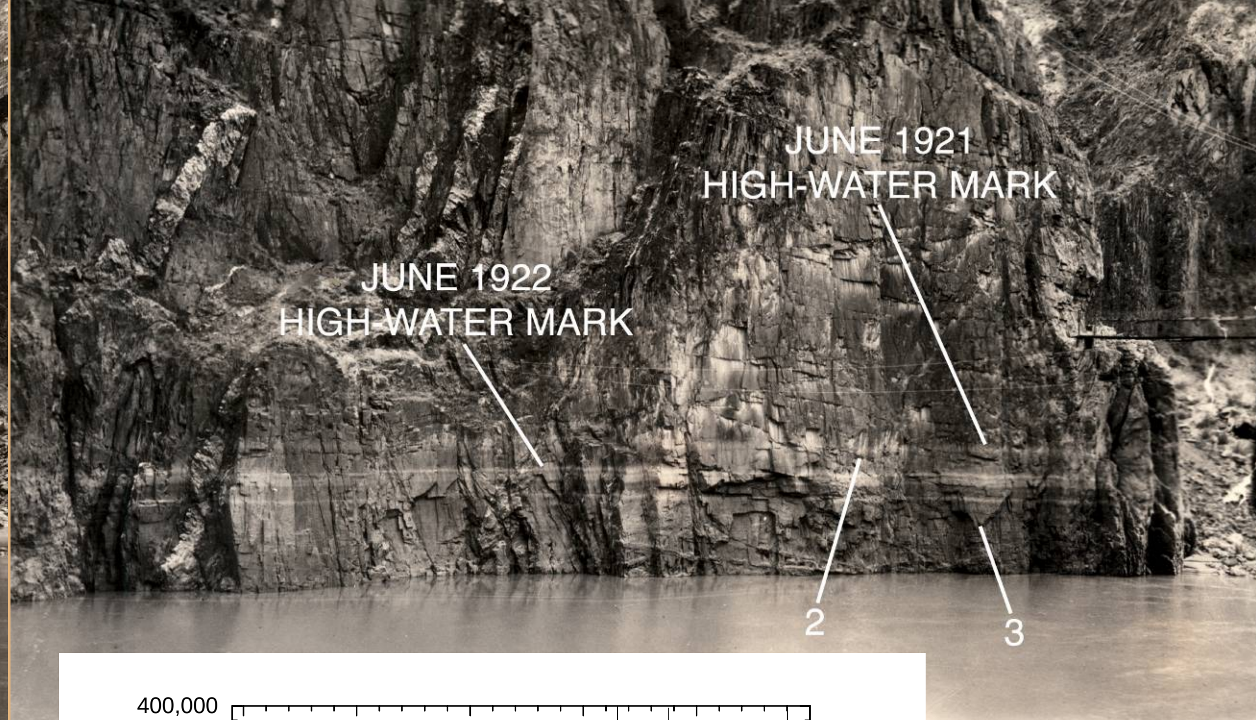
Largest flood within last 4,500 years occurred 1,200-1,600 years ago (O'Connor et al., 1994) ~ 300,000 ft^3/s

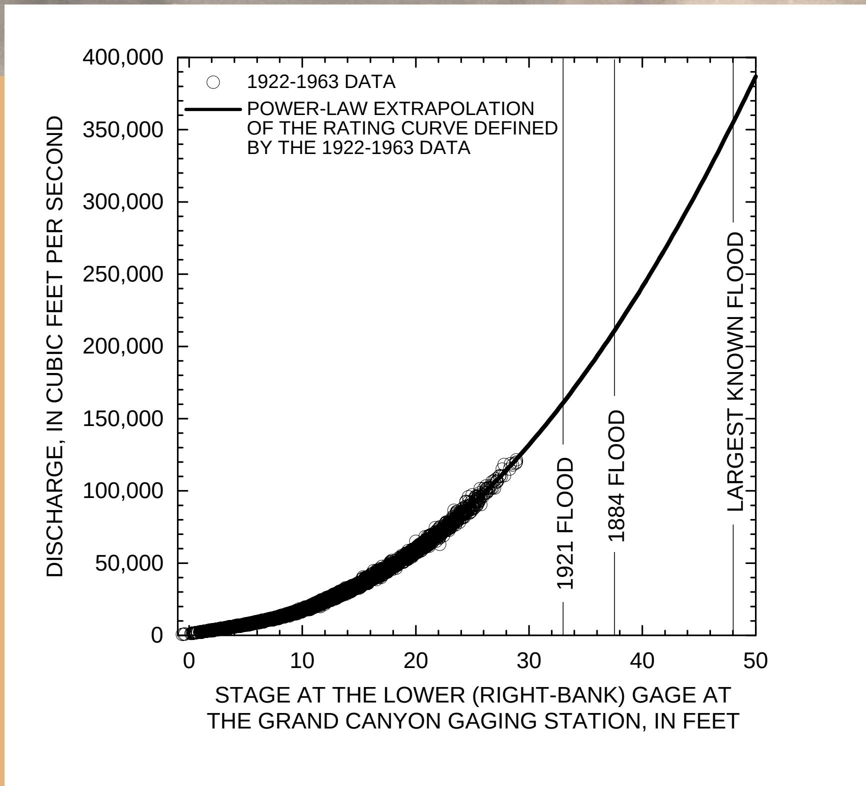

JUNE 1921
HIGH-WATER MARK
28
27
26
25
24
23

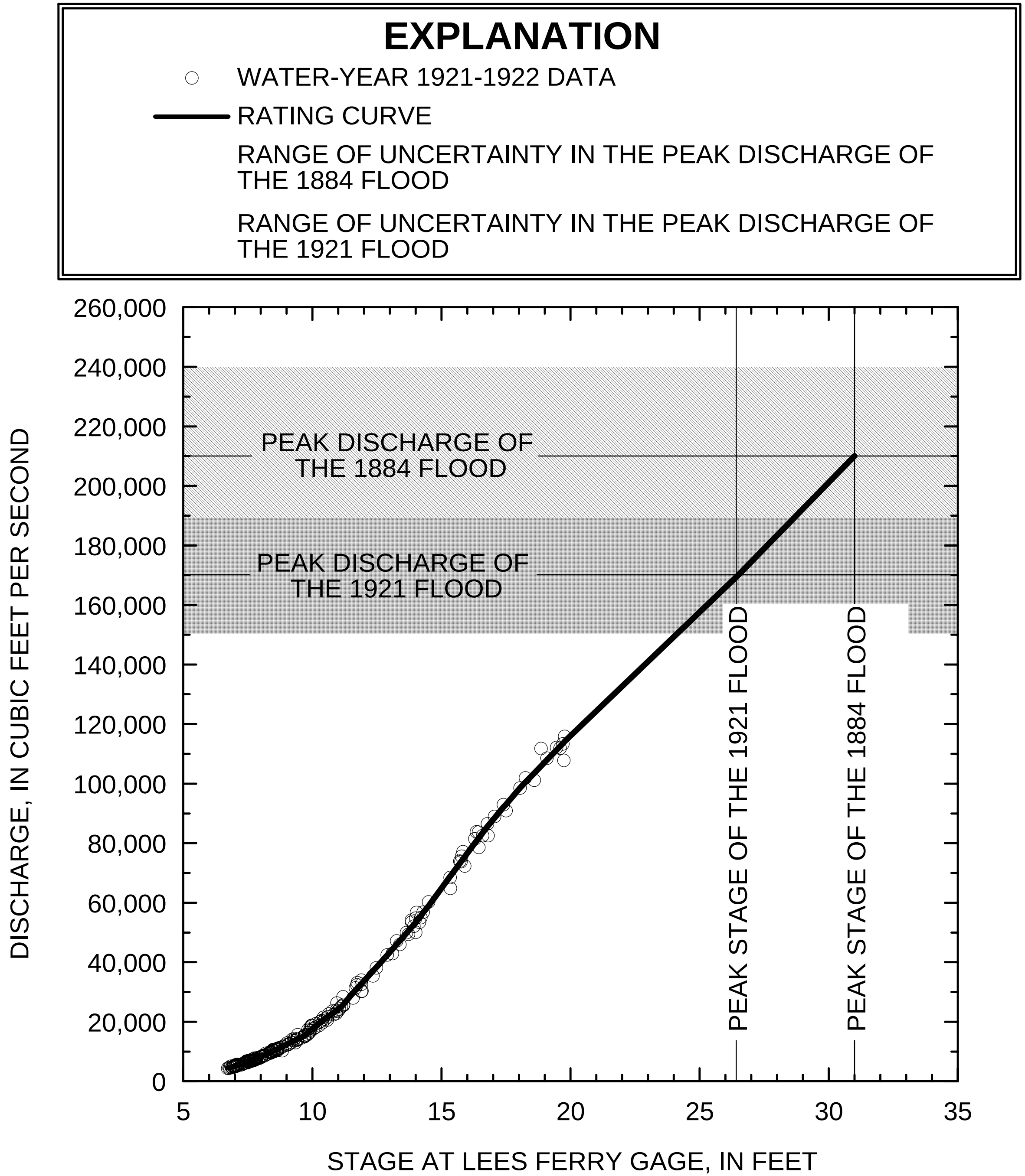

EXPLANATION
1921-1923 DATA
LINEAR AND NONLINEAR REGRESSIONS FIT TO THE 1921-1923 DATA ABOVE A STAGE OF 16 FEET
PUBLISHED PEAK DISCHARGE OF THE 1921 FLOOD
REVERSAL IN CURVATURE OF DATA
PEAK STAGE OF THE 1921 FLOOD
DISCHARGE, IN CUBIC FEET PER SECOND
0
20,000
40,000
60,000
80,000
100,000
120,000
140,000
160,000
180,000
200,000
220,000
240,000
5
10
15
20
25
30
35
40
STAGE AT NUMBER 4 GAGE, IN FEET


EXPLANATION
1921-1962 DATA
LINEAR AND NONLINEAR REGRESSIONS FIT TO ALL THE 1921-1962 DATA ABOVE A STAGE OF 15 FEET
LINEAR AND NONLINEAR REGRESSIONS FIT TO ONLY THE 1921-1922 DATA ABOVE A STAGE OF 15 FEET
PUBLISHED PEAK DISCHARGE OF THE 1921 FLOOD
REVERSAL IN CURVATURE OF DATA
PEAK STAGE OF THE 1921 FLOOD
PEAK STAGE OF THE 1884 FLOOD
DISCHARGE, IN CUBIC FEET PER SECOND
0
20,000
40,000
60,000
80,000
100,000
120,000
140,000
160,000
180,000
200,000
220,000
240,000
5
10
15
20
25
30
35
40
STAGE AT LEES FERRY GAGE, IN FEET

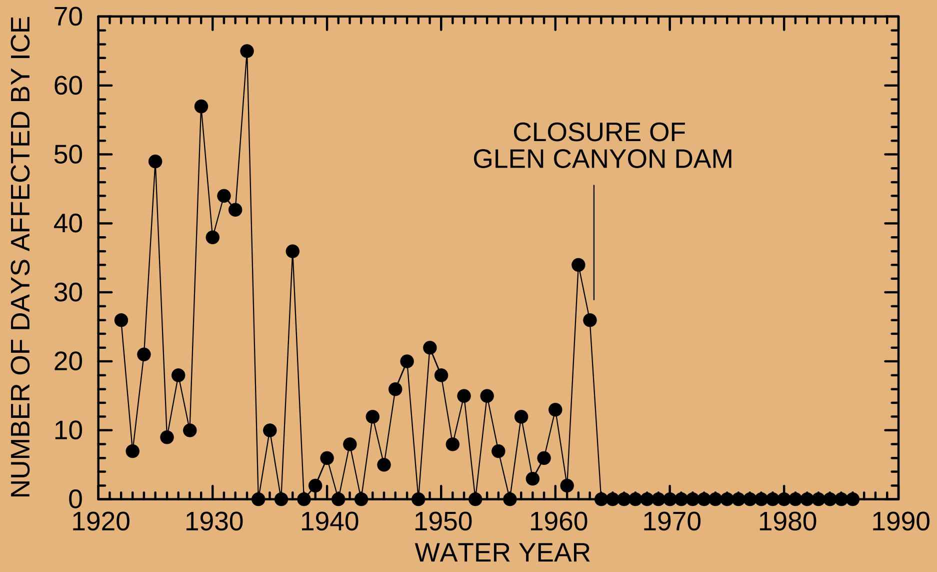

JUNE 1921
HIGH-WATER MARK
1
2
3
AUGUST 1921
HIGH-WATER MARK

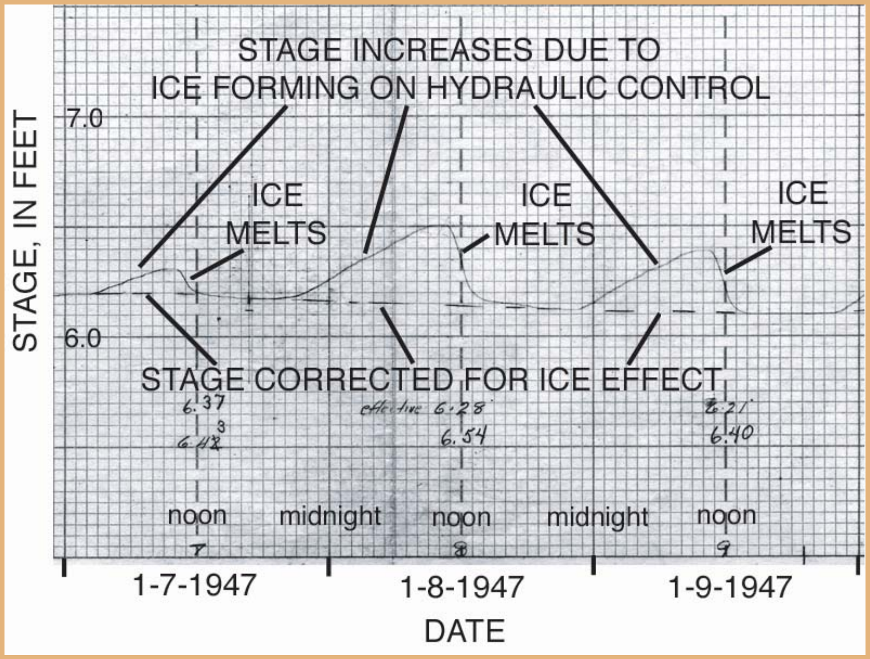

JUNE 1921
HIGH-WATER MARK
JUNE 1922
HIGH-WATER MARK
2
3

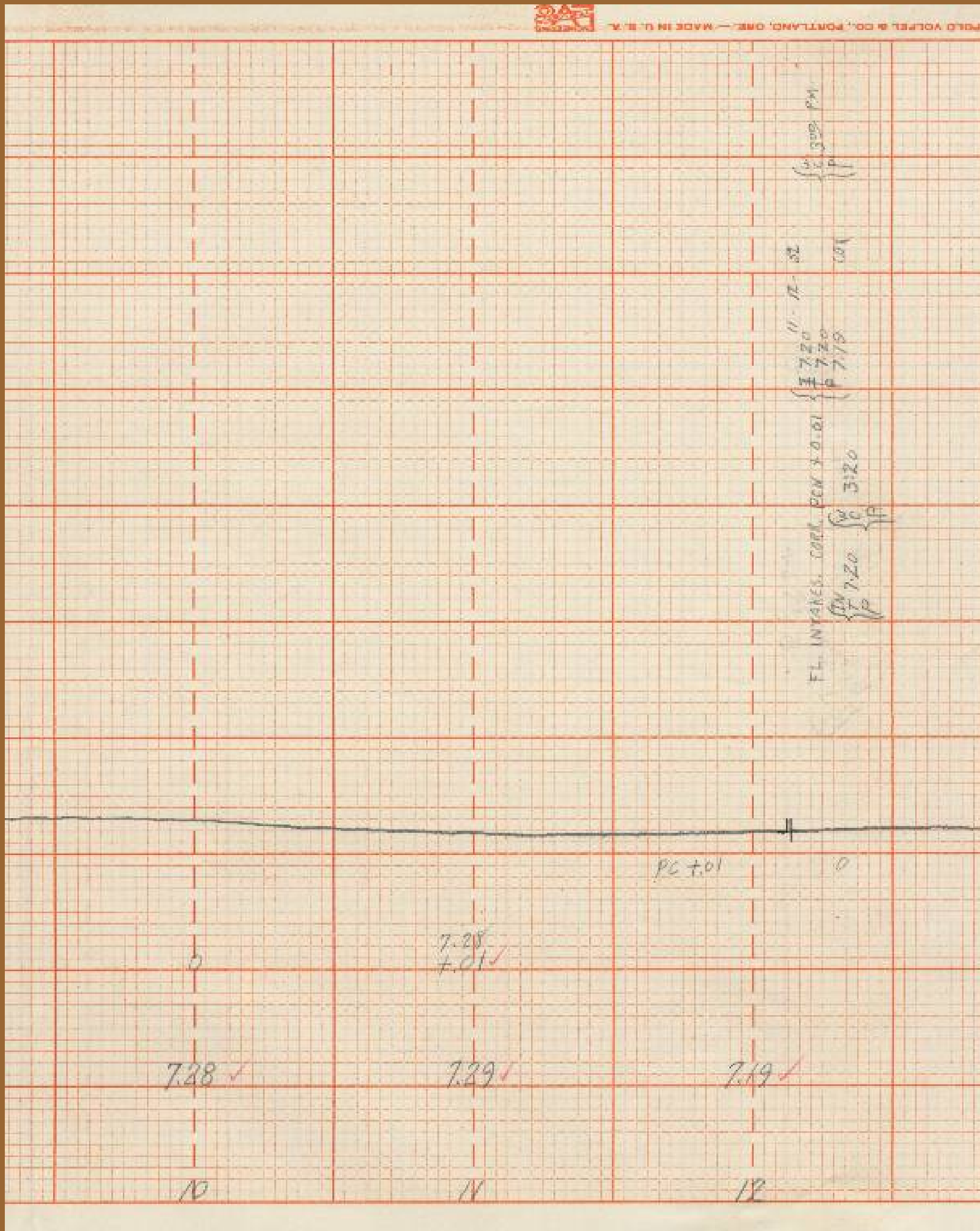

1922-1963 DATA
POWER-LAW EXTRAPOLATION
OF THE RATING CURVE DEFINED
BY THE 1922-1963 DATA
DISCHARGE, IN CUBIC FEET PER SECOND
0
50,000
100,000
150,000
200,000
250,000
300,000
350,000
400,000
1921 FLOOD
1884 FLOOD
LARGEST KNOWN FLOOD
0
10
20
30
40
50
STAGE AT THE LOWER (RIGHT-BANK) GAGE AT
THE GRAND CANYON GAGING STATION, IN FEET


EXPLANATION
WATER-YEAR 1921-1922 DATA
RATING CURVE
RANGE OF UNCERTAINTY IN THE PEAK DISCHARGE OF THE 1884 FLOOD
RANGE OF UNCERTAINTY IN THE PEAK DISCHARGE OF THE 1921 FLOOD
PEAK DISCHARGE OF THE 1884 FLOOD
PEAK DISCHARGE OF THE 1921 FLOOD
PEAK STAGE OF THE 1921 FLOOD
PEAK STAGE OF THE 1884 FLOOD
DISCHARGE, IN CUBIC FEET PER SECOND
0
20,000
40,000
60,000
80,000
100,000
120,000
140,000
160,000
180,000
200,000
220,000
240,000
260,000
5
10
15
20
25
30
35
STAGE AT LEES FERRY GAGE, IN FEET

Ice effects


NUMBER OF DAYS AFFECTED BY ICE
0
10
20
30
40
50
60
70
CLOSURE OF
GLEN CANYON DAM
1920
1930
1940
1950
1960
1970
1980
1990
WATER YEAR

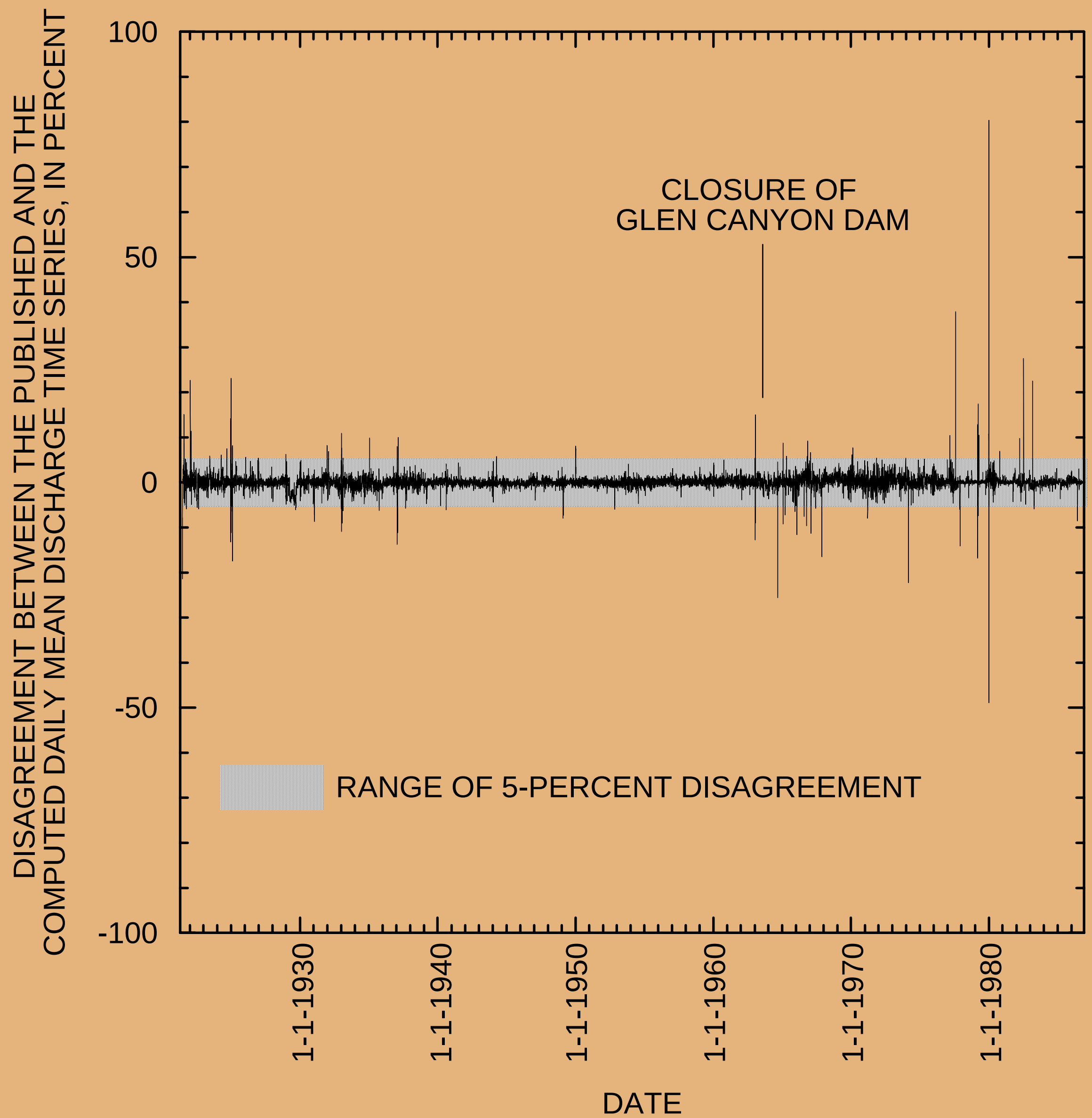

STAGE INCREASES DUE TO
ICE FORMING ON HYDRAULIC CONTROL
ICE
MELTS
ICE
MELTS
ICE
MELTS
STAGE, IN FEET
7.0
6.0
STAGE CORRECTED FOR ICE EFFECT
noon
midnight
noon
midnight
noon
1-7-1947
1-8-1947
1-9-1947
DATE



Errors

Example: 11-11-52 daily mean Stage incorrectly recorded as 7.29' instead of 7.19'

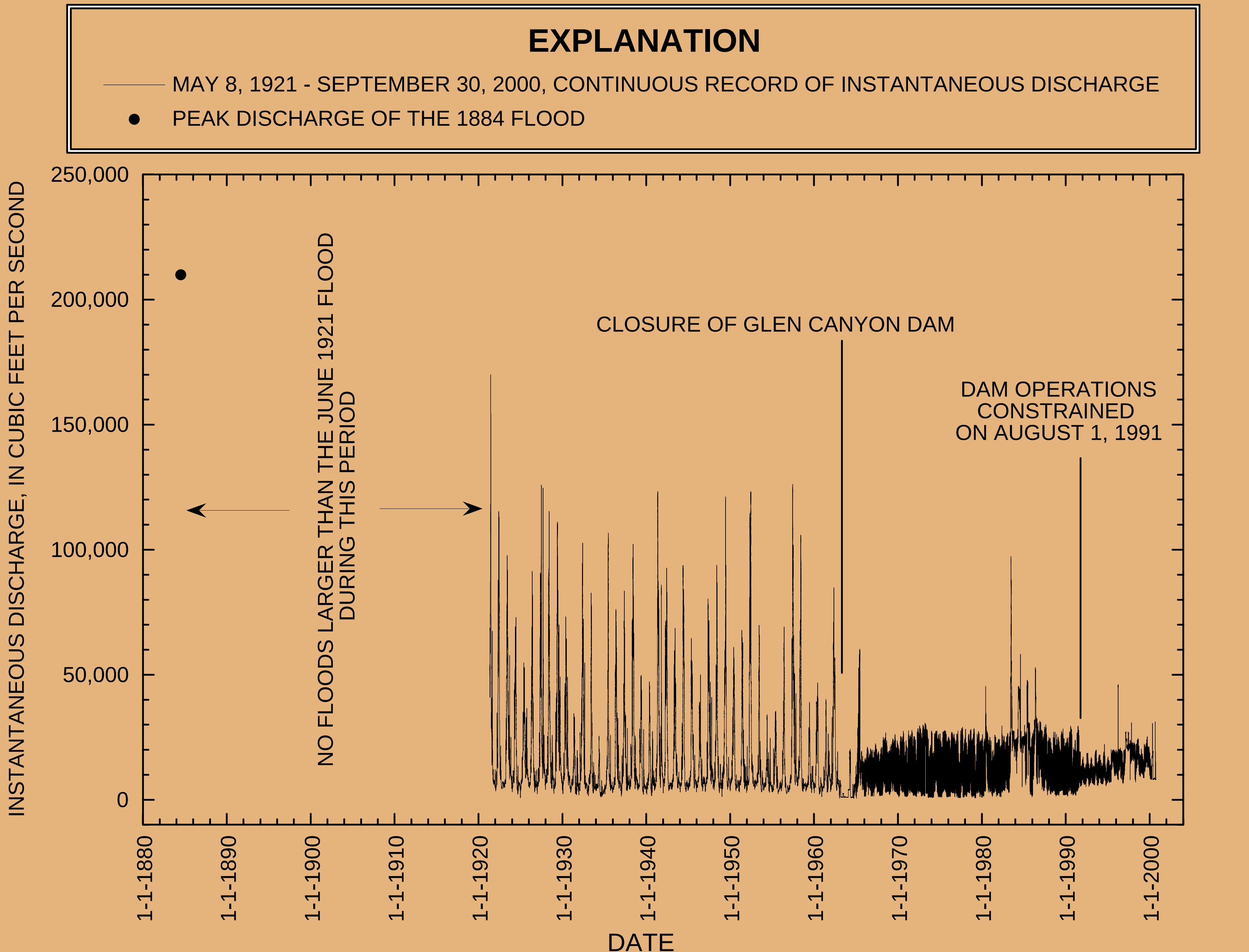
+6.0% discharge error

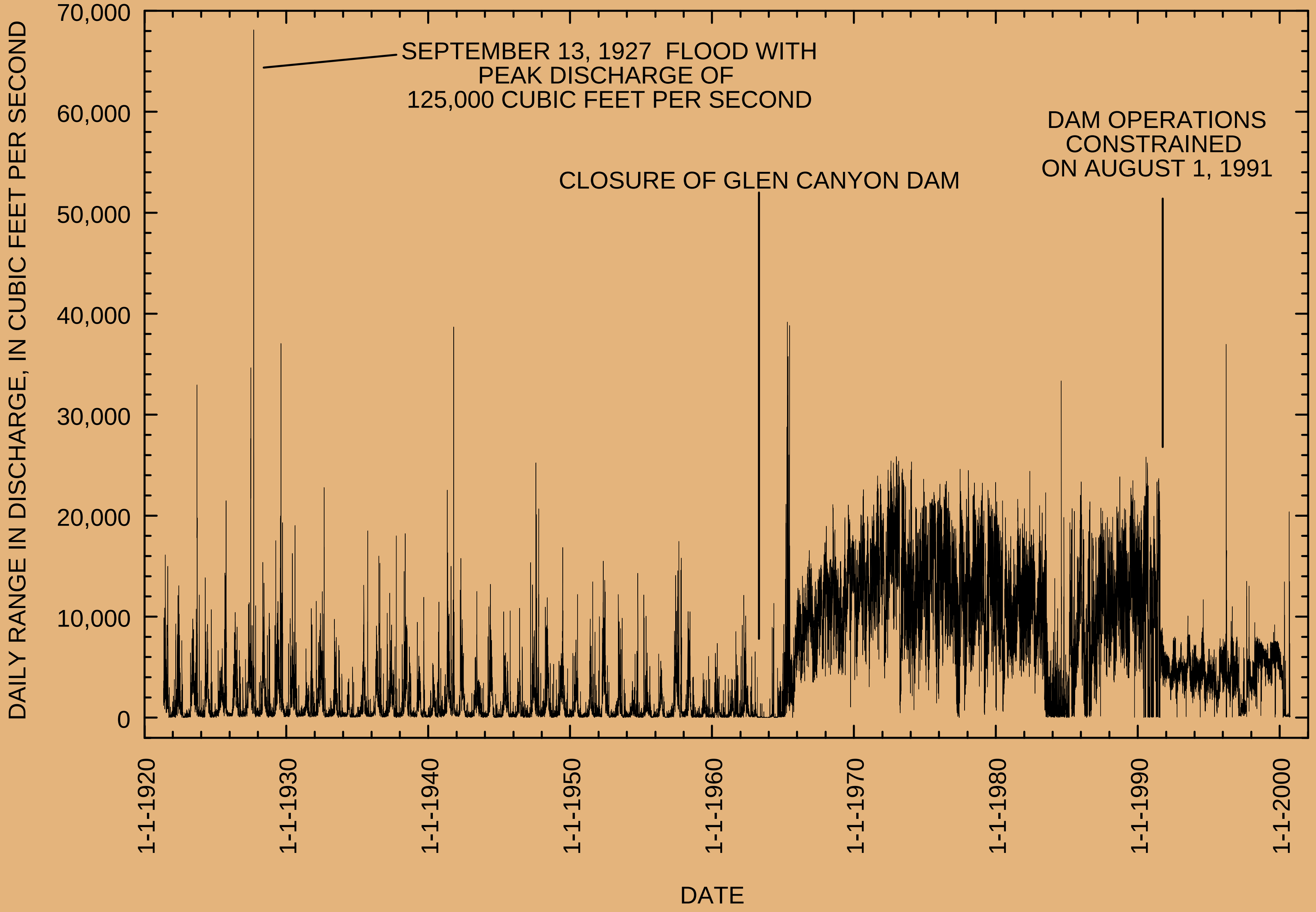


89 non-ice-effected days in the published daily mean discharge record were found to have errors in excess of 5%

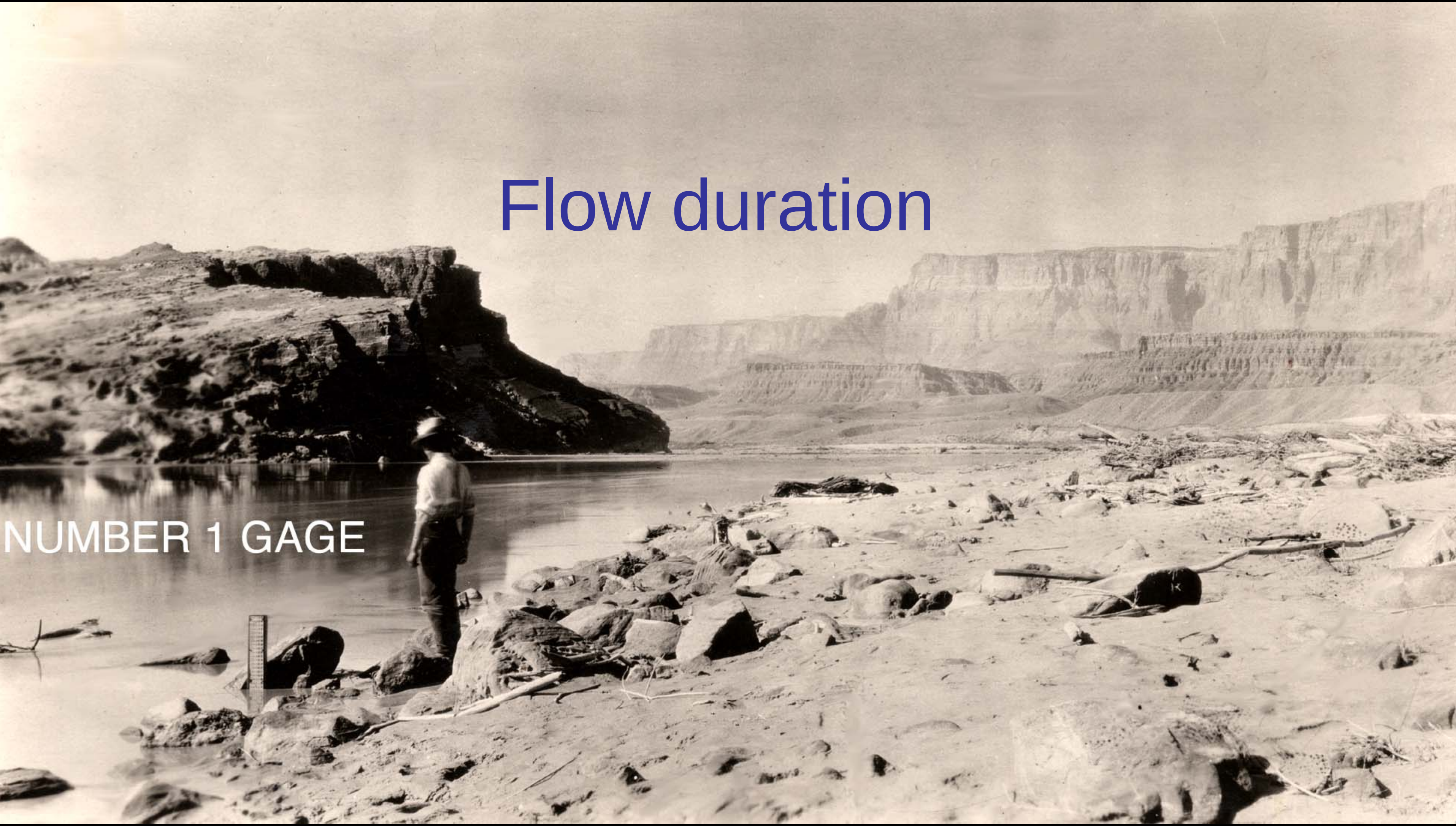
Mean disagreement = +0.055%

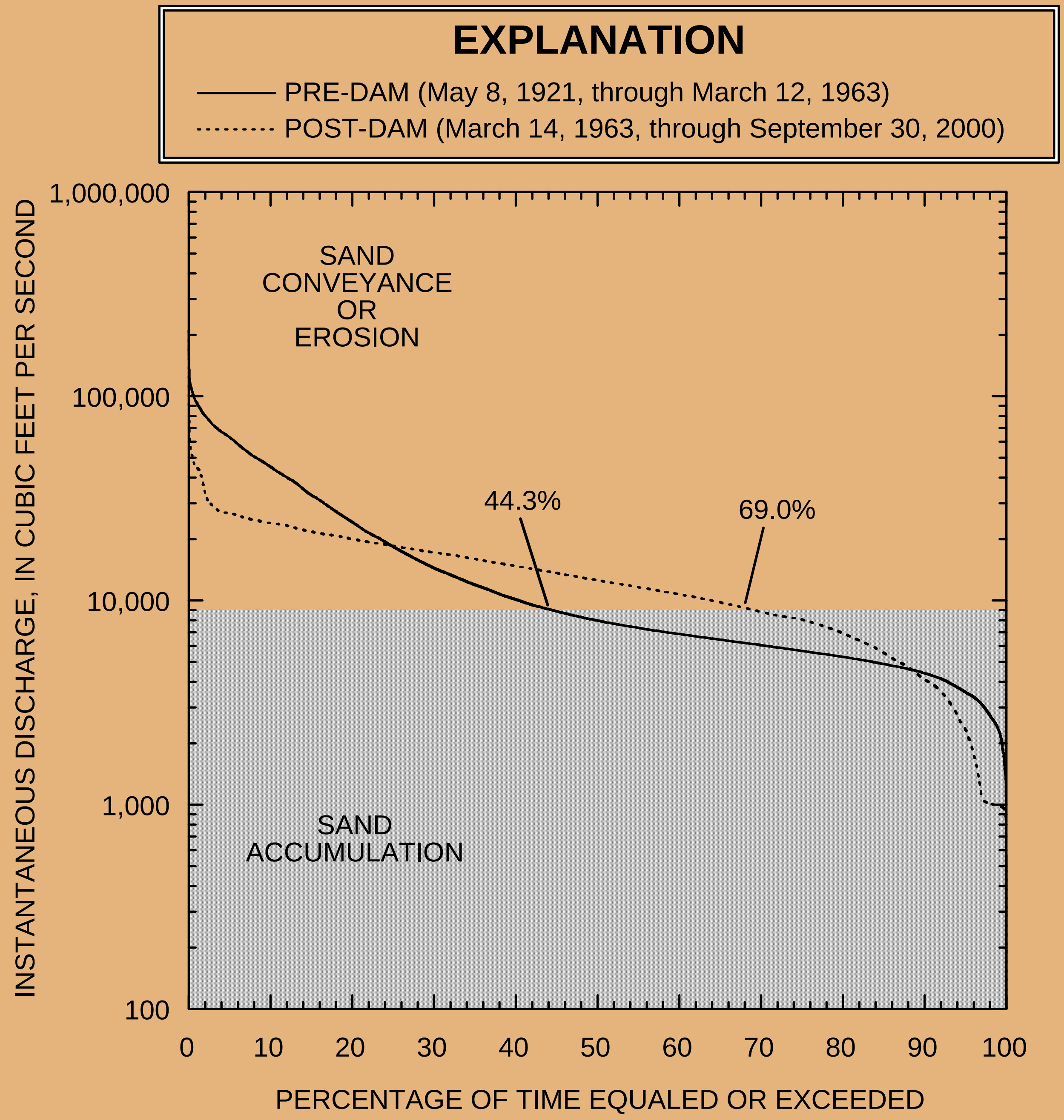
The continuous record of instantaneous discharge

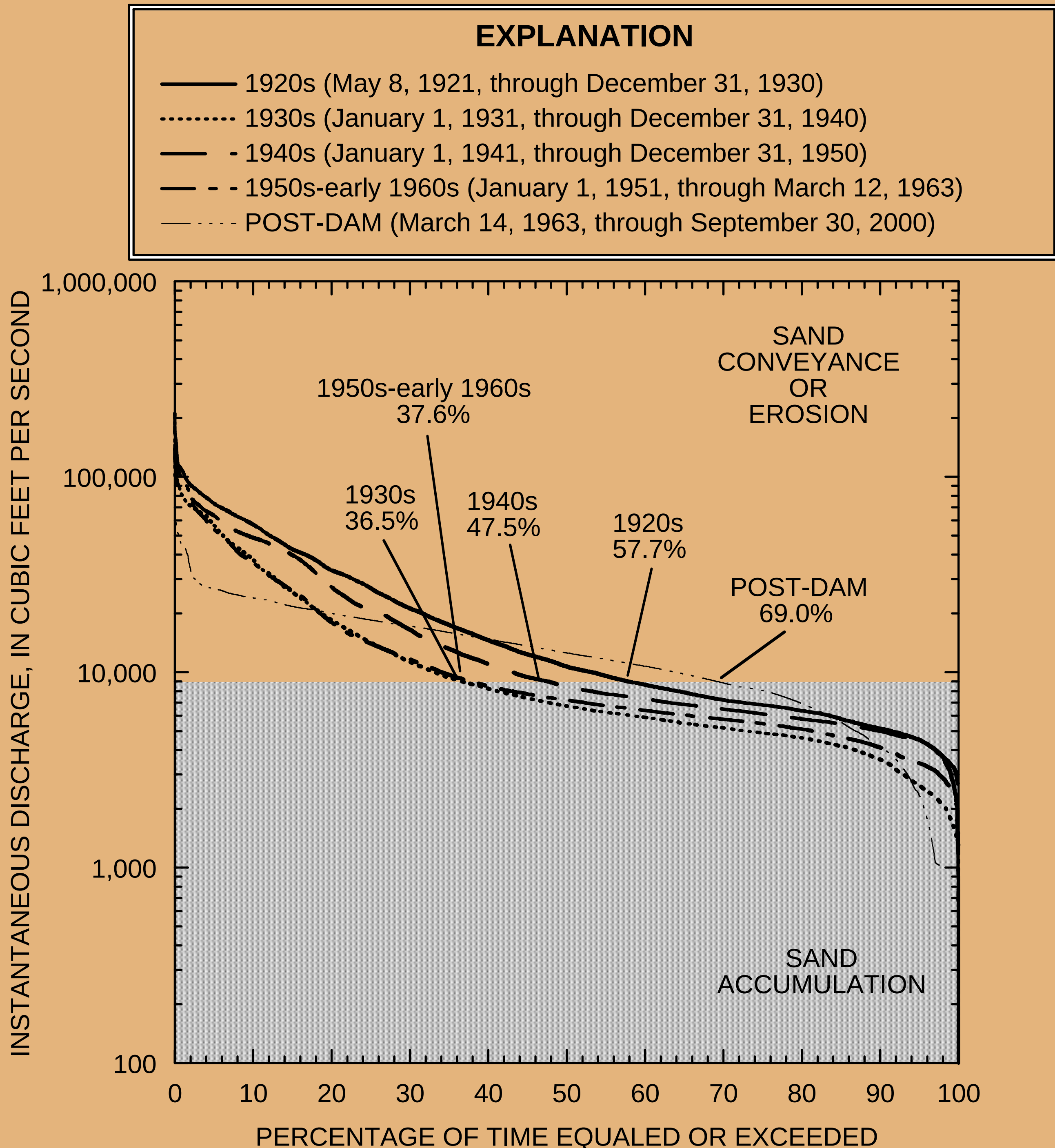

EXPLANATION
MAY 8, 1921 - SEPTEMBER 30, 2000, CONTINUOUS RECORD OF INSTANTANEOUS DISCHARGE
PEAK DISCHARGE OF THE 1884 FLOOD
INSTANTANEOUS DISCHARGE, IN CUBIC FEET PER SECOND
250,000
200,000
150,000
100,000
50,000
0
NO FLOODS LARGER THAN THE JUNE 1921 FLOOD DURING THIS PERIOD
CLOSURE OF GLEN CANYON DAM
DAM OPERATIONS CONSTRAINED ON AUGUST 1, 1991
1-1-1880
1-1-1890
1-1-1900
1-1-1910
1-1-1920
1-1-1930
1-1-1940
1-1-1950
1-1-1960
1-1-1970
1-1-1980
1-1-1990
1-1-2000
DATE

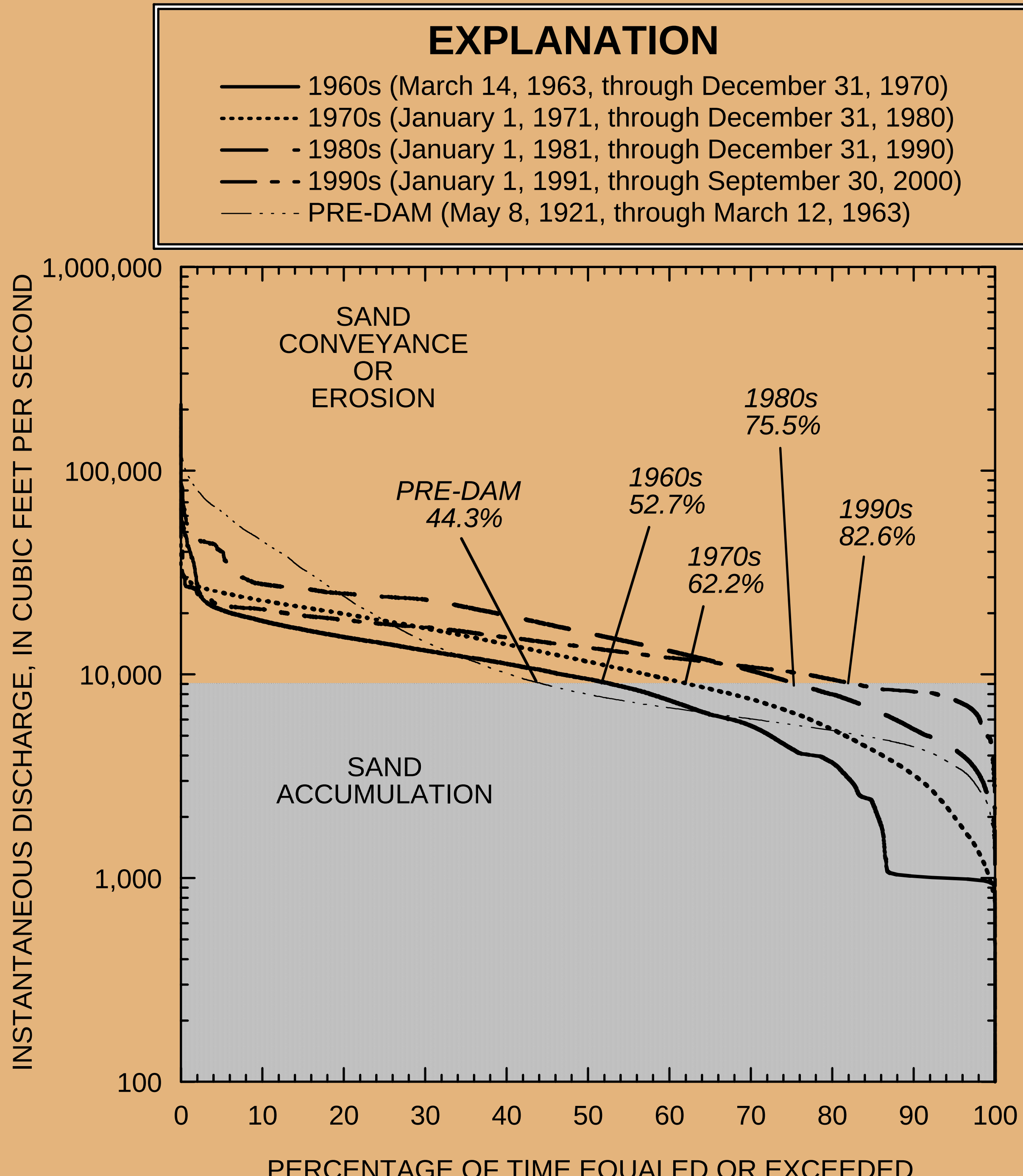

DAILY RANGE IN DISCHARGE, IN CUBIC FEET PER SECOND
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
SEPTEMBER 13, 1927 FLOOD WITH PEAK DISCHARGE OF 125,000 CUBIC FEET PER SECOND
CLOSURE OF GLEN CANYON DAM
DAM OPERATIONS CONSTRAINED ON AUGUST 1, 1991
1-1-1920
1-1-1930
1-1-1940
1-1-1950
1-1-1960
1-1-1970
1-1-1980
1-1-1990
1-1-2000
DATE

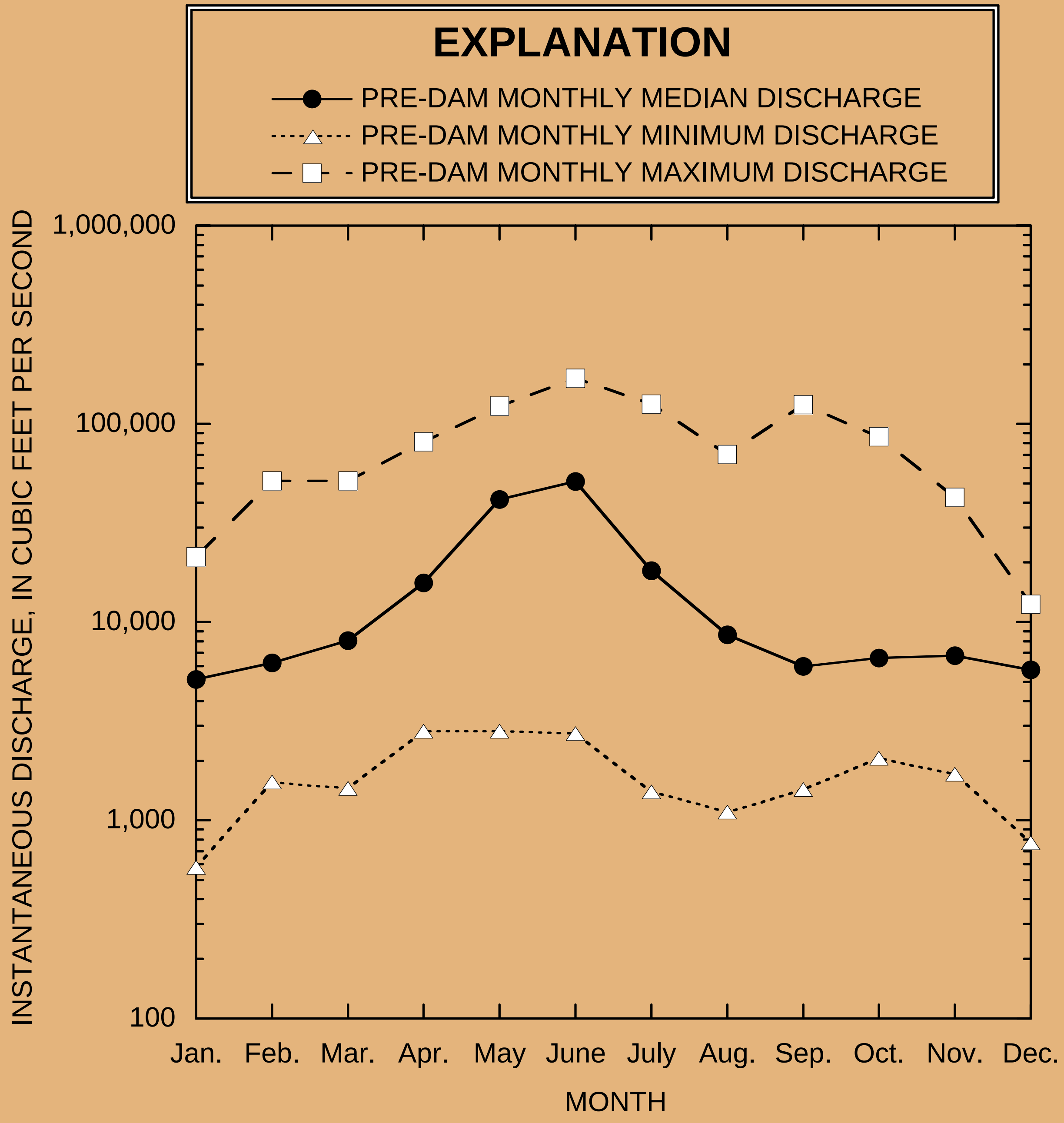
Flow duration

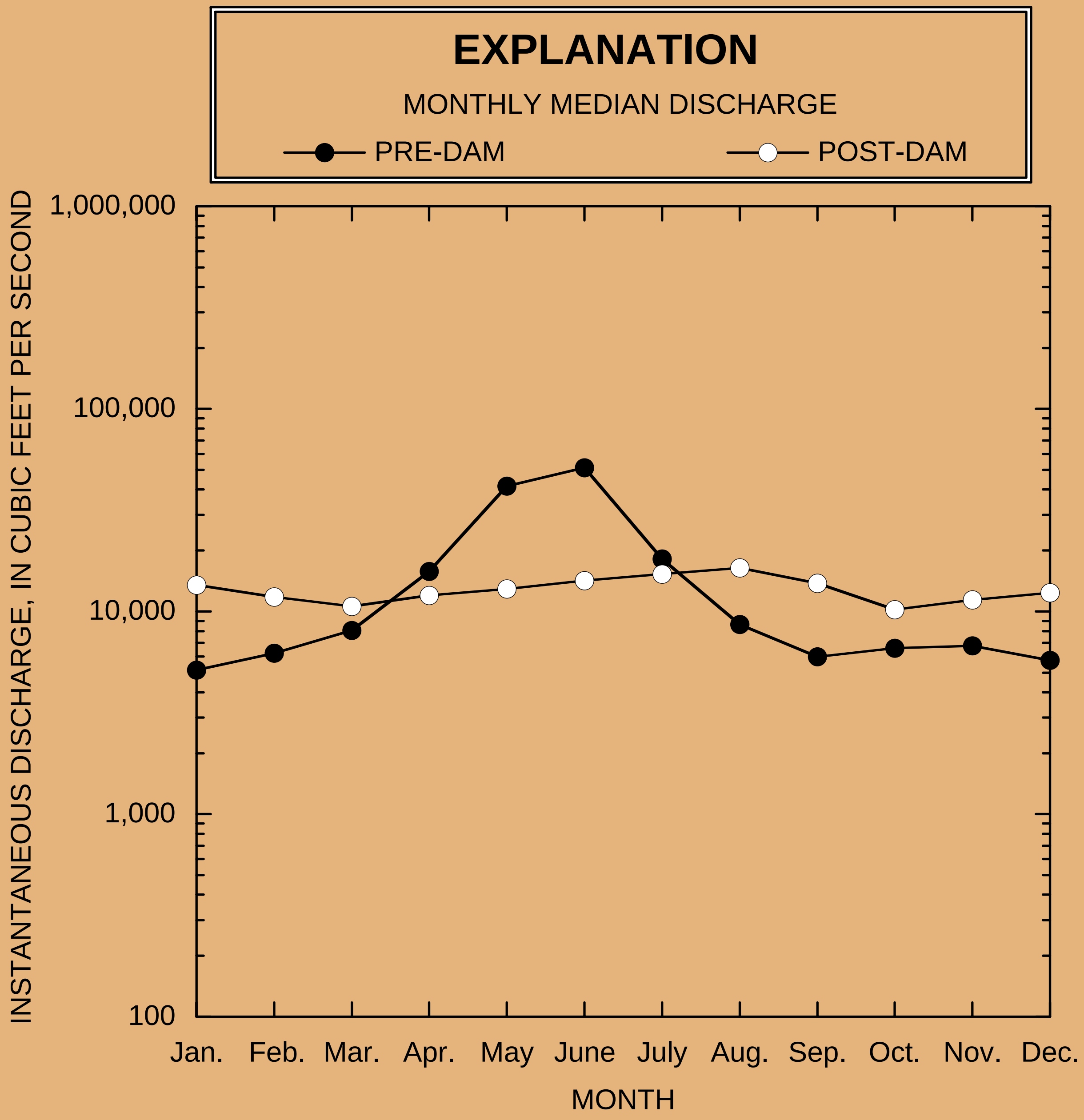


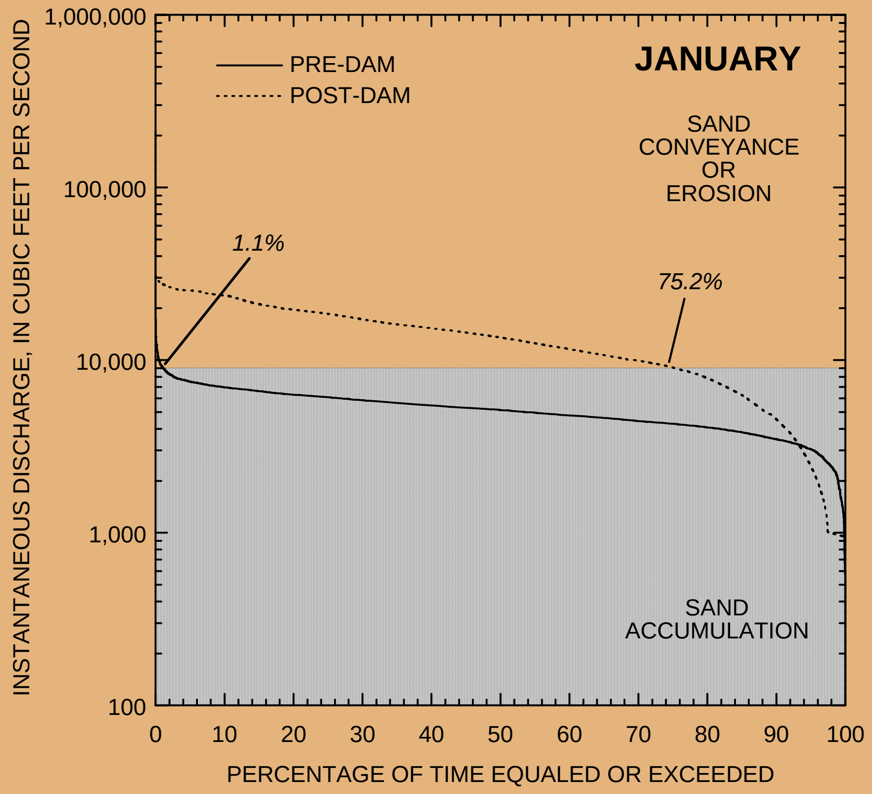

EXPLANATION
PRE-DAM (May 8, 1921, through March 12, 1963)
POST-DAM (March 14, 1963, through September 30, 2000)
SAND CONVEYANCE OR EROSION
SAND ACCUMULATION
44.3%
69.0%
1,000,000
100,000
10,000
1,000
100
0
10
20
30
40
50
60
70
80
90
100
INSTANTANEOUS DISCHARGE, IN CUBIC FEET PER SECOND
PERCENTAGE OF TIME EQUALED OR EXCEEDED

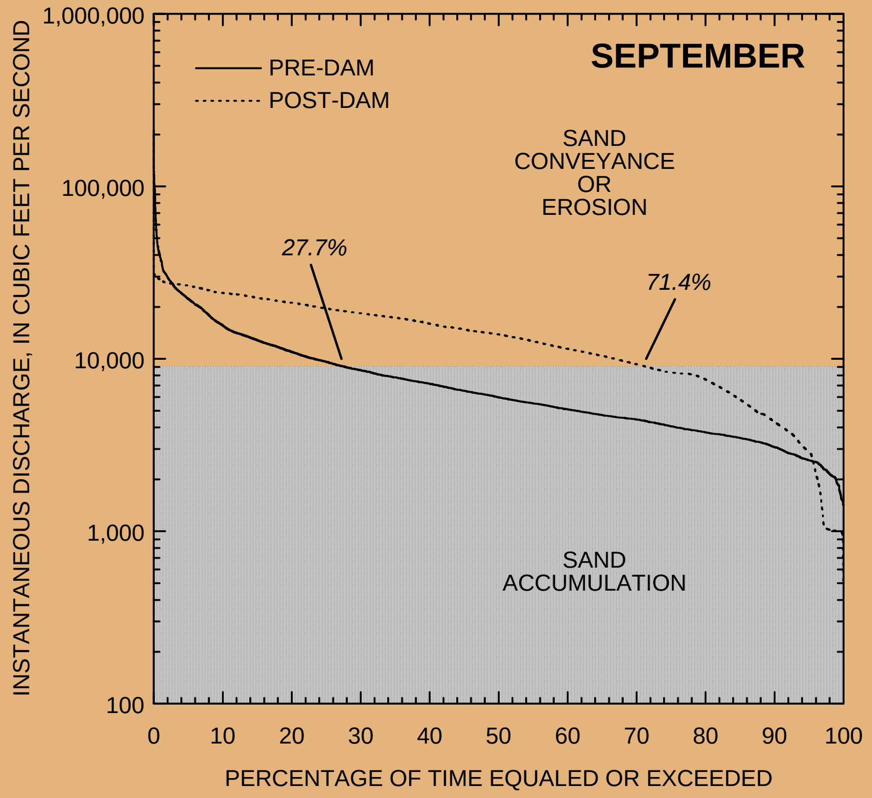

EXPLANATION
1920s (May 8, 1921, through December 31, 1930)
1930s (January 1, 1931, through December 31, 1940)
1940s (January 1, 1941, through December 31, 1950)
1950s-early 1960s (January 1, 1951, through March 12, 1963)
POST-DAM (March 14, 1963, through September 30, 2000)
INSTANTANEOUS DISCHARGE, IN CUBIC FEET PER SECOND
1,000,000
100,000
10,000
1,000
100
0
10
20
30
40
50
60
70
80
90
100
PERCENTAGE OF TIME EQUALED OR EXCEEDED
SAND CONVEYANCE OR EROSION
SAND ACCUMULATION
1950s-early 1960s 37.6%
1930s 36.5%
1940s 47.5%
1920s 57.7%
POST-DAM 69.0%

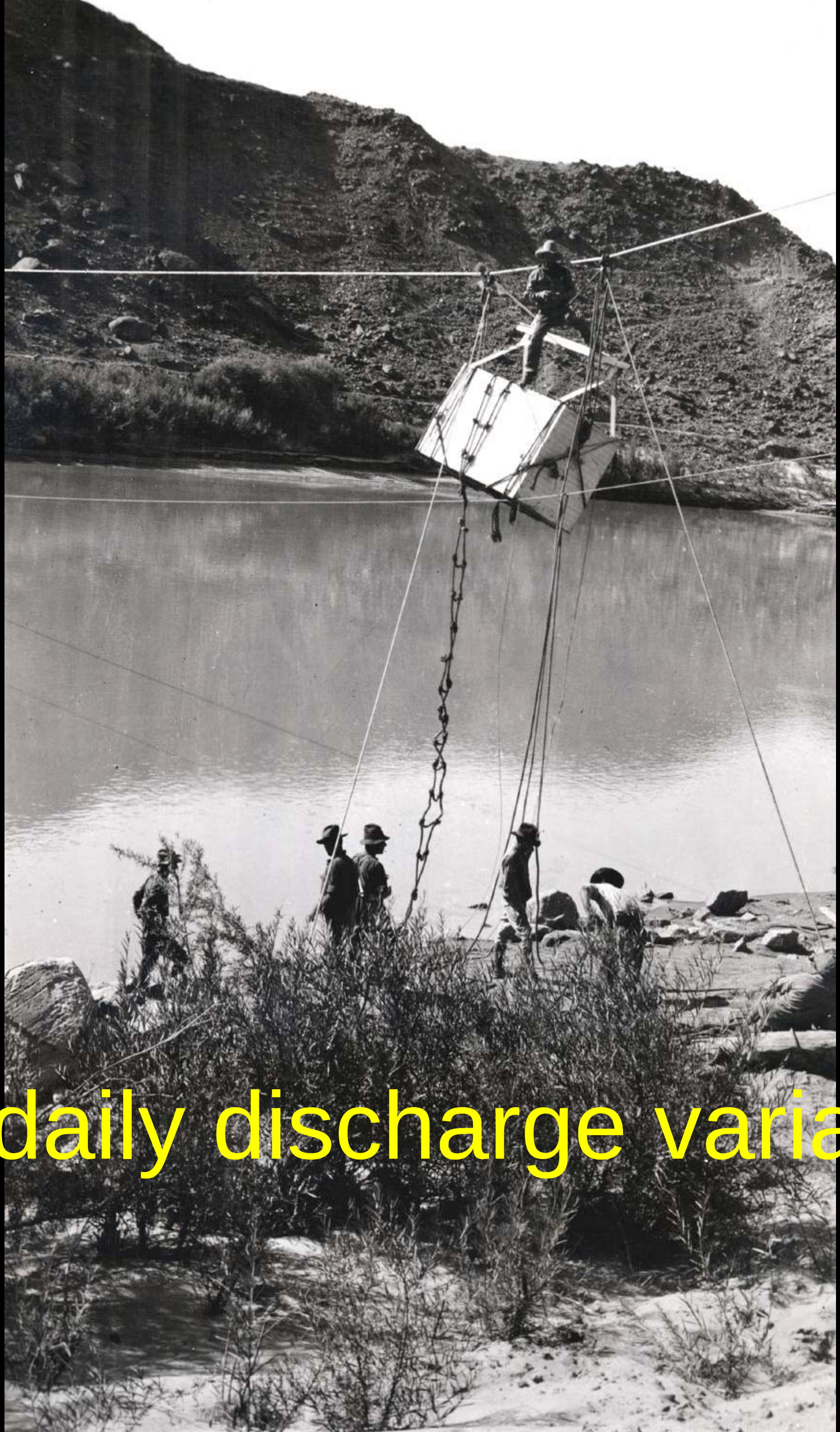

EXPLANATION
1960s (March 14, 1963, through December 31, 1970)
1970s (January 1, 1971, through December 31, 1980)
1980s (January 1, 1981, through December 31, 1990)
1990s (January 1, 1991, through September 30, 2000)
PRE-DAM (May 8, 1921, through March 12, 1963)
SAND CONVEYANCE OR EROSION
SAND ACCUMULATION
PRE-DAM 44.3%
1960s 52.7%
1970s 62.2%
1980s 75.5%
1990s 82.6%
1,000,000
100,000
10,000
1,000
100
0
10
20
30
40
50
60
70
80
90
100
INSTANTANEOUS DISCHARGE, IN CUBIC FEET PER SECOND
PERCENTAGE OF TIME EQUALED OR EXCEEDED


EXPLANATION
PRE-DAM MONTHLY MEDIAN DISCHARGE
PRE-DAM MONTHLY MINIMUM DISCHARGE
PRE-DAM MONTHLY MAXIMUM DISCHARGE
INSTANTANEOUS DISCHARGE, IN CUBIC FEET PER SECOND
1,000,000
100,000
10,000
1,000
100
Jan.
Feb.
Mar.
Apr.
May
June
July
Aug.
Sep.
Oct.
Nov.
Dec.
MONTH

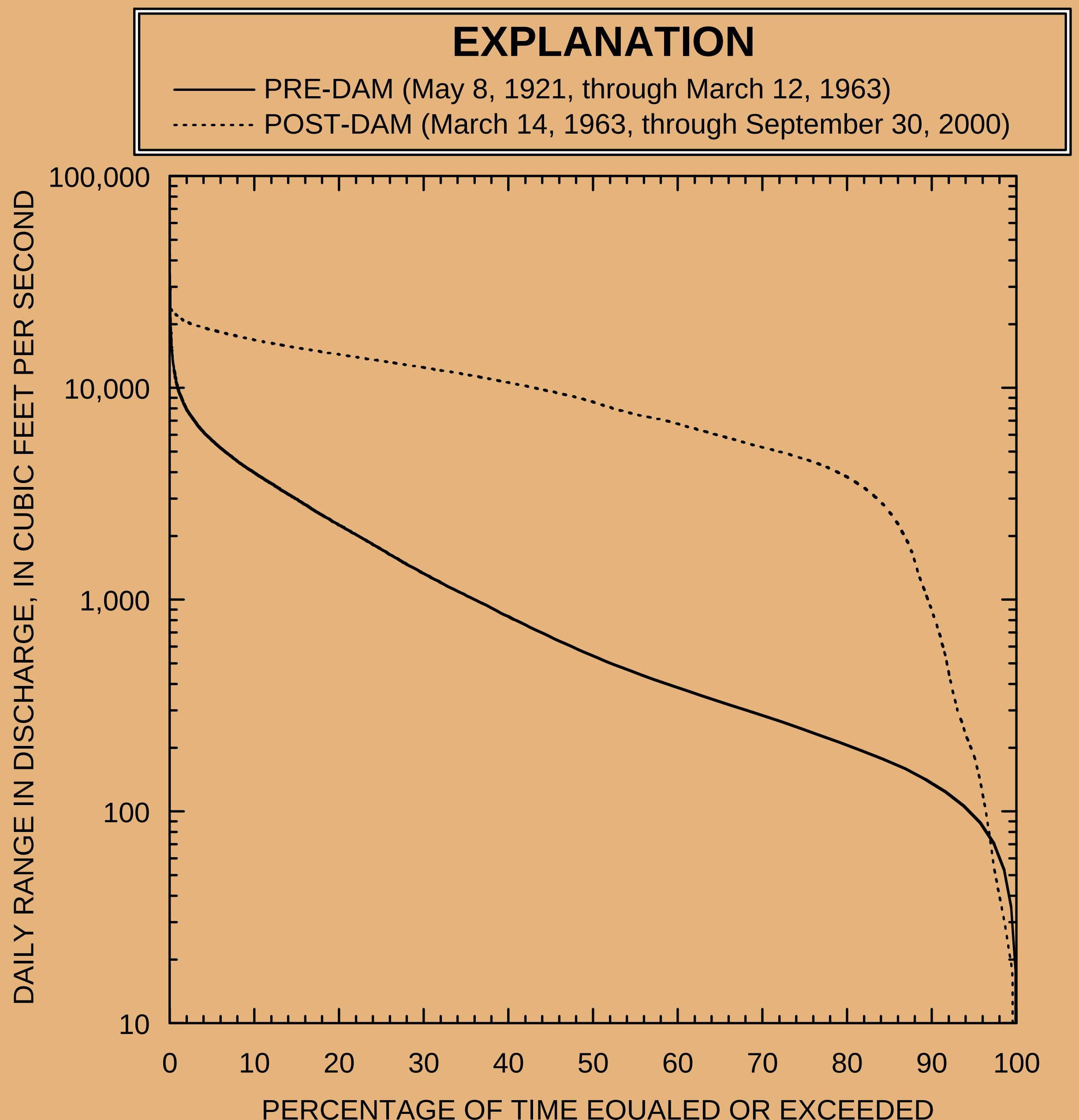

EXPLANATION
MONTHLY MEDIAN DISCHARGE
PRE-DAM
POST-DAM
INSTANTANEOUS DISCHARGE, IN CUBIC FEET PER SECOND
1,000,000
100,000
10,000
1,000
100
Jan.
Feb.
Mar.
Apr.
May
June
July
Aug.
Sep.
Oct.
Nov.
Dec.
MONTH

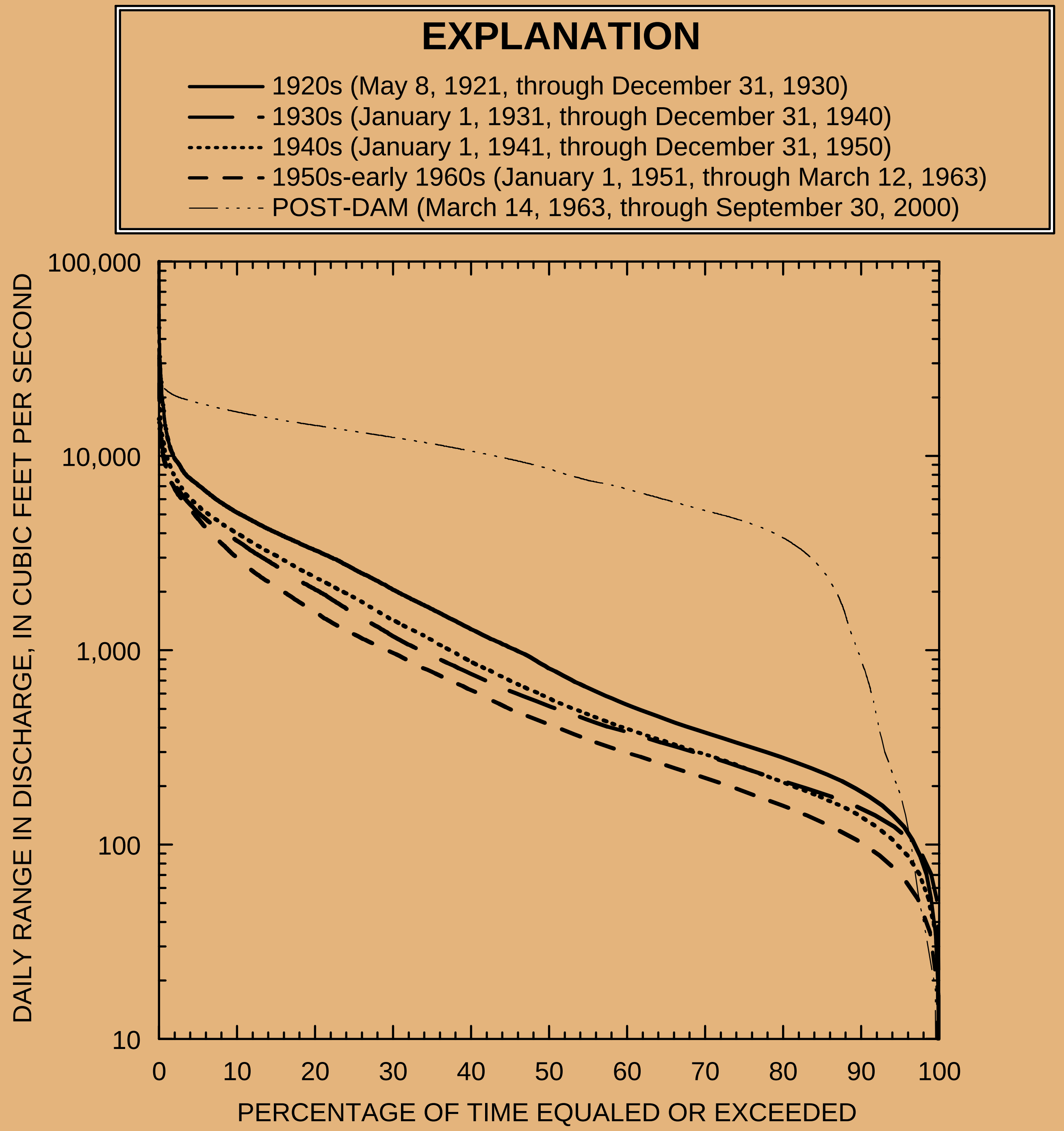

JANUARY
PRE-DAM
POST-DAM
SAND CONVEYANCE OR EROSION
SAND ACCUMULATION
1.1%
75.2%
INSTANTANEOUS DISCHARGE, IN CUBIC FEET PER SECOND
1,000,000
100,000
10,000
1,000
100
0
10
20
30
40
50
60
70
80
90
100
PERCENTAGE OF TIME EQUALED OR EXCEEDED

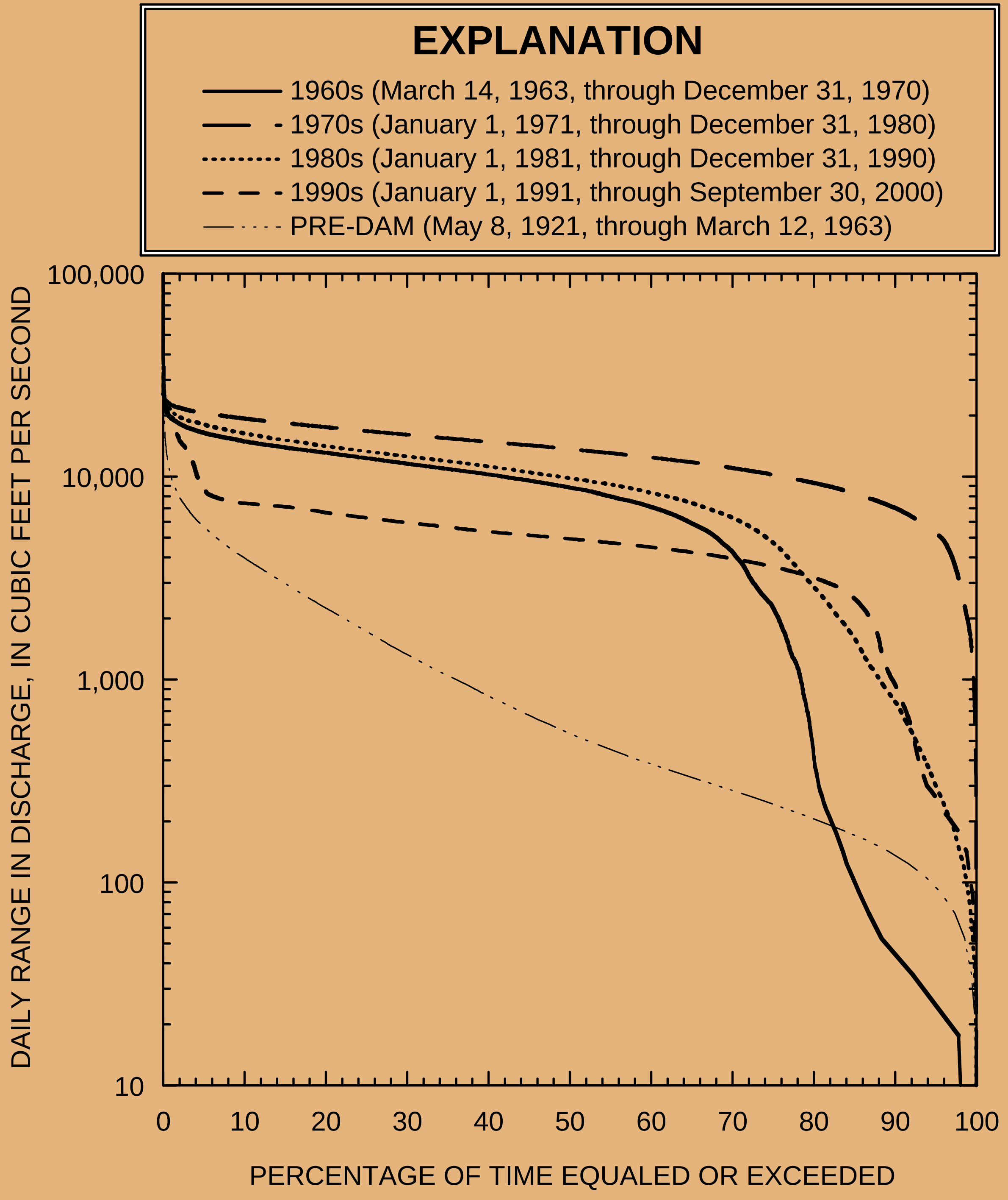

SEPTEMBER
PRE-DAM
POST-DAM
SAND CONVEYANCE OR EROSION
SAND ACCUMULATION
27.7%
71.4%
INSTANTANEOUS DISCHARGE, IN CUBIC FEET PER SECOND
1,000,000
100,000
10,000
1,000
100
0
10
20
30
40
50
60
70
80
90
100
PERCENTAGE OF TIME EQUALED OR EXCEEDED

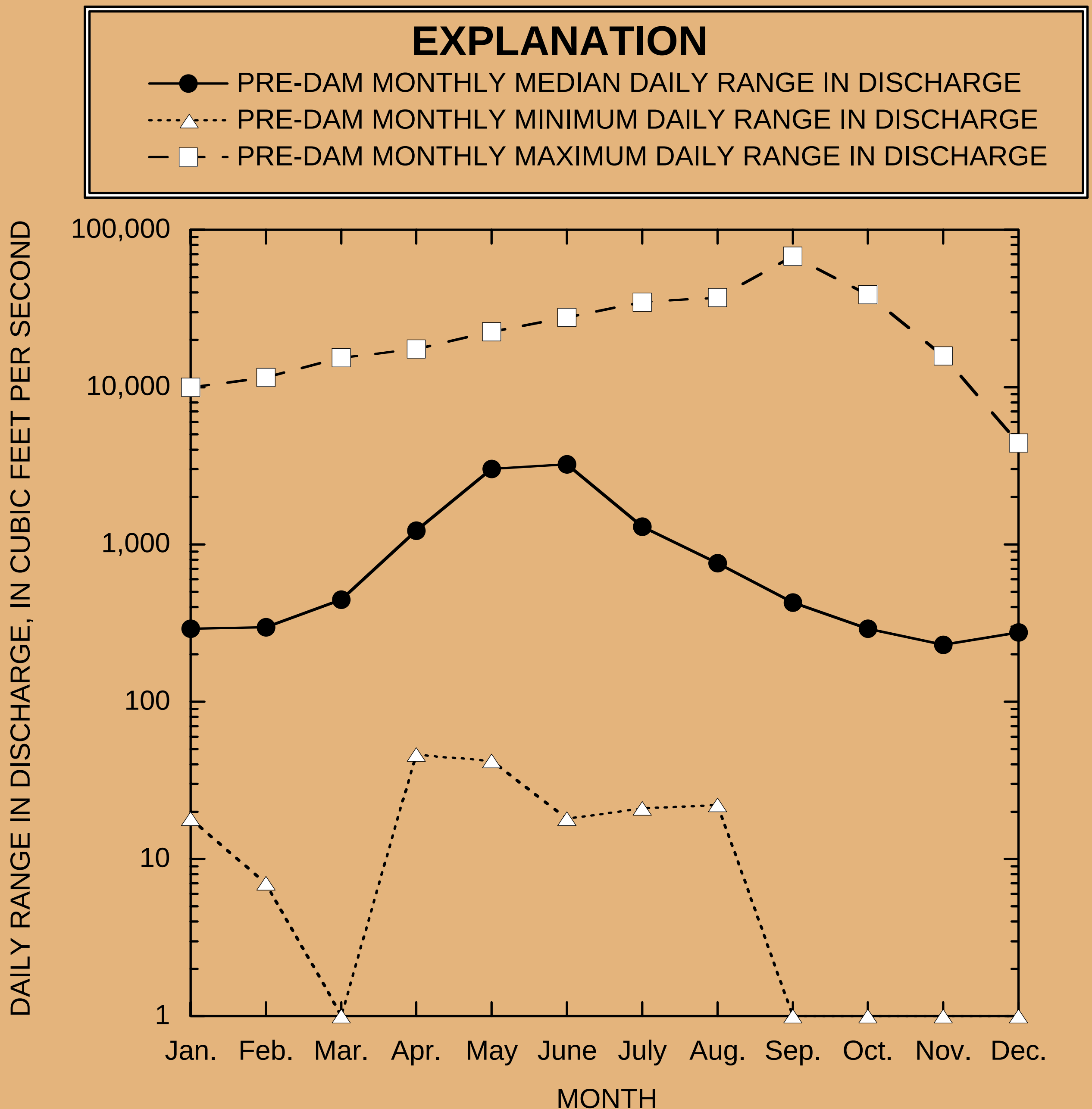


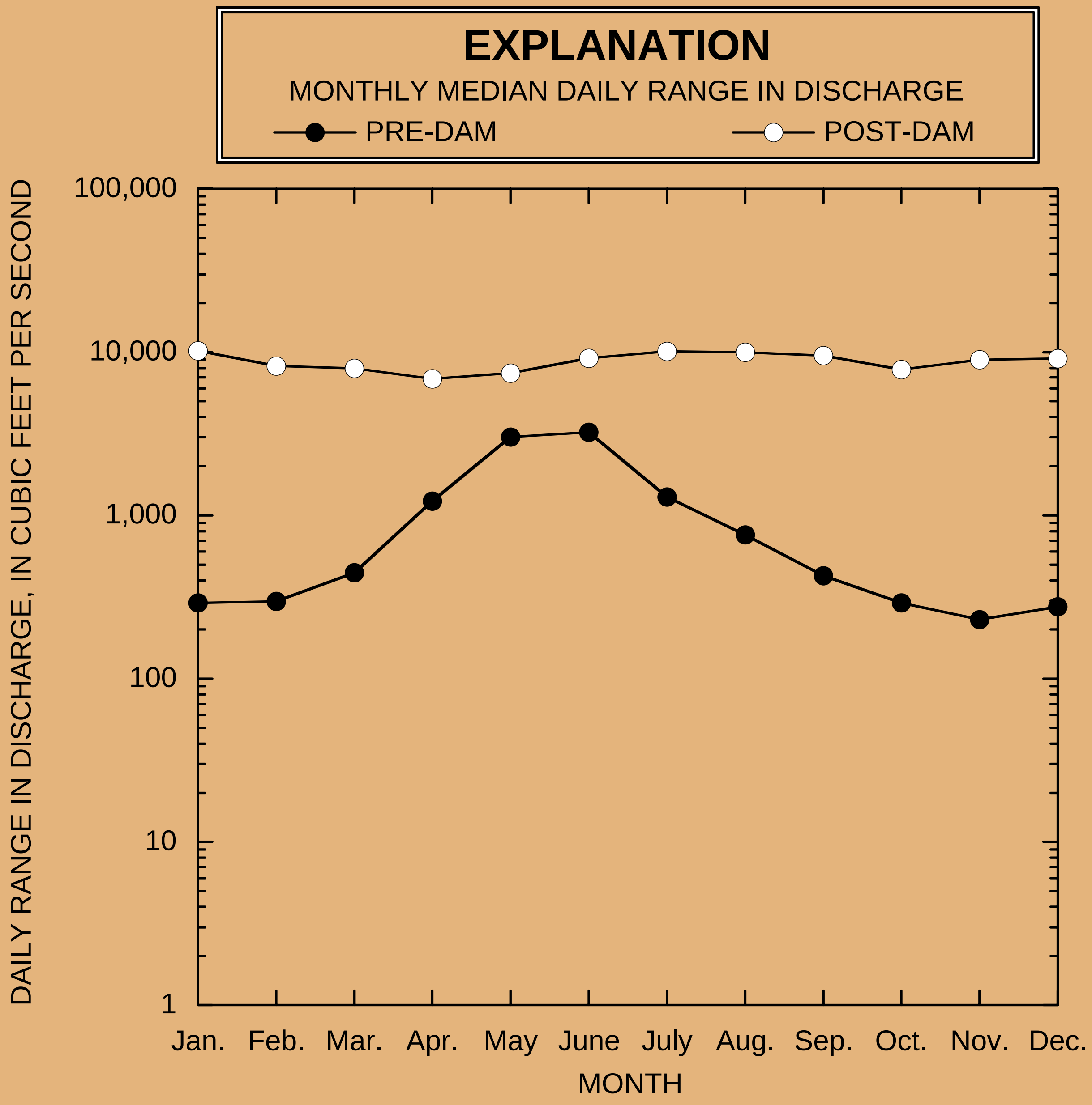
Sub-daily discharge variability

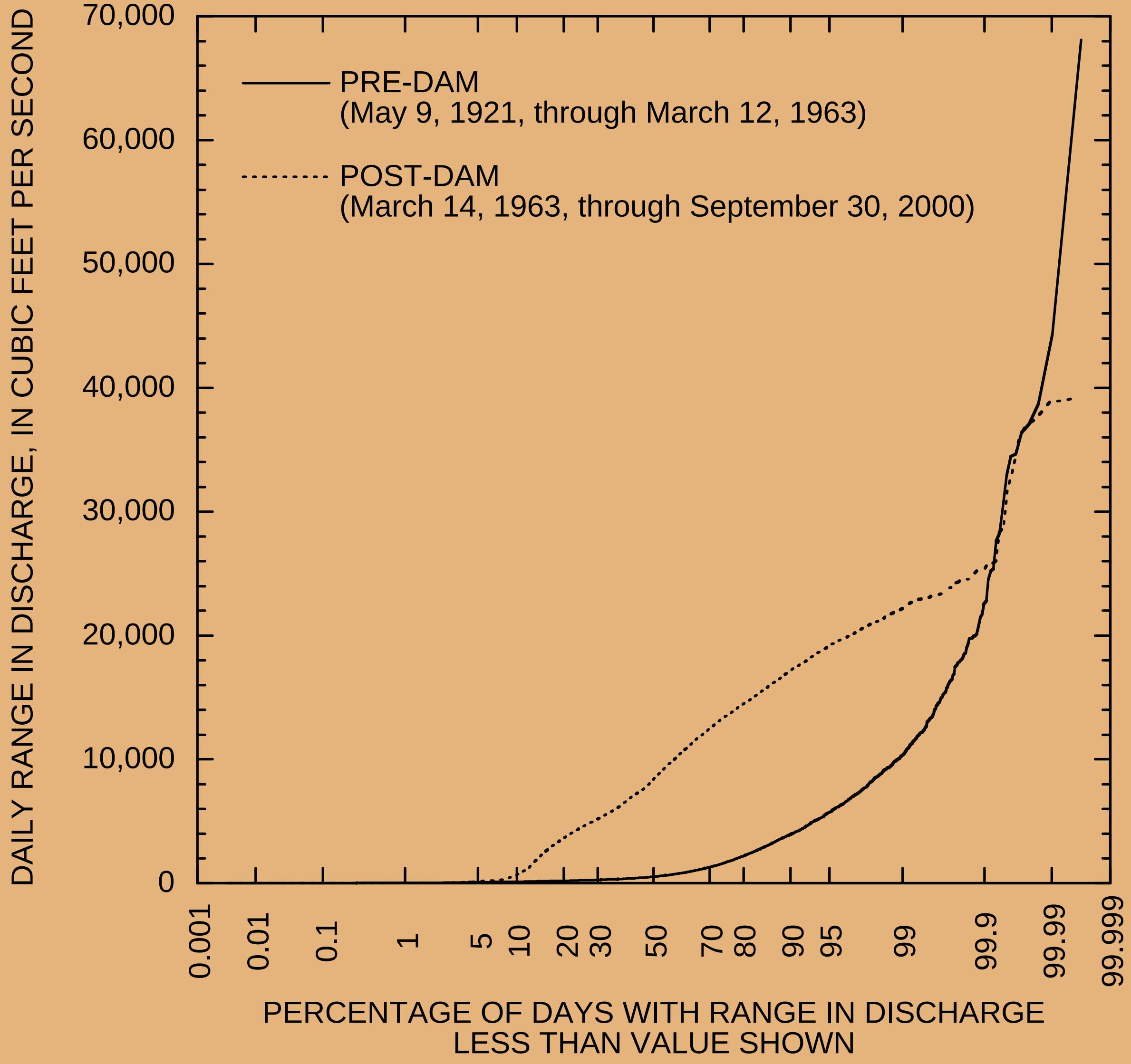

EXPLANATION
PRE-DAM (May 8, 1921, through March 12, 1963)
POST-DAM (March 14, 1963, through September 30, 2000)
DAILY RANGE IN DISCHARGE, IN CUBIC FEET PER SECOND
100,000
10,000
1,000
100
10
0
10
20
30
40
50
60
70
80
90
100
PERCENTAGE OF TIME EQUALED OR EXCEEDED


EXPLANATION
1920s (May 8, 1921, through December 31, 1930)
1930s (January 1, 1931, through December 31, 1940)
1940s (January 1, 1941, through December 31, 1950)
1950s-early 1960s (January 1, 1951, through March 12, 1963)
POST-DAM (March 14, 1963, through September 30, 2000)
DAILY RANGE IN DISCHARGE, IN CUBIC FEET PER SECOND
100,000
10,000
1,000
100
10
0
10
20
30
40
50
60
70
80
90
100
PERCENTAGE OF TIME EQUALED OR EXCEEDED

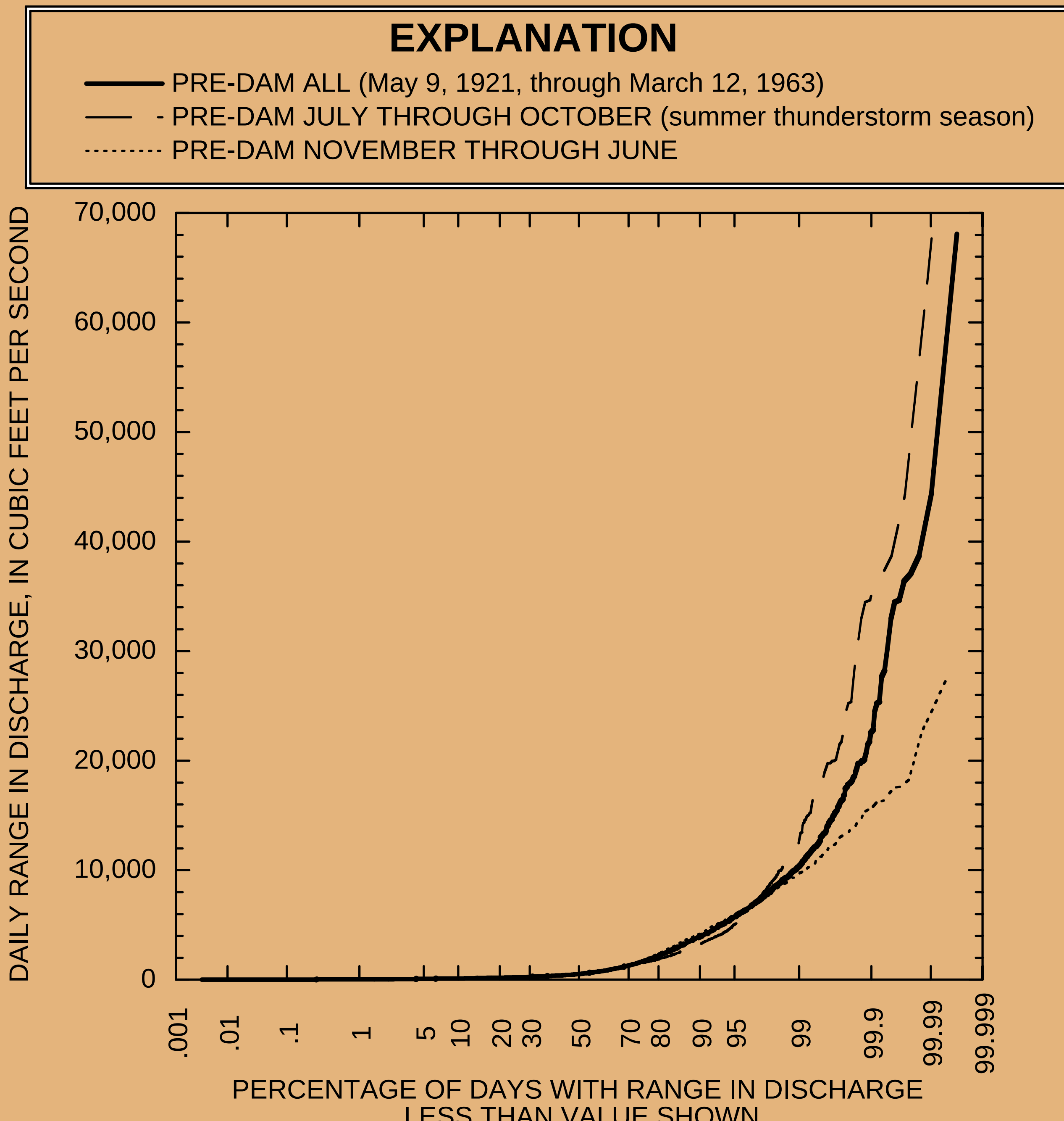

EXPLANATION
1960s (March 14, 1963, through December 31, 1970)
1970s (January 1, 1971, through December 31, 1980)
1980s (January 1, 1981, through December 31, 1990)
1990s (January 1, 1991, through September 30, 2000)
PRE-DAM (May 8, 1921, through March 12, 1963)
DAILY RANGE IN DISCHARGE, IN CUBIC FEET PER SECOND
100,000
10,000
1,000
100
10
0
10
20
30
40
50
60
70
80
90
100
PERCENTAGE OF TIME EQUALED OR EXCEEDED

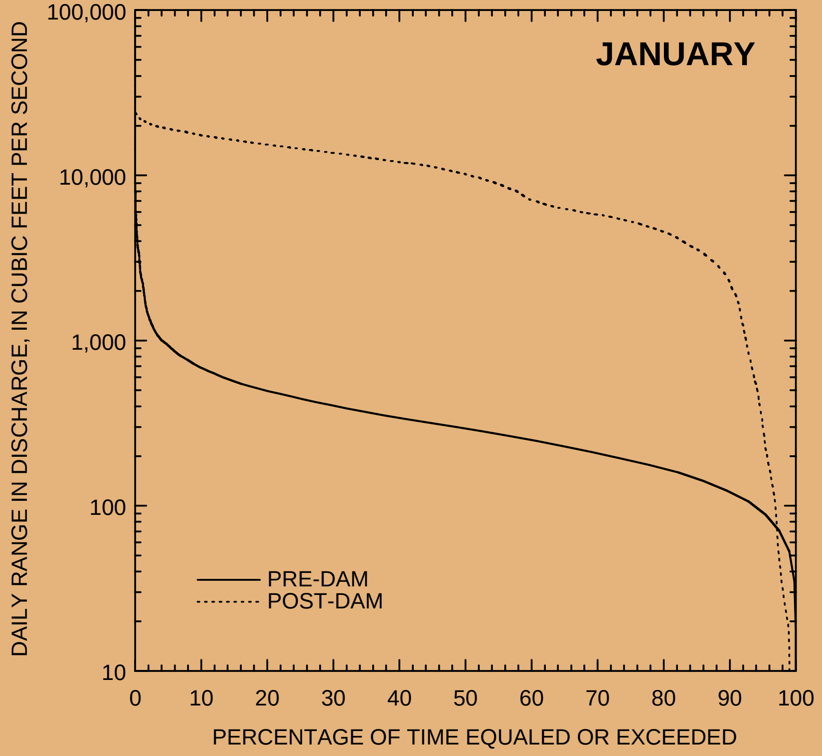

EXPLANATION
PRE-DAM MONTHLY MEDIAN DAILY RANGE IN DISCHARGE
PRE-DAM MONTHLY MINIMUM DAILY RANGE IN DISCHARGE
PRE-DAM MONTHLY MAXIMUM DAILY RANGE IN DISCHARGE
DAILY RANGE IN DISCHARGE, IN CUBIC FEET PER SECOND
100,000
10,000
1,000
100
10
1
Jan.
Feb.
Mar.
Apr.
May
June
July
Aug.
Sep.
Oct.
Nov.
Dec.
MONTH


EXPLANATION
MONTHLY MEDIAN DAILY RANGE IN DISCHARGE
PRE-DAM
POST-DAM
DAILY RANGE IN DISCHARGE, IN CUBIC FEET PER SECOND
100,000
10,000
1,000
100
10
1
Jan.
Feb.
Mar.
Apr.
May
June
July
Aug.
Sep.
Oct.
Nov.
Dec.
MONTH

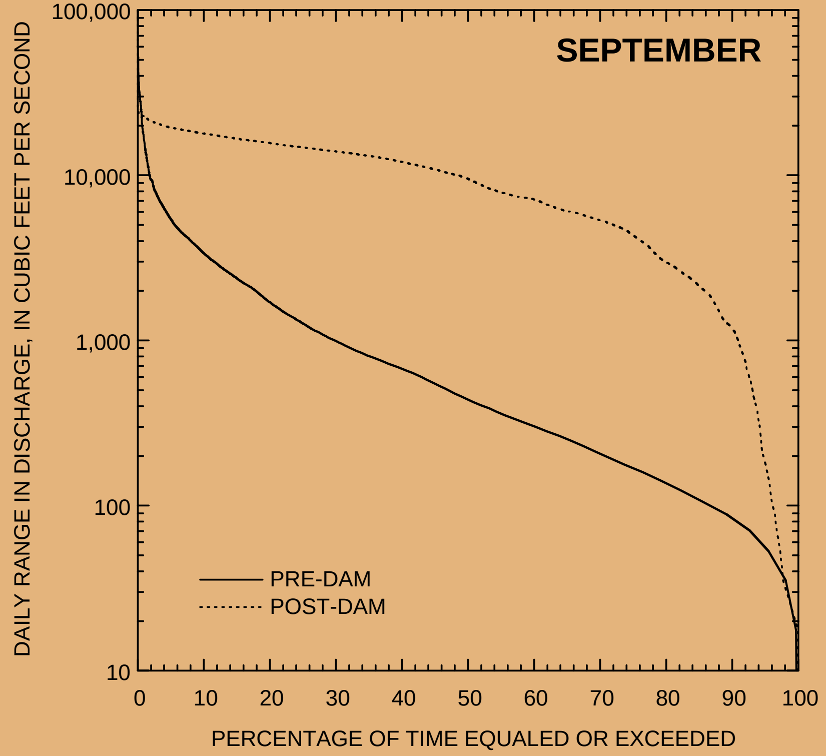


PRE-DAM
(May 9, 1921, through March 12, 1963)
POST-DAM
(March 14, 1963, through September 30, 2000)
DAILY RANGE IN DISCHARGE, IN CUBIC FEET PER SECOND
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
0.001
0.01
0.1
1
5
10
20
30
50
70
80
90
95
99
99.9
99.99
99.999
PERCENTAGE OF DAYS WITH RANGE IN DISCHARGE
LESS THAN VALUE SHOWN

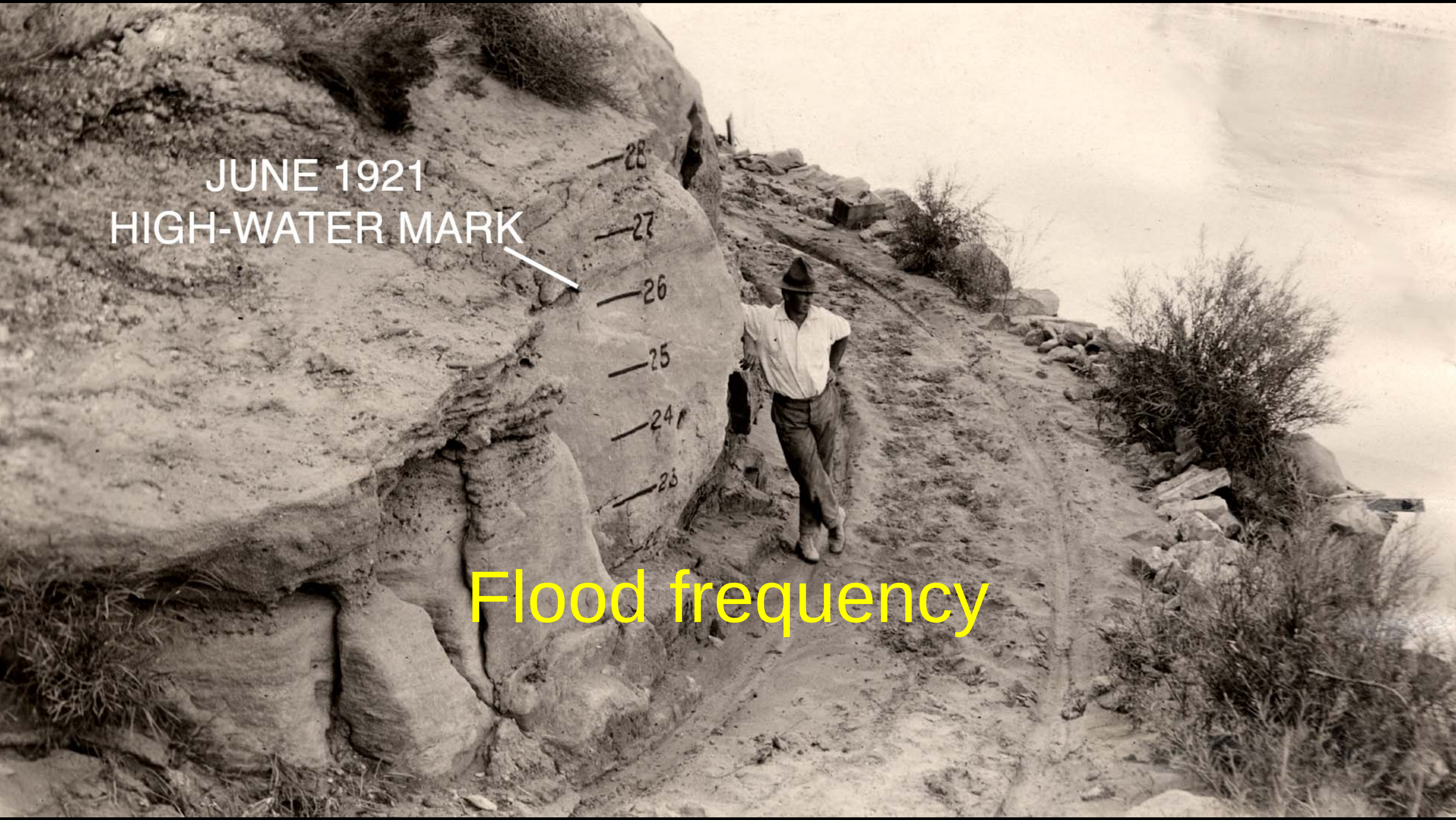

EXPLANATION
PRE-DAM ALL (May 9, 1921, through March 12, 1963)
PRE-DAM JULY THROUGH OCTOBER (summer thunderstorm season)
PRE-DAM NOVEMBER THROUGH JUNE
DAILY RANGE IN DISCHARGE, IN CUBIC FEET PER SECOND
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
.001
.01
.1
1
5
10
20
30
50
70
80
90
95
99
99.9
99.99
99.999
PERCENTAGE OF DAYS WITH RANGE IN DISCHARGE
LESS THAN VALUE SHOWN

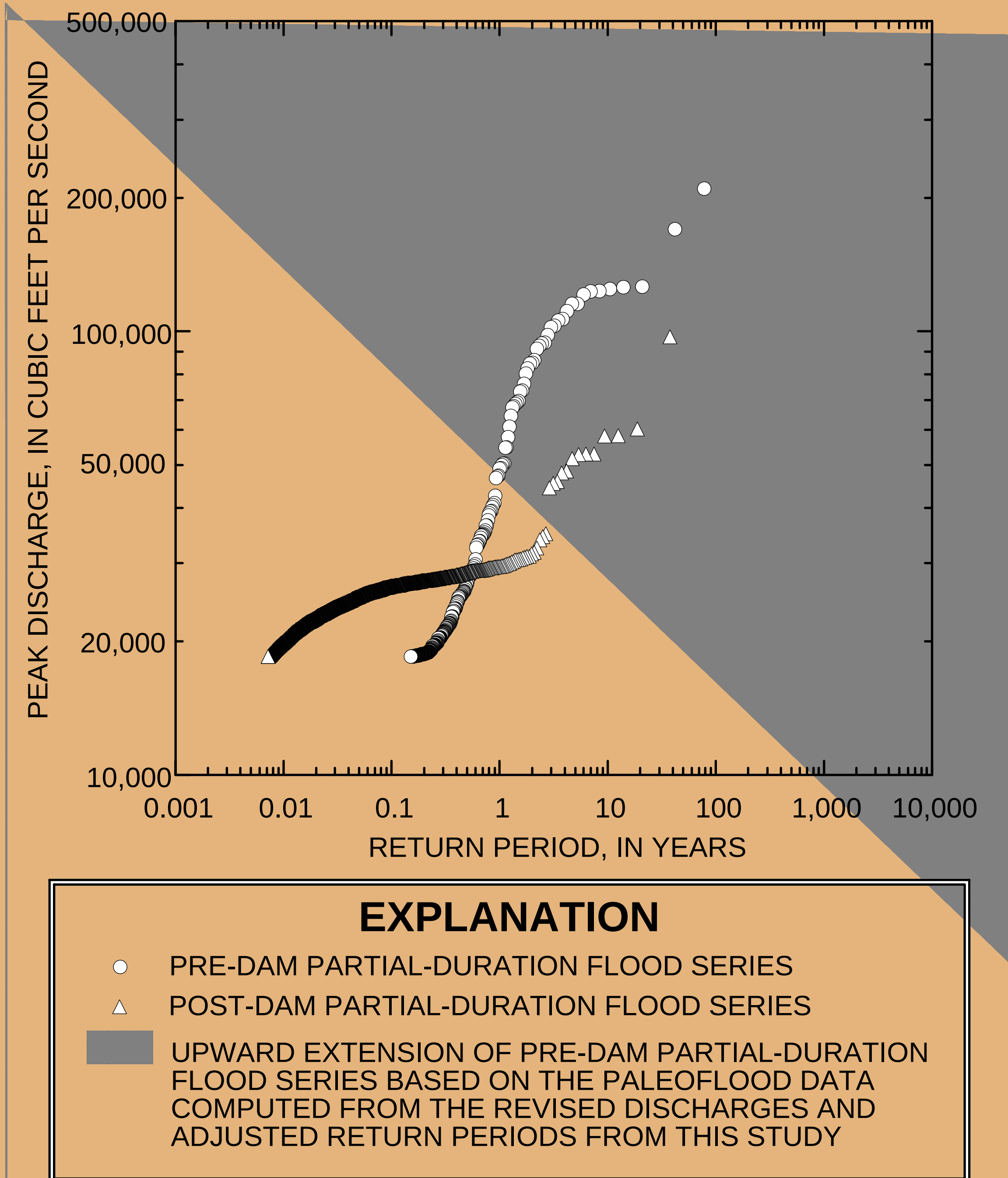


JANUARY
DAILY RANGE IN DISCHARGE, IN CUBIC FEET PER SECOND
100,000
10,000
1,000
100
10
0
10
20
30
40
50
60
70
80
90
100
PERCENTAGE OF TIME EQUALED OR EXCEEDED
PRE-DAM
POST-DAM



SEPTEMBER
DAILY RANGE IN DISCHARGE, IN CUBIC FEET PER SECOND
100,000
10,000
1,000
100
10
0
10
20
30
40
50
60
70
80
90
100
PERCENTAGE OF TIME EQUALED OR EXCEEDED
PRE-DAM
POST-DAM


JUNE 1921
HIGH-WATER MARK
28
27
26
25
24
Flood frequency

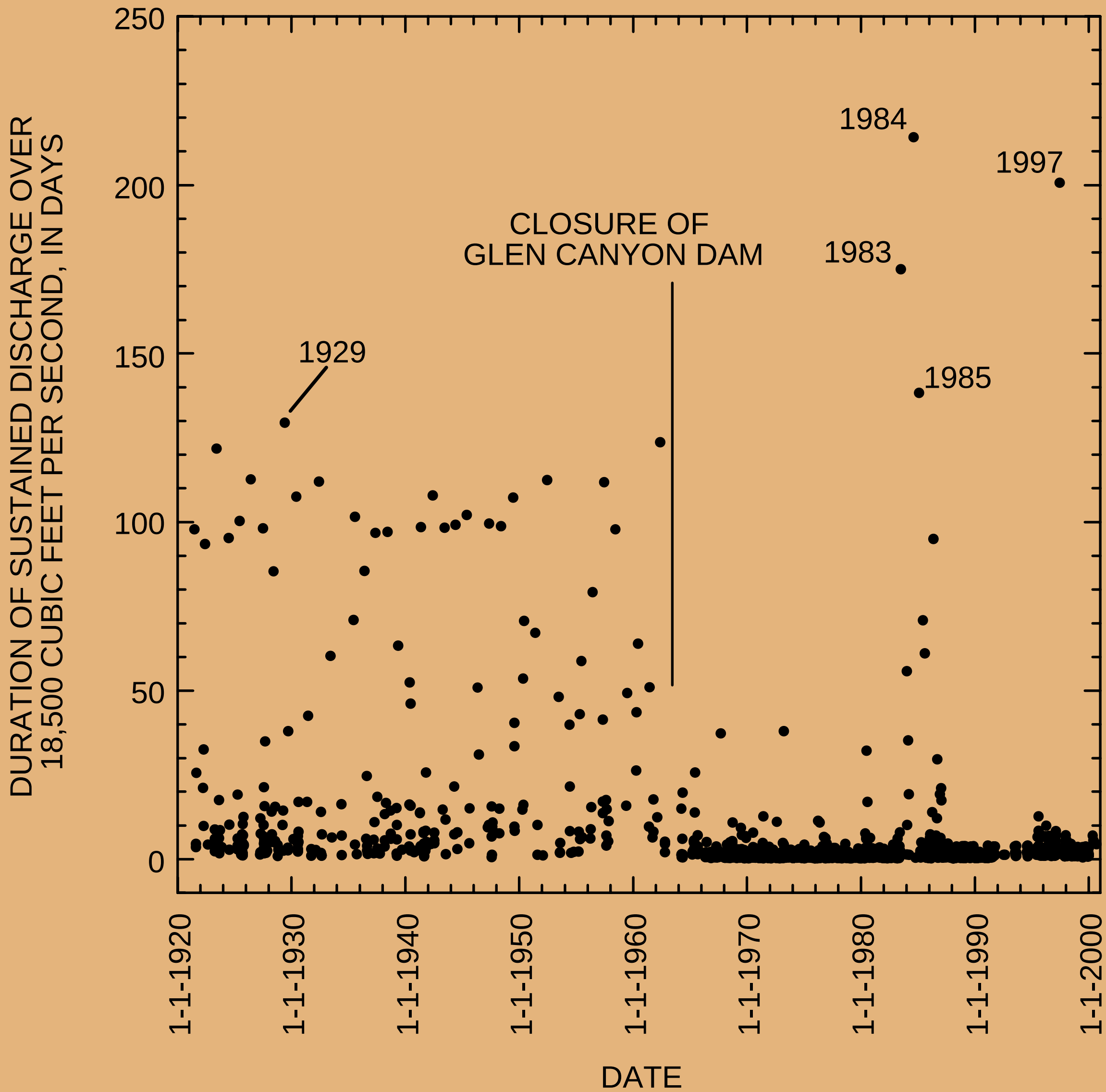


PRE-DAM
1 yr - 50,000 ft^3/s
2 yrs - 85,000 ft^3/s
6 yrs - 120,000 ft^3/s

POST-DAM
1 yr - 29,500 ft^3/s
2 yrs - 31,500 ft^3/s
6 yrs - 52,800 ft^3/s

PRE-DAM
20,000 ft^3/s - 97 days
POST-DAM
20,000 ft^3/s - 3.6 days


Duration of sustained high flows



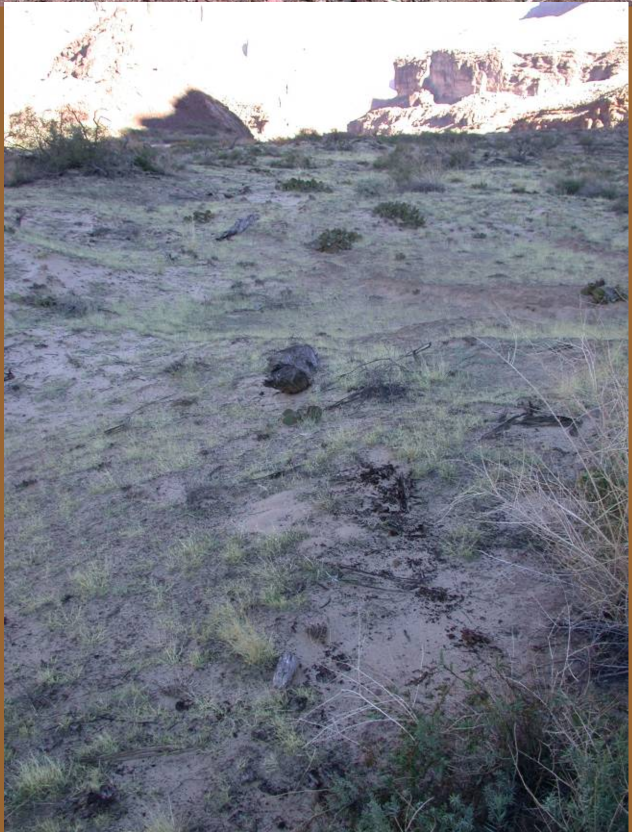
4 LONGEST PERIODS OF SUSTAINED HIGH DISCHARGE OCCURRED AFTER CLOSURE OF THE DAM

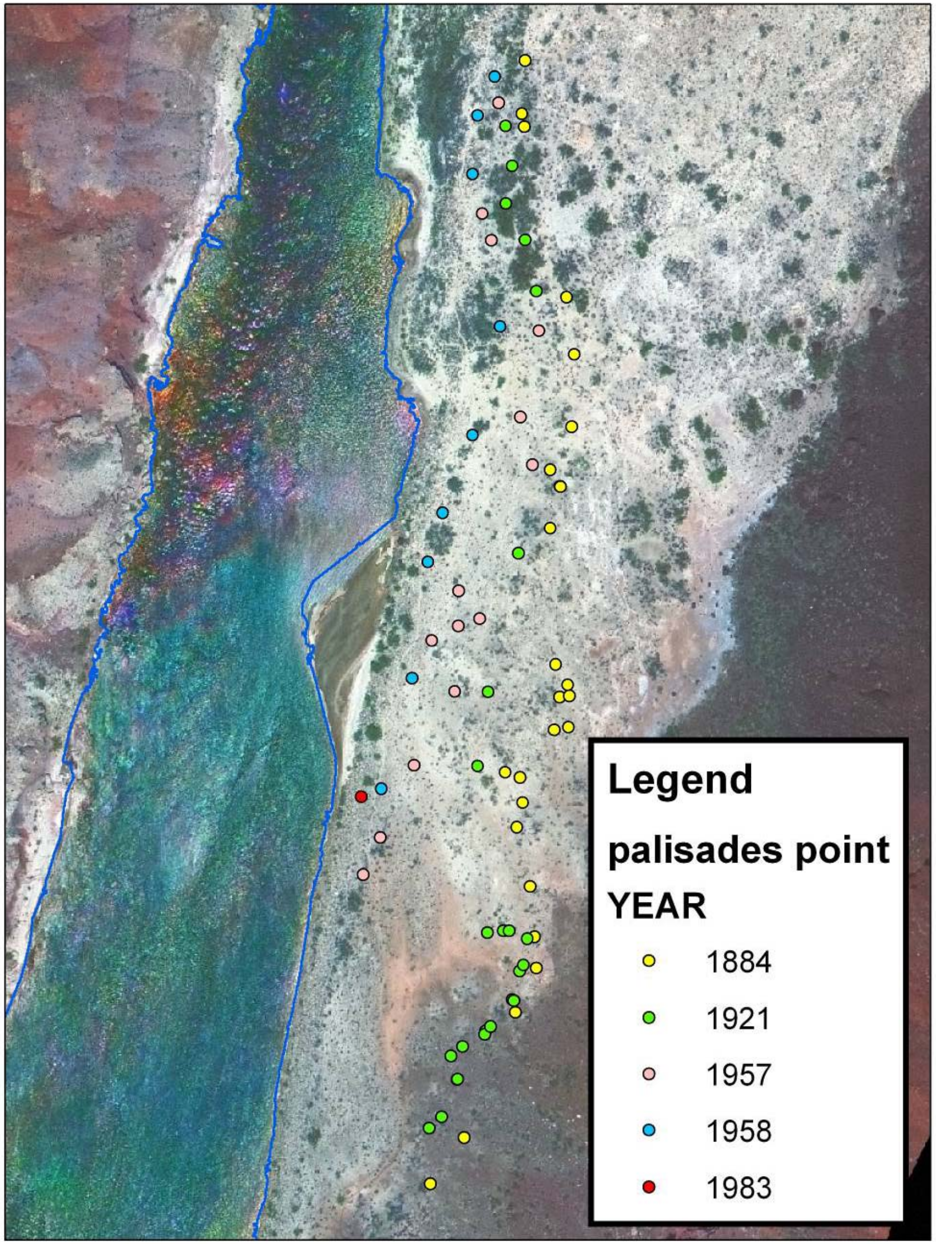
Conclusions --- pre-dam

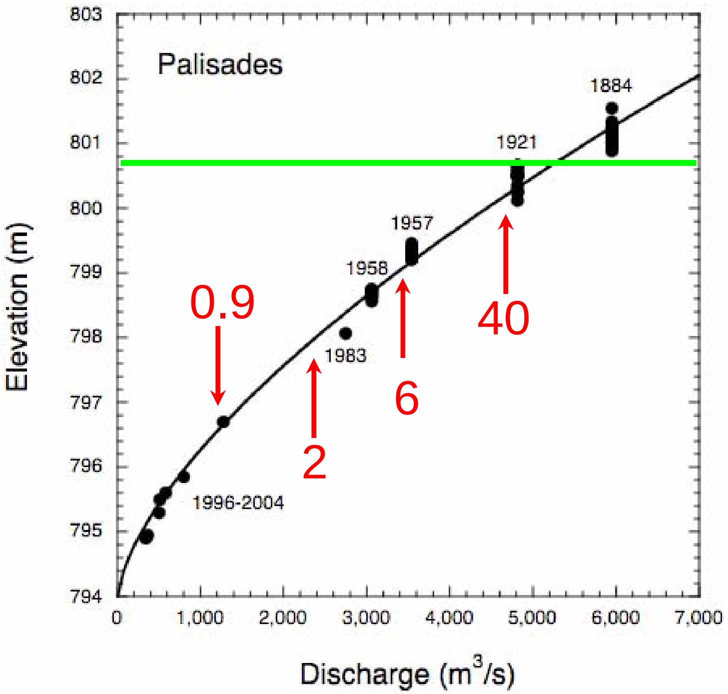
- Substantial natural variability existed in discharge and in the daily range in discharge over decadal timescales prior to construction of the dam
- Median discharge = 7,980 ft^3/s
- Median daily range in discharge 542 = ft^3/s
- Wettest decade---1920s---median discharge 10,700 ft^3/s , median daily range in discharge 808 ft^3/s
- Driest decade---1930s---median discharge 6,720 ft^3/s , median daily range in discharge 516 ft^3/s
- Flows conducive to sand accumulation occurred 55.7% of the time between 1921 and 1963, with the 1930s likely being the decade most dominated by sand accumulation
- Discharges in excess of 18,500 ft^3/s occurred only 25% of the time pre-dam
- Daily ranges in discharge exceeded 10,000 ft^3/s only during 1% of all pre-dam days and exceeded 30,000 ft^3/s during 1 day every 3 years
- On average, floods with peak discharges of 50,000 ft^3/s occurred every year, floods with peak discharges of 85,000 ft^3/s occurred every 2 years, and floods with peak discharges of 120,000 ft^3/s occurred every 6 years

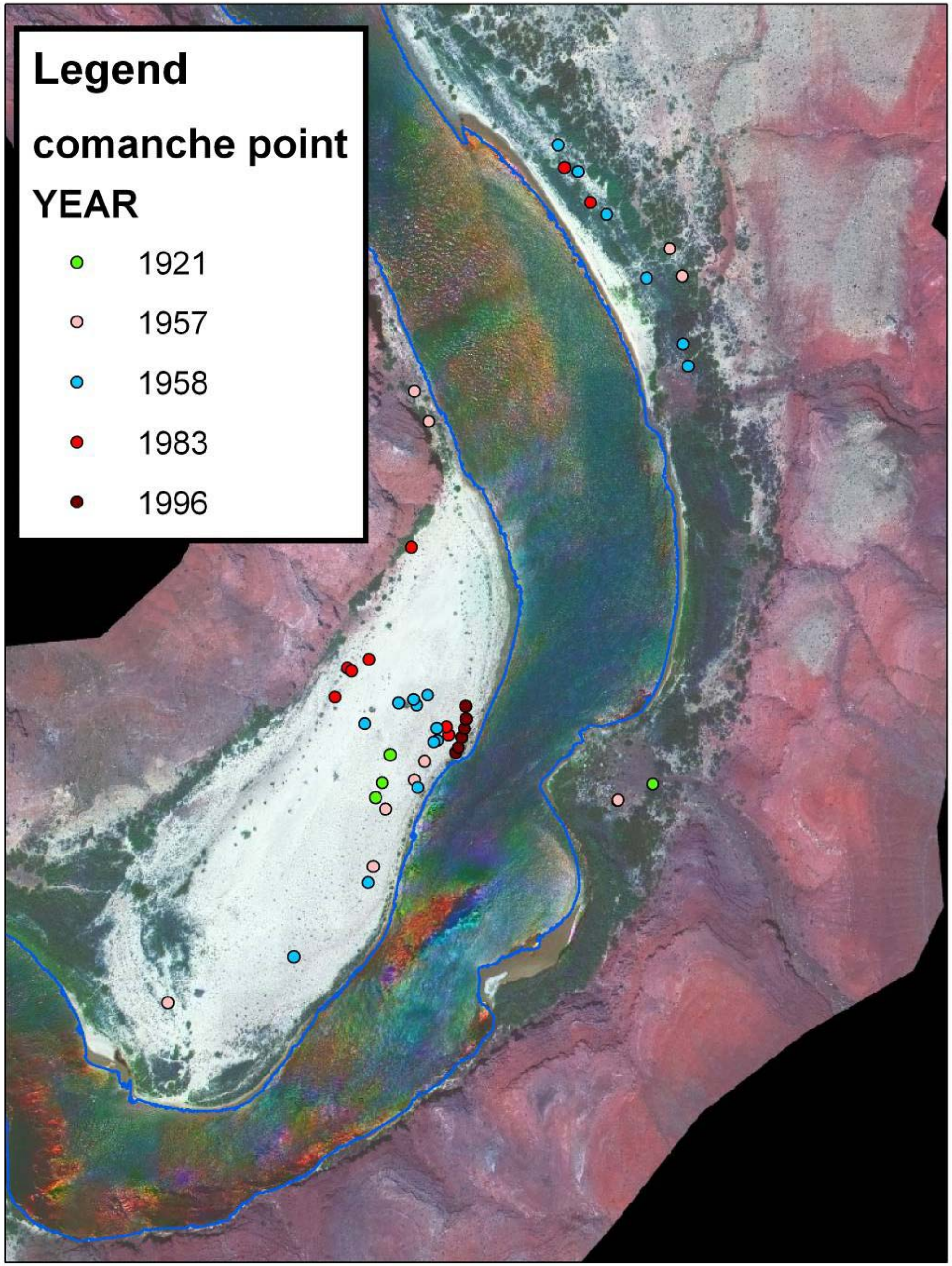
Conclusions --- post-dam

- Changes imposed on the hydrology by dam operations exceed anything in the quasi-natural pre-dam period of record; seasonality removed from both discharge and the daily range in discharge
- Median discharge -- 1960s = 9,490 ft^3/s --- 1990s = 13,500 ft^3/s
- Dam operations have largely eliminated base flows; pre-dam minimum discharge = 483 ft^3/s; pre-dam discharges < 5,000 ft^3/s 32.7% of the time
- Median daily range in discharge has increased by a factor of 15.8 relative to pre-dam; post-dam median daily range (8,580 ft^3/s) exceeds pre-dam median discharge (7,980 ft^3/s)
- Post-dam daily range in discharge exceeds pre-dam daily range in discharge except during 0.1% of all pre-dam days
- Flows conducive to sand accumulation have progressively disappeared; discharge exceeded 9,000 ft^3/s --in 1960s, 52.7% of the time--in 1970s,62.2% of the time--in 1980s, 75.5% of the time--in 1990s, 82.6% of the time
- Dam operations have maintained the frequency of floods with peak discharges of 29,000 ft3/s, have decreased the frequency of floods with larger peak discharges, and have greatly increased the frequency of "smaller" floods
- Pre-dam 2-year flood = 85,000 ft^3/s ; post-dam 2-year flood = 31,500 ft^3/s
- Recurrence interval of 20,000 ft^3/s flood -----97 days pre-dam, 3.6 days post-dam (factor of 27 increase)
- Longest 4 periods of sustained high discharge all post-date the dam: 1984, 1997, 1983, 1985

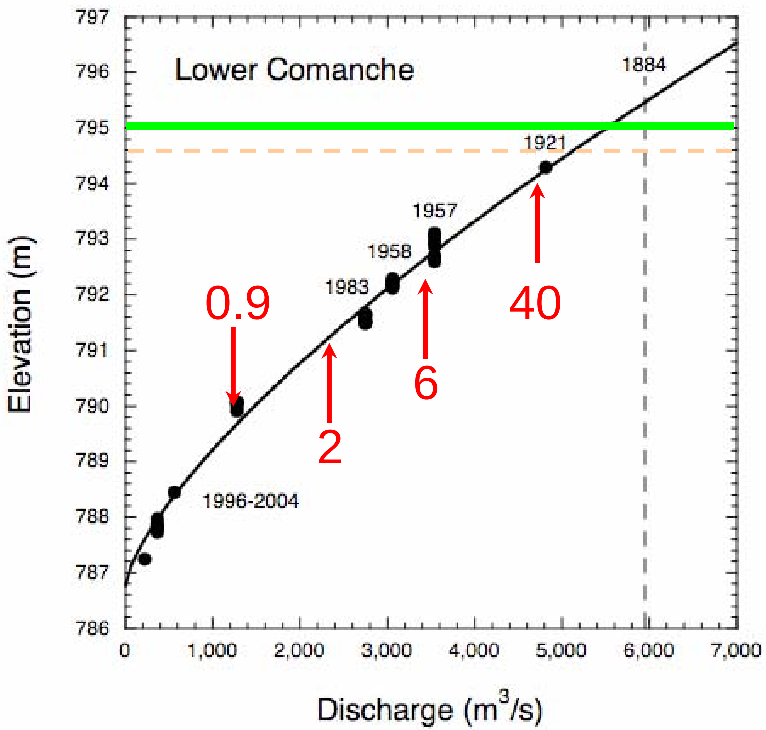





Legend
palisades point
YEAR
1884
1921
1957
1958
1983


Palisades
Elevation (m)
Discharge (m³/s)
803
802
801
800
799
798
797
796
795
794
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
1884
1921
1957
1958
1983
1996-2004
0.9
2
6
40



Legend
comanche point
YEAR
1921
1957
1958
1983
1996



Lower Comanche
1884
1921
1957
1958
1983
1996-2004
0.9
2
6
40
Elevation (m)
Discharge (m3/s)
797
796
795
794
793
792
791
790
789
788
787
786
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000

More conclusions

- Largest flood in the 80-year period prior to 1963 would completely fill many arroyos
- Pre-dam floods with 6-year recurrence interval would deposit 4-5 m of sand in lower portions of arroyos
- Flood deposits are common up to stage of 1921 flood, some deposits 4,500 years old
- Flood deposits above stage of 1884 flood are rare; now have 4 likely occurrences of 1,200-1,600 year old ~300,000 ft^3/s flood (RM 2, 70.5, 73, 88)