A

PALEOFLOOD HYDROLOGY OF THE ALLUVIAL SALT RIVER,

TEMPE, ARIZONA

by

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STATEMENT BY AUTHOR

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ABSTRACT

The paleoflood history of the lower Salt River was documented using slackwater sedimentation techniques. Slackwater sediments are fine-grained alluvial deposits which accumulate in zones of ineffective flow along the margins of flood channels. The tops of slackwater deposits can be used as a proxy for the water surface of the flood responsible for their deposition. Slackwater deposits used in this study also included post-abandonment fill in ancient Hohokam Indian irrigation canals. Paleodischarges were estimated using the HEC-II water-surface profile computer model. Cross-section information for the prehistoric Salt River channel was derived from a 1904 contour map of the Salt River Valley. This study is the first application of the slackwater technique to an . alluvial river.

Flood deposits dating from 1100 years before present to 1976 were analyzed. HEC-II modelling indicates that 27 floods during that time period exceeded the bankful discharge of 175,000 cfs (5000 cms). Two floods exceeded 420,000 cfs (11,900 cms). One of these large floods occurred around A.D. 890. The other occurred within the past 410 years. The largest flood of the historical era was the February, 1891 flood which had a peak discharge of 260,000 cfs (7400 cms). The findings of this study compare favorably with previous studies of the paleohydrology of the Salt River.

INTRODUCTION

Catastrophic flooding experienced along the Salt River near Phoenix, Arizona in the winters of 1978, 1979, and 1980 (Figure 1) caused severe doubts regarding the accuracy of flood-frequency determinations based on extrapolation of short-term gage records. Therefore, hydrologists have employed several methods of increasing the accuracy of predicting potential flood peaks. These methods include climatic and hydrologic . modelling of maximum flood events--usually the probable maximum flood (World Meteorological Organization, 1969), variations on conventional statistical distributions of flood series (Malvick, 1980; Reich and Renard, 1981), and attempts to extend the time base of flood series using historical (Stedinger and Cohn, 1986), geological (Baker, 1977, 1982, 1983), and dendrochronological (Stockton, 1975) information. This study uses geologic analysis of flood sediments, called slackwater deposits, to reconstruct the timing and magnitude of prehistoric flooding along the alluvial Salt River in Tempe and Phoenix, Arizona.

The slackwater technique, developed by Baker (c.f. 1977; 1983), has been successfully employed elsewhere in the semi-arid Southwest USA. Study sites include central Texas (Baker, 1977); the Escalante River, Utah (Webb, 1985); Boulder Creek, Utah (O'Connor, 1985); Kanab Creek, Arizona (Smith, in preparation); and Aravaipa Creek, Arizona (Roberts, in preparation). Slackwater sediment techniques also have been used in paleoflood studies funded by the Salt River Project. Ely (1985) and Partridge (1985) documented the flood history of bedrock canyon reaches of the Verde River and Salt River, respectively. O'Connor and Fuller

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Figure 1. The lower Salt River in flood, Phoenix, Arizona, January,
1979. Photograph taken at 40th St. looking north when the
river was running at 72,000 cfs (2000 cms), estimated to be
the 19-year flood. (Photograph No. 4242 by Troy L. Péwé,
January 19, 1797).

(1986), using slackwater sedimentation techniques, restudied the Salt and Verde Rivers, as well as Tonto Creek.
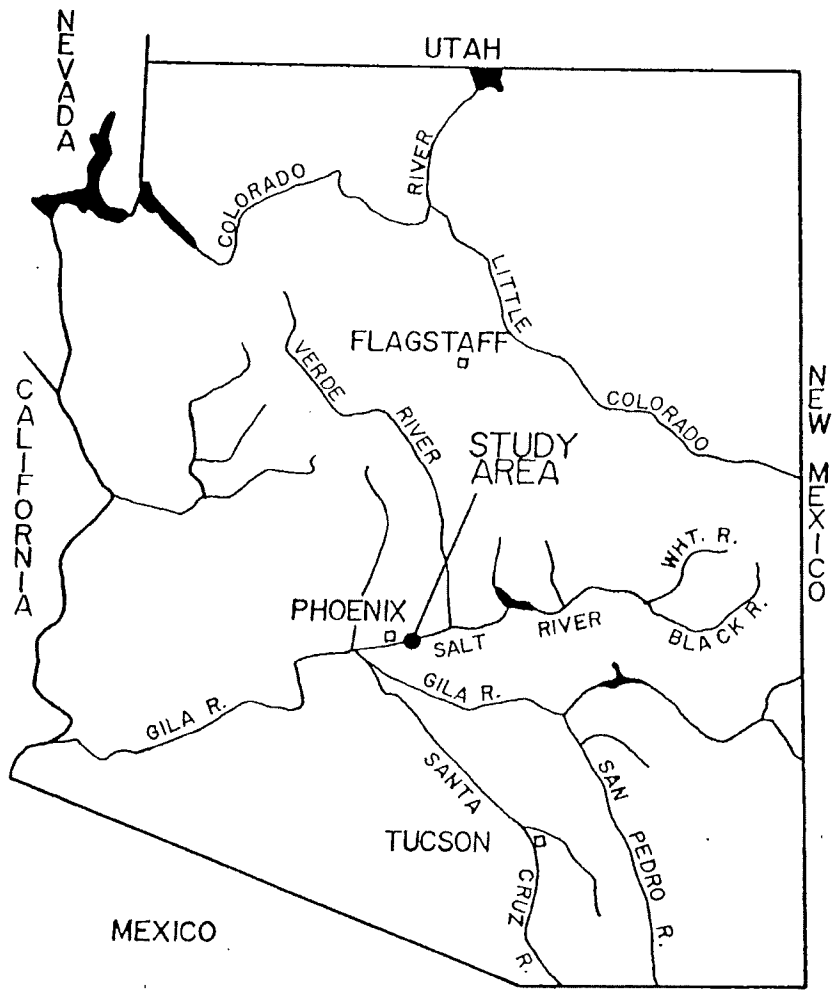
This study differs from previous slackwater studies in several important aspects. First, earlier studies were performed in stable bedrock canyon reaches. The Salt River near Phoenix is largely an alluvial river and, as such, has the potential for mobile boundaries through time and during individual flood events. Second, slackwater sediments examined within the study reach near Phoenix are preserved as post-abandonment fill in ancient Hohokam irrigation canals as well as in "typical" slackwater sites along the channel margins. These canals were begun and redug during several periods of Hohokam history, thus creating new slackwater sites not susceptible to erosion and leaving a more complete, permanent record of the flood history of the Salt River. Third, the study reach has been drastically affected by the urban sprawl of metropolitan Phoenix over the past 35 years. Thus, the pre-historic channel had to be reconstructed before paleofloods could be modelled. Fourth, no accurate, continuous gage record has been maintained close to the study site, thereby making comparisons between modern and prehistoric floods difficult. Finally, upstream reservoir control, initiated in 1910 with the completion of Roosevelt Dam, complicates comparisons between post- and pre-reservoir flooding.

GEOGRAPHY AND CLIMATE

The Salt River is the second largest river system in Arizona. Together with its major tributary, the Verde River (Figure 2), it drains approximately 13,000 square miles (21,000 km^2). It ranges in elevation from a high of over 12,000 feet (3700 m) above sea level at Humphrey's Peak near Flagstaff, to a low of 1087 feet (330 m) above sea level at the mouth of the study reach in Phoenix. Major tributaries in the Salt River system include the White, Black, Verde, and East Verde Rivers, and Tonto Creek. Five major reservoirs harvest the runoff of the Salt and Verde Rivers, limiting runoff within the study reach downstream.

The climate within the Salt River system is highly varied. It ranges from semi-arid Sonoran desert at the study site, to pine-oak woodlands near the headwaters. Precipitation falls in two major seasons, in late summer as intense local orographic thunderstorms, and in winter as large-scale cyclonic storms which originate over the Pacific Ocean (Sellers and Hill, 1974; Hirshbock, 1986); 92.5 percent of 40 of the largest gaged floods on the upper Salt and Verde Rivers resulted from runoff from large-scale Pacific storms. The relationship between winter storms and major flooding will be even stronger for the much larger watershed of the Salt River at the study site. Also, 100 percent of the years with gaged yearly peak discharges occurring in summer had below-average total yearly discharges. This relationship between climate, winter floods and total yearly flow is reflected in tree-ring chronologies reported by Smith (1981) and Nials et al (in press).

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Figure 2. Drainage net of the Salt River, showing the location of the study reach.

NEVADA

UTAH

COLORADO

RIVER

LITTLE

FLAGSTAFF

VERDE

RIVER

CALIFORNIA

COLORADO

NEW MEXICO

STUDY
AREA

WHT. R.

PHOENIX

SALT   RIVER

BLACK R.

GILA R.

GILA R.

SANTA

SAN   PEDRO   R.

TUCSON

CRUZ R.

MEXICO

Dendrochronological records (Smith, 1981) also indicate that the present climate has not shifted over the past several hundred years.
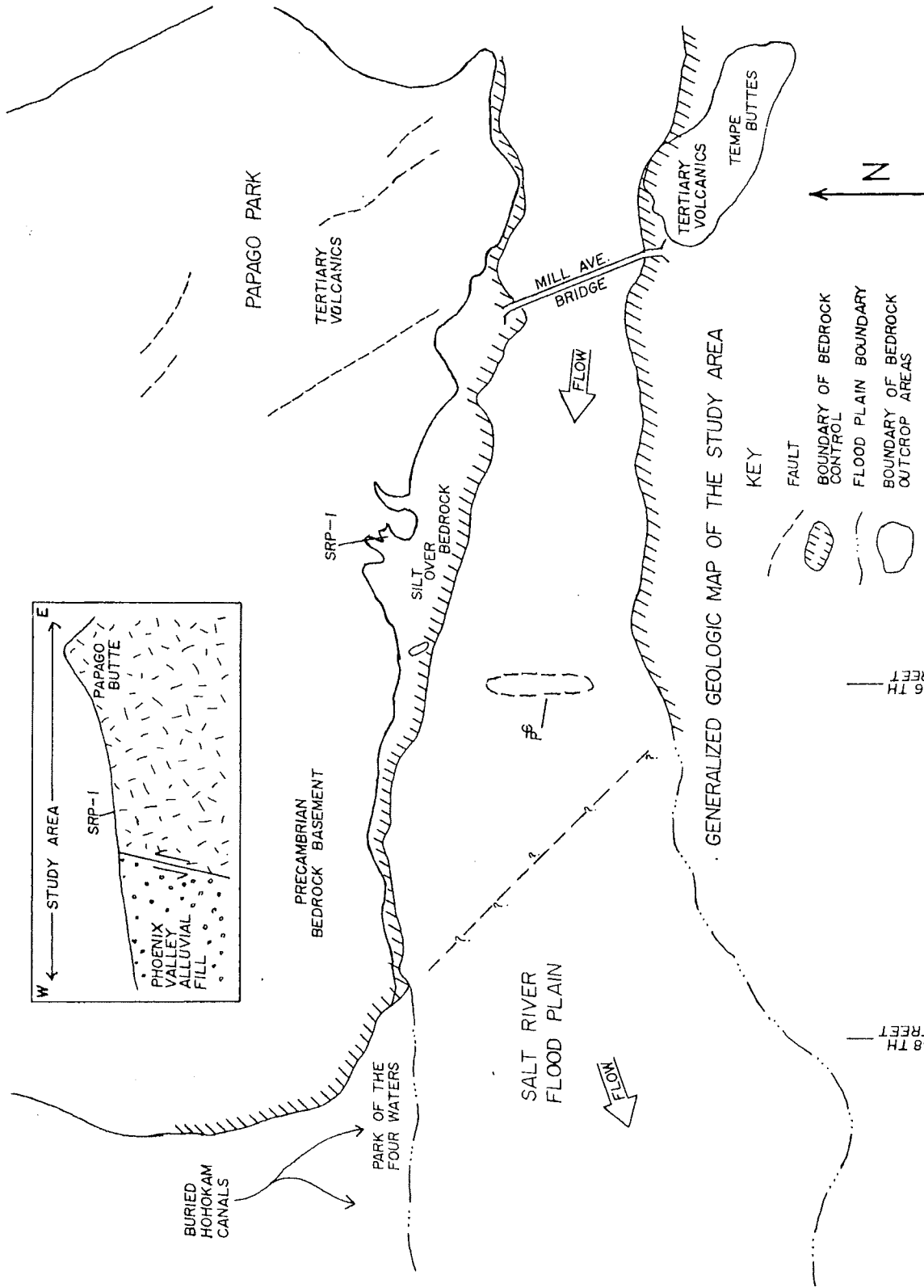
GEOLOGY

The Salt River near Phoenix is located within the Basin and Range Physiographic Province of south-central Arizona. The Basin and Range Province consists of long, parallel, block-faulted mountain ranges upthrust during early Tertiary crustal extension and thinning, with intervening down-faulted alluvial-fill valleys. The study reach is located at the interface of one such mountain/valley system (Figure 3). A normal fault, lying just west of the Tempe Narrows (Schulten, 1979), forms the boundary between bedrock-controlled and alluvial reaches within the study area. This fault can be considered inactive within the time scale of this study (Péwé, 1978).

Bedrock exposed east of the fault, a pediment surface remnant, represents the upthrust block. Bedrock units cropping out in the study reach have been mapped by Schulten (1979). Precambrian granite and metarhyolite make up the bedrock basement. Unconformably overlying the Precambrian units are the early Tertiary fanglomerate units of the Camels Head Formation and arkose of the Tempe Beds. These units crop out at river level in the study area and form the bedrock shelter which prevents erosion of slackwater deposits located at SRP-1 (Figure 3). Strati-graphically above the Tempe Beds are undifferentiated Tertiary volcanic units which comprise Tempe Butte.

West and downstream of the fault-bounded pediment surface, bedrock drops steeply beneath the Phoenix Basin. Three types of valley fill, slope wash, colluvium, and Salt River alluvial fill, are found within the Phoenix Basin (Bales, 1985). Salt River alluvium makes up the vast

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Figure 3. Generalized geologic map of the study reach, showing the
           location of bedrock control, the basin bounding fault, and
           major slackwater sites. See Schulten (1979) and Bales (1985)
           for detailed geologic mapping.

N

PAPAGO PARK

TERTIARY VOLCANICS

TEMPE BUTTES

TERTIARY VOLCANICS

MILL AVE. BRIDGE

FLOW

SRP-1

SILT OVER BEDROCK

pЄ

56 TH STREET

SALT RIVER FLOOD PLAIN

48 TH STREET

FLOW

PRECAMBRIAN BEDROCK BASEMENT

PARK OF THE FOUR WATERS

BURIED HOHOKAM CANALS

GENERALIZED GEOLOGIC MAP OF THE STUDY AREA

KEY

FAULT

BOUNDARY OF BEDROCK CONTROL

FLOOD PLAIN BOUNDARY

BOUNDARY OF BEDROCK OUTCROP AREAS

SCALE: 1:24000

W — STUDY AREA — E

SRP-1

PAPAGO BUTTE

PHOENIX VALLEY ALLUVIAL FILL

majority of the valley fill. It is represented by sand, gravel, and cobbles deposited as the river slowly shifted its course across its broad geologic floodplain. The Phoenix Basin has been gradually filling in this manner over the last 50 million years as it slowly subsides (Péwé, 1978).

Four paired alluvial (fill) terraces mapped along the lower Salt River reflect tectonic uplift of the headwater region to the east (Kokalis, 1971). These terraces converge well above Tempe Butte. Only the Lehi Terrace can be distinguished at an elevation of 1.5 meters above the present geologic floodplain at the upstream end of the study area (Péwé, 1978). Within the study reach, below Tempe Butte, a single low terrace, referred to here as "Lehi?", is defined on the basis of soils associations (Means, 1902; Eckmann and others, 1917; Cable and Doyel, 1983) and prehistoric land use (Cable and Allen, 1982; Cable and others, 1983). The age of this terrace is unknown, but it certainly predates Hohokam Indian occupation which began about 300 B.C. Within the study reach, floodplain aggradation over the last 2000 years has obscured elevational differences between the terrace and the geologic floodplain.

Analysis of the geologic setting of the study reach provides evidence of the geologic (long-term) stability of the reach. A stable channel reach is essential to accurate reconstruction of the magnitude of paleofloods. Channel stability will be discussed more fully in the Methodology section of this report.

METHODOLOGY

The Slackwater Technique

This report uses slackwater sedimentation techniques to document the paleoflood history of the lower Salt River near Phoenix. Slackwater sediments are silts and fine sands transported in high-velocity flood waters. Slackwater sediments drop out of suspension in areas of ineffective, low-velocity flow. Typical slackwater sites include tributary mouths, channel margins upstream of major channel contractions and downstream of major channel expansions, rock shelters located above the low-flow channel, and areas of thick vegetation (Figure 4). The top of an individual slackwater unit serves as a minimum highwater mark for the flood which deposited it. Over time, if slackwater deposits are sheltered from erosion, a layered sequence of sediment accumulates. This sequence defines the paleoflood history of the river (Figure 5).

Radiometric dating of carbon-bearing material entrained within the slackwater sequence helps establish the timing of past flooding. Archaeological artifacts, soil-horizon development, and dendrochronology may also be used to constrain the age of flood deposits. O'Connor and Fuller (1986) and Baker, Pickup and Pollach (1985) provide more complete discussions of radiocarbon dating of slackwater deposits.

Radiocarbon dates, as well as stratigraphic and sedimentological characteristics of slackwater deposits, are used to correlate multiple slackwater sites within a single study reach. Once correlation of flood units has been made within the reach, the tops of individual slackwater

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Figure 4. Illustration showing typical sites of slackwater deposition.
          From Baker (1983).
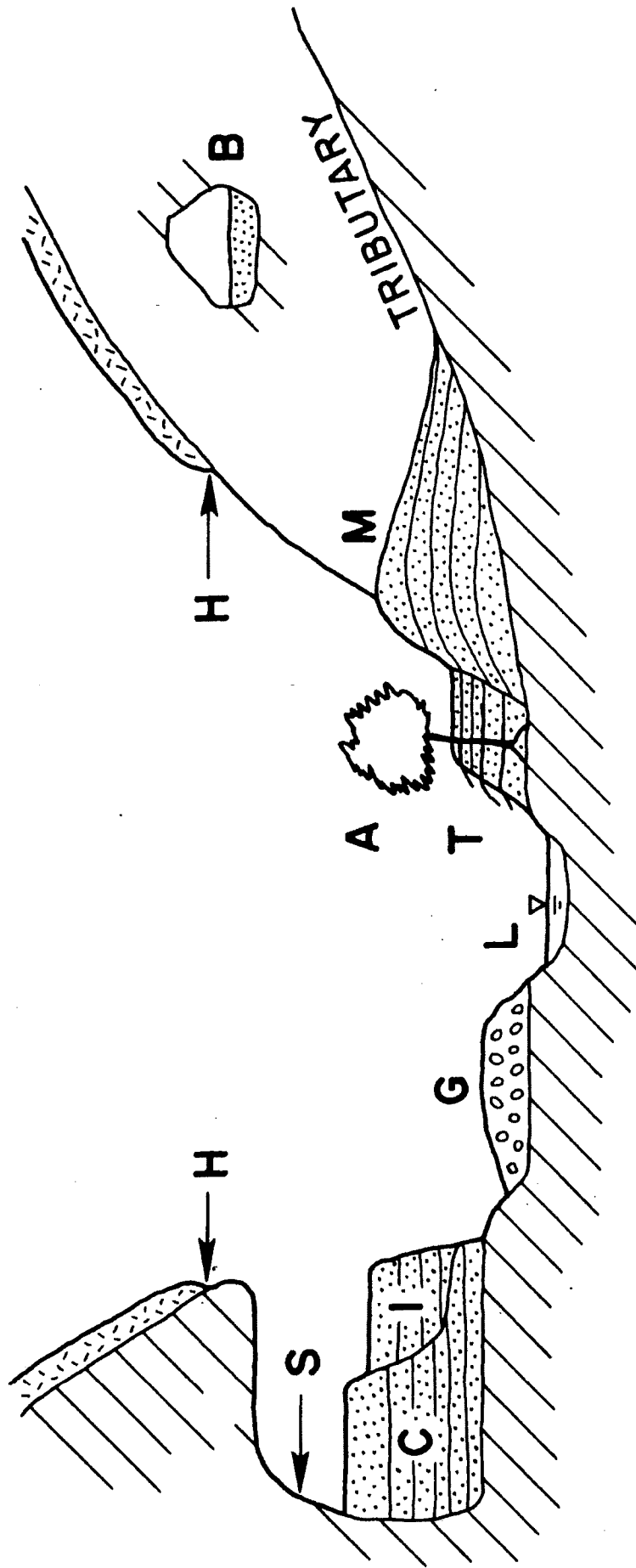
BEDROCK

GRAVEL

SLACK-WATER SEDIMENTS

REGOLITH

TRIBUTARY

Figure 5. Illustration showing the method of emplacement of typical
           slackwater sites. From Baker (1983).

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units from a given flood are used to estimate flood stage within the reach. Flood debris lines from recent floods, vegetation scars, and/or other highwater indicators, if age constraints are available, may be included to further define flood stage throughout the reach.

Flood stage estimates made from highwater marks and slackwater deposits are then compared to computer-generated water-surface profiles for known discharges. In this study, computer-generated profiles were generated by inputting cross-section data, roughness coefficients, and. other hydraulic variables describing the study reach, into the U.S. Army Corps of Engineering HEC-II (1979) computer program. A range of discharges was then routed through the computer-modelled channel until best-fit matches between documented paleoflood stages and computed water-surface profiles were obtained. The modelled discharge which produced the best match was assumed to be the minimum discharge for the paleoflood which deposited the slackwater units being tested.

Accuracy of HEC-II modelling depends on several factors. First, a good (high) stage-discharge relationship, normally obtained in narrow, steep-walled bedrock canyon, results in more precise matching between known and computed water-surface profiles. Second, flow in straight, hydraulically simple reaches better approximates gradually-varied, one-dimensional flow assumed by the HEC-II model. Third, reaches with multiple slackwater sites provide more points of comparison with computed water-surface profiles, allowing more confident matching of water-surface profiles and stage indicators. Fourth, rivers with high silt loads during flooding have slackwater deposits which better approximate the actual flood water surface elevation. Finally, a nearby stream-gage site

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allows a basis of comparison for historic, gaged discharges and estimates of paleodischarges made using the slackwater technique.

The Salt River near Phoenix presents an unconventional environment for applying the slackwater technique. Several key differences from previous applications exist. First, the Salt River at the study reach is partially an alluvial river. That is, its bed and banks have the potential to scour, fill, or erode during and between flood events. Thus, the assumption of a stable stage-discharge relationship must be proven. Also, because of periodic shifting of the low-flow channel within the floodplain and lack of adequate gage control, no stream gage has been continuously maintained near the study reach. Hence, no comparisons of paleodischarges to recent gaged flows could be made.

Second, this study represents the first attempt to apply the slackwater technique to an urban river. Urbanization presents several problems for paleoflood analysis. Within the study reach, the Salt River is channelized, bank-protected, and traversed by four bridges and two grade crossings. Upstream dams, irrigation diversions, and accelerated withdrawal of ground water have cut off all streamflow in the study reach except during floods. Lack of regular streamflow has led to the demise of most of the bank-stabilizing vegetation within the floodplain. In addition, extensive gravel mining in the Salt River has resulted in channel degradation at a rate of up to 1 foot (0.3 m) per year over the past 20 years (Graf, 1983). These factors have created a channel morphology very different than the one which conveyed paleoflood dis- charges and emplaced slackwater deposits in the study reach. Thus, a simple channel survey could not accurately depict the (pre-

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development) paleochannel, and could not be used as input for the HEC-II computer model.

Channel Reconstruction

In order to route paleodischarges through an appropriate series of HEC-II cross sections, the prehistoric channel was accurately reconstructed through map analysis, and careful analysis of historical records, photographs, and archaeological evidence. Detailed topographic maps of the Salt River channel made in 1904, 1915, 193?, 1952, 1962, 1978, 1979, and 1980 were compared. Generalized maps of the Salt River Valley dating to 1902, and 1868 Bureau of Land Management section line surveys were also studied to document the exact position of the river throughout the past 118 years. Several generalizations were made from this analysis.

First, the low-flow channel was distinguished from the high-flow, or flood, channel. The boundaries of the two channels are clearly delineated by vegetation along the channel banks (Figure 6). Large cottonwood and mesquite trees lined the high-flow channel as late as 1926. Smaller, faster growing brush such as salt cedar line the unstable margins of the low-flow channel.

The low-flow channel demonstrated considerable locational instability over the past 119 years. Figure 7 shows the migrations of the low-flow channel within the floodplain. Graf (1983) characterized these migrations by defining locational probability zones according to the percentage of time the low-flow channel occupied a given position within the floodplain, over the period from 1868 to 1983 (Figure 8). The

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Figure 6.   Photograph of the study area looking downstream (west) from
            Tempe Butte. Photograph taken on March 21, 1926, after winter
            flooding. Photograph from the Salt River Project Archives.
            Note vegetation which defines the low- and high-flow margins
            of the Salt River.

Approximately To S.F. at Tempe, noon, Mar 21, 1926

Figure 7. Migration of the low-flow channel margins of the Salt River
            near Phoenix, AZ within the floodplain from 1868 - 1982.
            Channel position information based on survey notes, historic
            photographs, and maps.

LOCATION OF THE SALT RIVER LOW-FLOW CHANNEL NEAR TEMPE AND PHOENIX, ARIZONA; 1868-1952
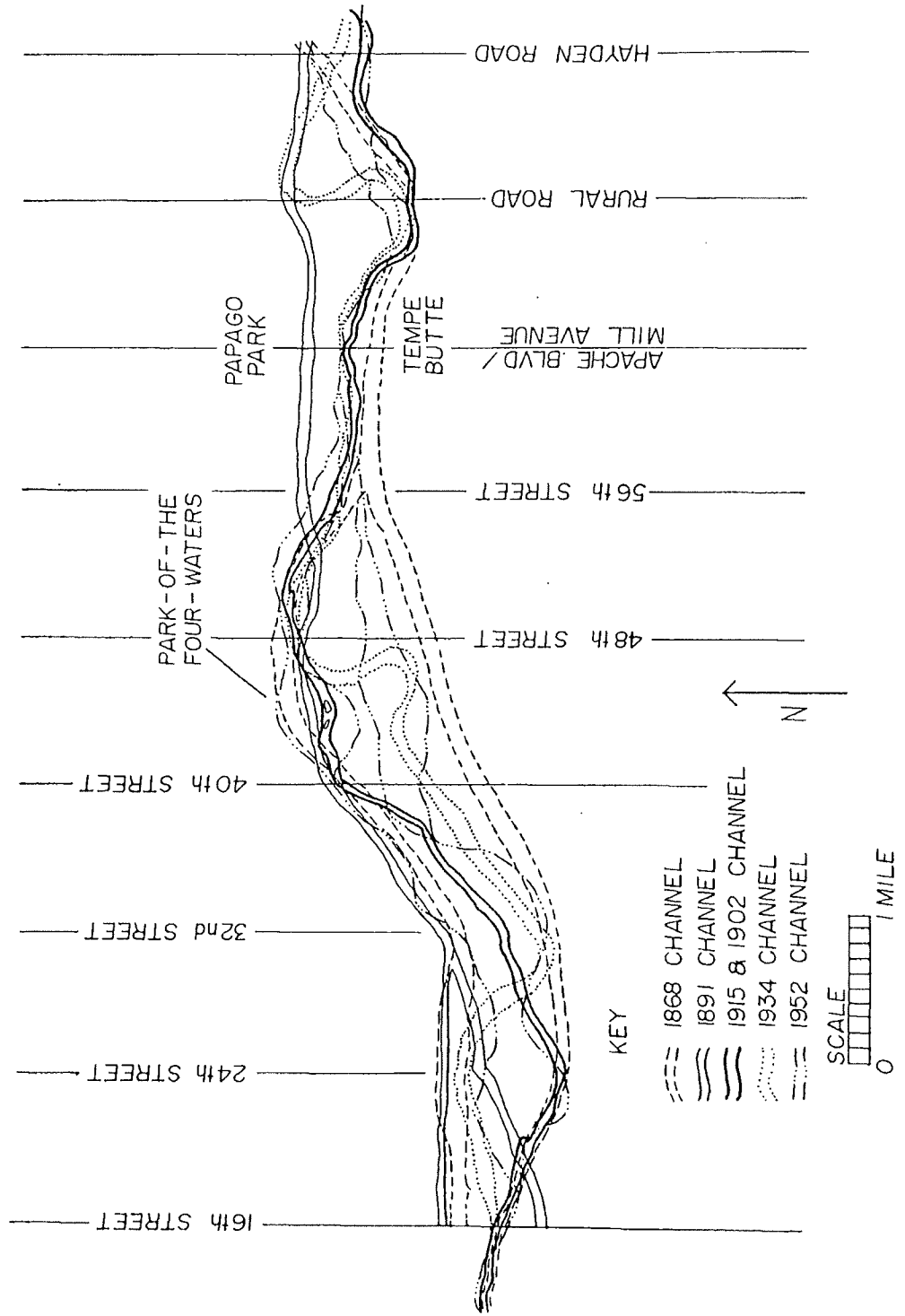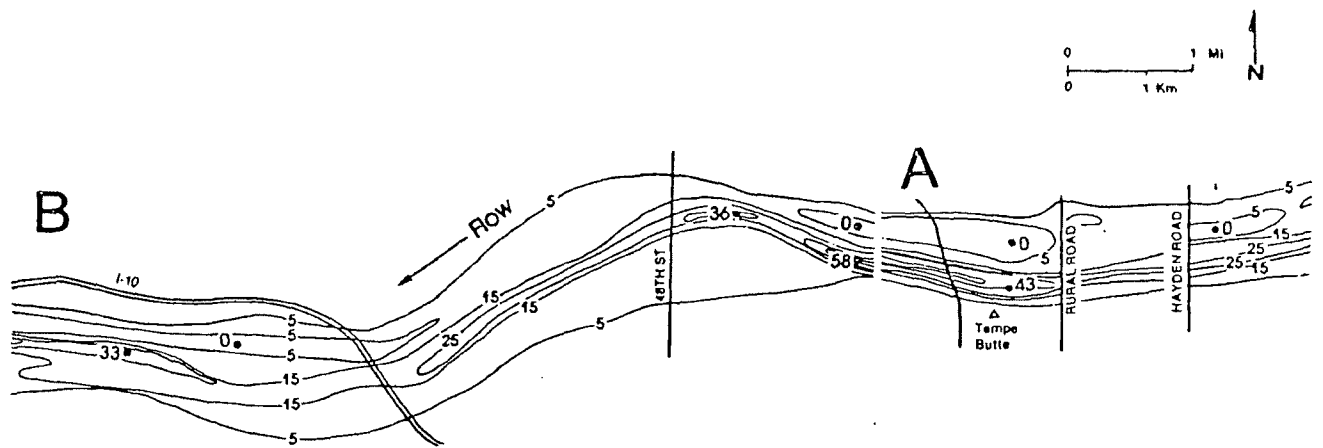
Figure 8. Locational probability zones of the Salt River low-flow
           channel. From Graf (1983).

upstream half of the study reach is located within the zone of highest locational probability, and hence, least channel change, in the lower Salt River.

The location of the high-flow channel boundaries over the period of record was also determined. In contrast to the low-flow channel, the high-flow channel has demonstrated remarkable lateral stability (Figure 9). Stability of the high-flow channel is more significant to the modelling of paleodischarges, and places the instability of the low-flow channel into perspective. All of the migrations of the low-flow channel were within the stable dimensions of the high-flow channel. Also, Graf (1983) reports that no downcutting, change in channel slope, or significant widening of the low-flow channel occurred between 1868 and 1962. Thus, regardless of the position of the low-flow channel within the stable high-flow channel, the total conveyance capacity of the flood channel of the Salt River remained relatively unchanged during that period. This stability was preserved in spite of geomorphic pressure from urbanization, gravel mining, removal of protective vegetation, and 16 major floods (Table 1) over 165,000 cfs (1800 cms). Archaeological evidence, discussed later, indicates that this channel stability can be extended back through the period of Hohokam occupation. Because of this long-term stability, any accurate topographic map drawn before the recent episode of downcutting and overbank modification by farming could be used to obtain cross-section information for input into the HEC-II model. A 1904 topographic map of the Salt River Valley (Davis, 1904) proved to be the most accurate and detailed map for modelling purposes. Twelve evenly spaced cross sections between Tempe Butte and the 24th Street alignment

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Figure 9. Location of the high-flow channel margins of the Salt River near Phoenix, AZ. Compare the stability of the high-flow channel with instability of the low-flow channel illustrated in Figure 7.

LOCATION OF THE HIGH-FLOW CHANNEL BOUNDARIES OF THE SALT RIVER IN TEMPE AND PHOENIX, AZ; 1902-1982

7 th STREET

16 th STREET
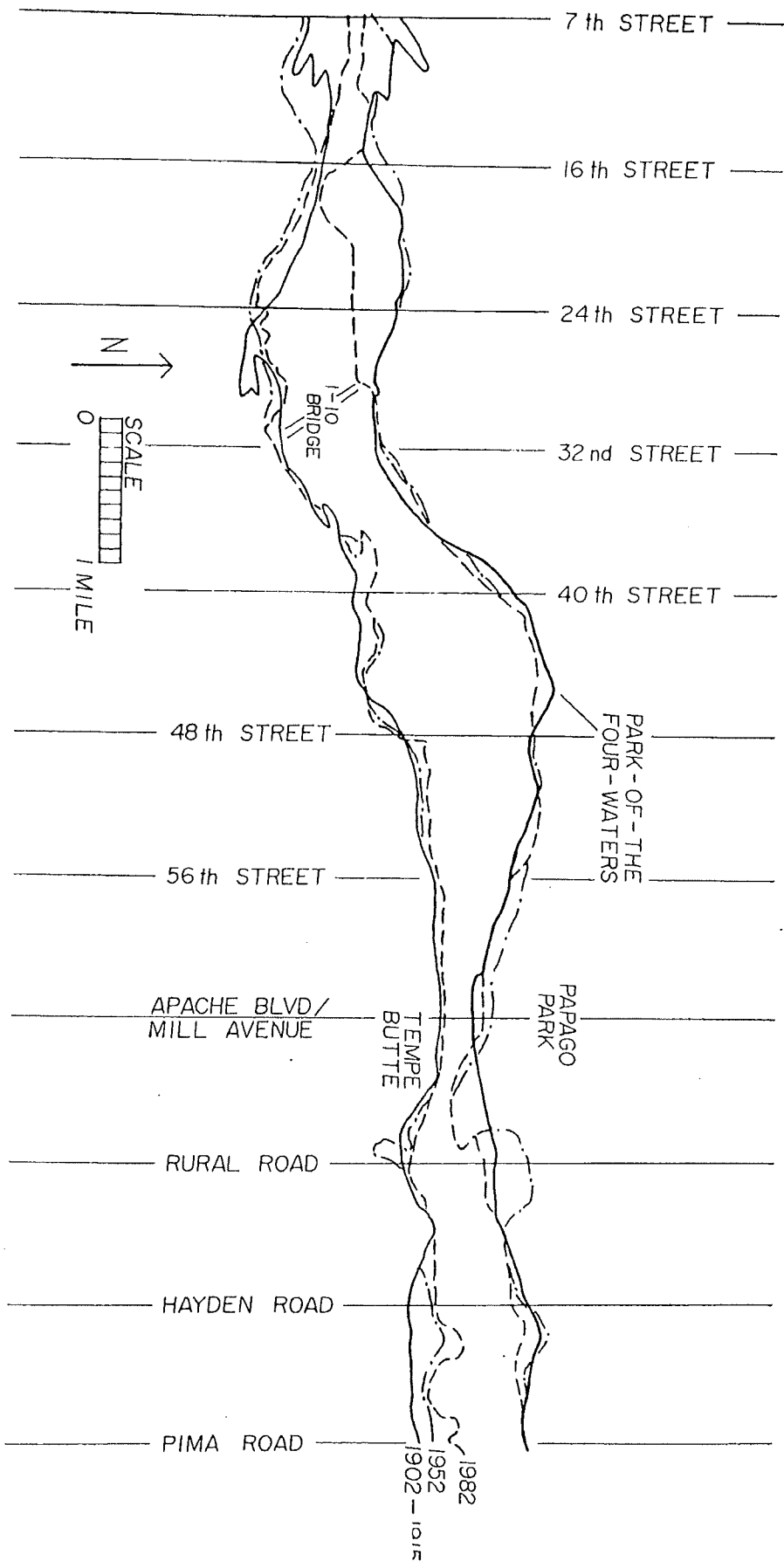
24 th STREET

N →

SCALE
0   1 MILE

32 nd STREET

I-10 BRIDGE

40 th STREET

48 th STREET

PARK-OF-THE FOUR-WATERS

56 th STREET

PAPAGO PARK

APACHE BLVD/ MILL AVENUE

TEMPE BUTTE

RURAL ROAD

HAYDEN ROAD

PIMA ROAD

1982
1952
1902-1915

Table 1. Periods of Hohokam Occupation

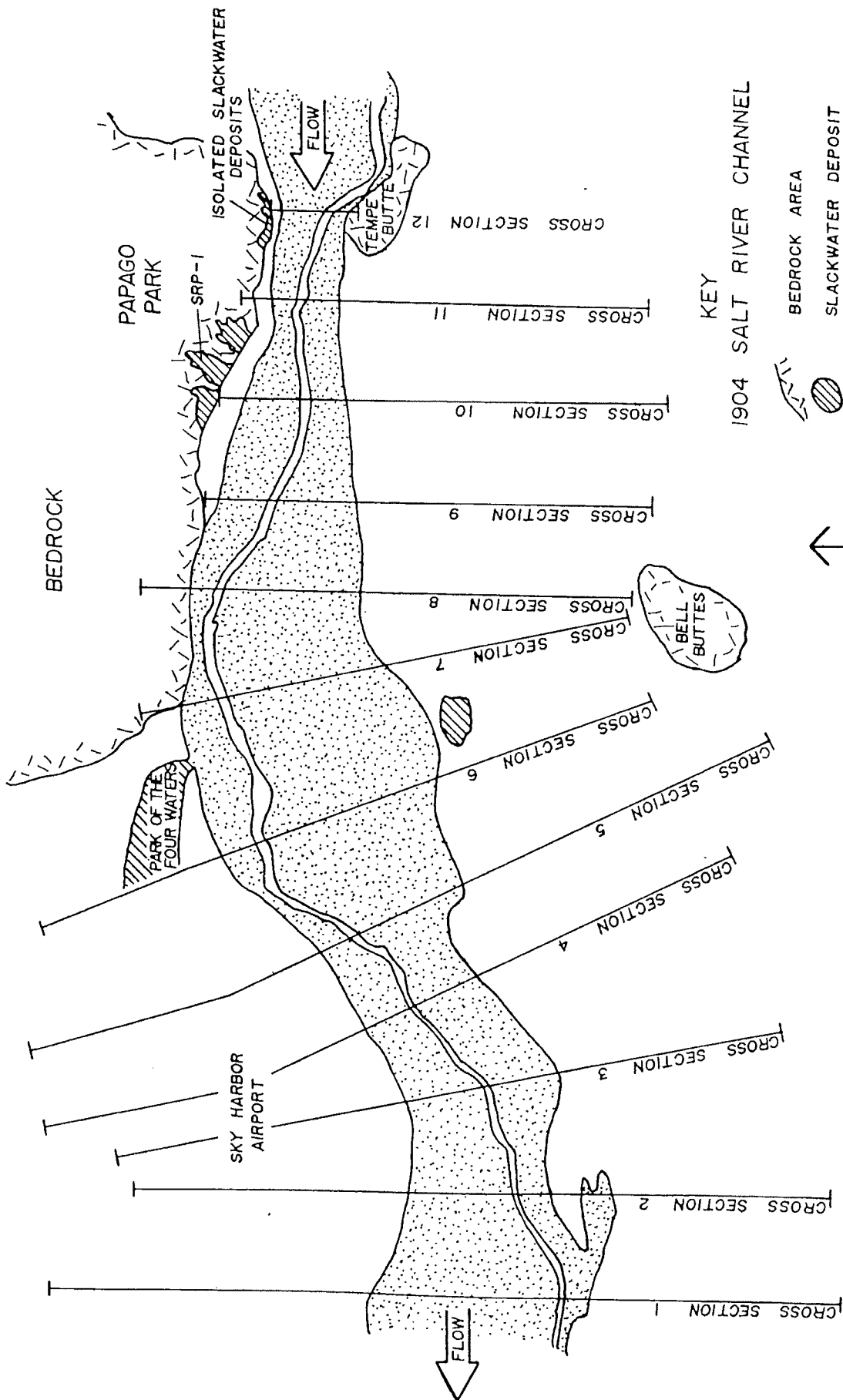| Period	Dates	Phase	Dates
Pioneer	? - 550 A.D.		
Colonial	550 - 900 A.D.	Gila Butte Santa Cruz	500 - 700 A.D. 700 - 900 A.D.
Sedentary	900 - 1150 A.D.	Sacatan Sacatan	900 - 1100 A.D. 1100 - 1150 A.D.
Classic	1150 - 1450 A.D.	Soho Civano	1150 - 1300 A.D. 1300 - 1400 A.D.

(Figure 10) were positioned on the map. Elevation and station data were then read from the map at each cross-section alignment. The accuracy of cross-section information derived from a topographic map, rather than direct surveying, is discussed later in this report.

Roughness characteristics and other hydraulic variables were determined by comparing known land-use patterns and historic photographs from the SRP archives and the Arizona Historical Society with published values determined by Barnes (1967) and Faskin (1963). This information was then input into the HEC-II computer program.

Channel Stability

Long-term stability of the study reach made accurate modelling of paleoflood discharges possible. This stability is due primarily to the reach's location at the inflection point between erosional and deposi-tional portions of the alluvial Salt River. Four converging terraces upstream of the study area document the erosional character of the upper Salt River. The depth of alluvial fill and lack of terraces below the bedrock reach at Tempe Narrows testifies to the depositional character of the lower Salt River. A point of no deposition and no erosion which must exist at the boundary of the two opposite sedimentological regimes is located within the study area. While this theoretical balance point may have shifted slightly within the study area during the period of record, bedrock cropping out at the upper end of the reach served as a maximum point of migration for each regime. Several lines of evidence indicate that the overall (flood) channel stability already documented for the historical period can be extrapolated over the entire period of the paleoflood record.

Figure 10. Map of the study reach on the Salt River near Phoenix,
            Arizona showing the location of the HEC-II cross sections and
            slackwater sites.

FLOW

ISOLATED SLACKWATER DEPOSITS

TEMPE BUTTE

CROSS SECTION 12

CROSS SECTION 11

CROSS SECTION 10

CROSS SECTION 9

CROSS SECTION 8

CROSS SECTION 7

CROSS SECTION 6

CROSS SECTION 5

CROSS SECTION 4

CROSS SECTION 3

CROSS SECTION 2

CROSS SECTION 1

FLOW

PAPAGO PARK

SRP-1

BEDROCK

PARK OF THE FOUR WATERS

SKY HARBOR AIRPORT

BELL BUTTES

N

KEY
1904 SALT RIVER CHANNEL

BEDROCK AREA

SLACKWATER DEPOSIT

CROSS SECTION

GEOLOGIC FLOODPLAIN OF THE SALT RIVER

SCALE

0   1 MILE
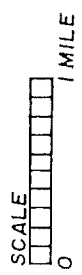
SLOPE:
LOW FLOW CHANNEL = 0.0017
OVERBANK AREA = 0.0016
FLOODPLAIN = 0.0019

First, geologic evidence supports the theory of stable channel margins within the study reach. Bedrock cropping out at river level from Tempe Narrows to the 56th Street alignment (cross sections 8-12 of this study, Figures 3, 10) provides natural erosion control especially along the north bank of the reach. The down-dropping Phoenix Valley creates an environment of deposition within the channel in order to maintain the grade control provided by bedrock at Tempe Butte (Pewe, 1978). The lack of alluvial terraces in the reach indicates a depositional environment rather than an erosional environment. Expanding flow downstream of the major contraction at Tempe Narrows (Figure 10) also favors deposition, rather than scour, much like a mountain stream which drops its sediment load when it reaches the wider channel cross sections at the mountain front. Finally, because the upstream portion of the reach is straight, neither bank receives the full erosive force of flood flow. No major back-bank erosion accompanied historic flooding.

Some theoretical data regarding the reach's resistance to scour are available. Graf (1983) reports that the bed of the Salt River is mobilized at discharges above 67,000 cfs (1900 cms) in reaches where scour occurs. Graf's estimate was made for modern, sediment-poor flows. Floods prior to modern dam construction and urbanization probably carried more sediment and required higher discharges to erode the bed. Simons, Li, and Li (1980) determined that the upper portion of the study reach was the one most resistant to scour over 30 miles (50 km) of the lower Salt River in the vicinity of the I-10 bridge.

Second, archaeological evidence within the study reach also supports the idea of a stable channel. W. B. Masse's (1976) and R. B. Woodbury's

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Figure 11. Stratigraphy of the upper and inset slackwater sediments at slackwater site SRP-1.

DESCRIPTION OF SLACKWATER SITE SRP-1

TRENCH

1153 FEET ABOVE MEAN SEA LEVEL

VERTICAL SCALE : 1" = 0.50 M = 50 CM

0.0 M

MODERN FILL

⑧

⑦

1.0 M

⑥

⑤

2.0 M

④ C-14   TRENCH-1   410 ± 100 YRS B.P.

③ I+

3.0 M

② I+

①

SLIGHTLY DECOMPOSED   3.6 M

VOLCANIC BEDROCK   4.0 M

INSET DEPOSIT

EXPLANATION

FLOOD UNIT

COLLUVIAL LAYERS

ERODED SURFACE

STONE LAYER

③   FLOOD UNIT NUMBER

PIT

1143 FEET

Ⓒ

Ⓑ   SR-3   14,000 YRS B.P.

Ⓐ   SR-4   1956

25
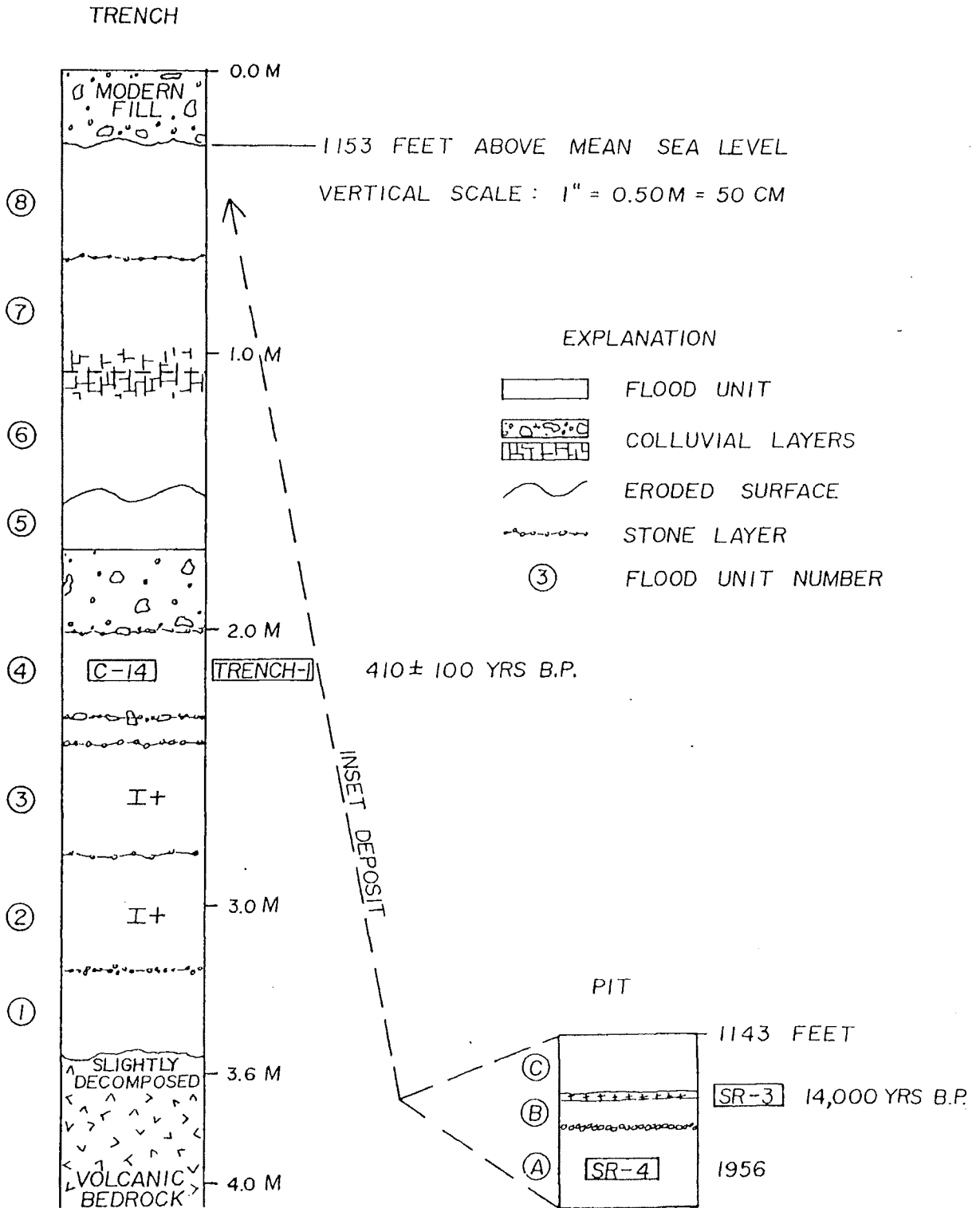
(1960) detailed examinations of Hohokam irrigation canals at Park of the
Four Waters reveal that the prehistoric canal inverts are at an elevation
approximately equal to that of the 1904 river bottom. Since irrigation
canals cannot be deeper than their source river, no permanent deepening
of the river could have occurred between canal abandonment in A.D. 1370,
and 1904 (Masse, 1976; Nials et al, in press).

Continuous use of irrigation canals within the study area by the
Hohokam from A.D. 400 to A.D. 1370 also indicates that no prehistoric
channel downcutting occurred. Canals continued to function after
withstanding some of the largest floods of the past 2000 years. Canals
which were filled by slackwater silts were merely redug, not relocated,
as would be necessary if the river channel morphology were significantly
modified (Halseth, 1947). Also, early Mormon settlers in the Phoenix
area reportedly cleaned out the ancient canals before they used them; no
deepening was required (Halseth, 1947; Turney, 1929).

Long-term high-flow channel stability within the study reach does
not preclude the possibility of significant scour and fill occurring
during individual floods. Such scour and fill would make peak discharge
estimates based on slackwater deposit elevations highly tenuous, since
varying bed elevations would significantly alter channel conveyance.

Several factors act to protect the Salt River channel bed against
scour. First, bedrock cropping out in the river bed from Tempe Narrows
to the 56th Street alignment results in a shallow (insignificant) depth
of scour. Second, expanding flow, as described above, limits the
potential capacity for scour. Third, increased vegetative cover in the
prehistoric channel (Bartlett, 1854; Ingalls, 1868; photographic

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evidence) anchored floodplain soils and reduced flood velocities, and hence, erosive capacity. Finally, the coarseness of the bed load prevents bed mobility at discharges less than 65,000 cfs (1800 cms; Graf, 1983).

Some documentation of the channel's resistance to scour within the study reach is available. Graf (1983) cites photographic evidence that no change in bed elevation or channel slope occurred from the 1880's to 1960. Historical accounts of flooding during this period mention local scour and fill elsewhere in the lower Salt River, but not within the upper portion of the study reach (Turney, 1929; Halseth, 1936; Schroeder, 1943). Simons, Li, and Li (1980) conducted an analysis of potential scour at the lower end of the study reach near the I-10 bridge. Their study concludes that 3 to 5 feet (1-1.5 cm) of natural scour could occur at the I-10 bridge location in undeveloped conditions. Depth of scour upstream is reported as minimal, on the order of 1 to 3 feet (0.3-1 m). The effect of small-scale scour on the accuracy of discharge estimates is discussed later in this report.

Channel aggradation between preserved (slackwater depositing) flood events would also make paleoflood discharge estimates inaccurate. Despite the reach's location in a largely depositional regime, evidence against the occurrence of significant fill is available. Archaeologic and historic (Forbes, 1902, 1911) evidence of low silt loads in the Salt River indicates that aggradation was not as significant on the pre-1900 Salt River as on other rivers in central Arizona. The fact that the Salt River was not a true braided river within the study reach indicates that little aggradation was occurring in pre-historic times. Low recurrence

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interval floods greater than 65,000 cfs (1800 cms) mobilize the channel
bed (Graf, 1983) and return the channel bed to its equilibrium position.
Several 65,000 cfs (1800 cms) or greater floods are likely to occur
between minimum-threshold-of-preservation floods of 175,000 cfs (5000
cms). Thus, floods which were preserved occurred within an approximately
uniform channel or scoured to an equilibrium position. The low recur-
rence interval of a 65,000 cfs (1800 cms) flood (approximately the 5-year
event; Péwé, 1982) makes it very likely that equilibrium conditions were
almost continuously maintained.

Historic, geologic, and archaeologic analysis of the Salt River
channel has shown that the study reach remained stable through the period
of record, including the period of Hohokam occupation. Geologic and
hydraulic analyses showed that the channel will resist significant scour
and fill during short-term events. Thus, cross-section information
derived from a 1904 topographic map may be used to model accurately the
prehistoric channel morphology of the Salt River.

Slackwater Deposits

Three types of highwater marks were used to model paleodischarges in
the study area: (1) "typical" slackwater sediments preserved along the
channel margins, (2) overbank flood silts preserved as post-abandonment
fill in ancient Hohokam irrigation canals, and (3) actual measurements of
the extent and elevation of the February 1891 flood waters.

A single, large slackwater deposit, SRP-1, is located just west of
the Salt River Project Crosscut Power Facility on the north overbank of
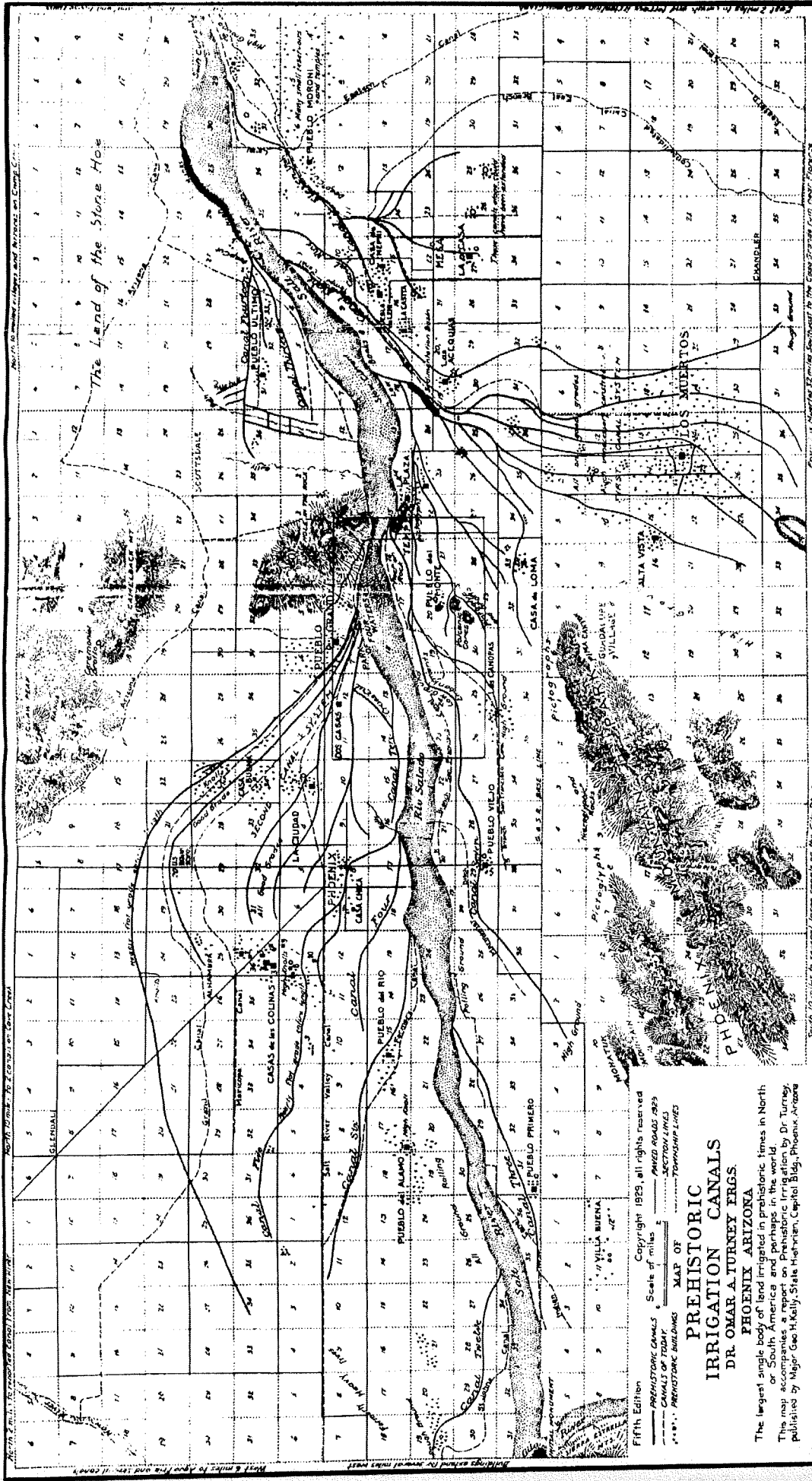the study reach (Figure 10). The slackwater site lies within a modern-

era dump. Use of the area as a dump rather than other forms of urbanization has prevented destruction of the slackwater deposits by protecting them from grading and bulldozing. Also, the Southern Pacific railroad grade located riverward of the slackwater deposits has isolated and protected the deposits from Salt River flooding since the railroad's construction in the 1880's.

Slackwater sediments from at least eight and at most ten distinct floods are preserved at the site (Figure 11). Individual flood units within the slackwater sequence were distinguished by the presence of intervening lenses of colluvium, varying sedimentological characteristics, and by stratigraphic relationships. Slackwater sediments at SRP-1 were shown to be the product of Salt River flood sedimentation by their degree of sorting, roundedness of clasts, mineralogy, and organic content. Also, upward fining sequences found within individual slackwater units indicated slackwater sedimentation.

Typical slackwater silts within bedrock areas were also found at several other isolated locations upstream of SRP-1 (Figure 10). However, the elevation and lack of shelter from erosion apparently prevented the preservation of multiple slackwater layers at these sites. These isolated deposits do not define a single consistent water-surface profile and thus, are probably the result of several discrete floods.

A second source of highwater information was slackwater sediment preserved as post-abandonment fill in ancient Hohokam irrigation canals (Figures 12, 13). Recent archaeological work on these Hohokam canals (Masse, 1976; Nials et al, in press) confirms the link between canal sedimentation and Salt River flooding. Some early investigators

Figure 12.   Omar A. Turney's (1929) map of prehistoric (Hohokam) irriga-
              tion canals in the Salt River Basin. The study reach of this
              report extends downstream of Tempe Butte approximately 5
              miles. Hohokam canals examined in this report are located
              just below Pueblo Grande at Park of the Four waters.

PREHISTORIC
IRRIGATION CANALS
DR. OMAR A. TURNEY ERGS.
PHOENIX ARIZONA

Fifth Edition

Copyright 1929, all rights reserved

Scale of miles

MAP OF

The largest single body of land irrigated in prehistoric times in North
or South America and perhaps in the world.

This map accompanies a report on Prehistoric Irrigation by Dr. Turney,
published by Major Geo. H. Kelly, State Historian, Capitol Bldg., Phoenix, Arizona

Legend:
- ———— PREHISTORIC CANALS
- ———— CANALS OF TODAY
- ∙∙∙∙∙ PREHISTORIC BUILDINGS
- ———— PAVED ROADS 1923
- ———— SECTION LINES
- ———— TOWNSHIP LINES

Canal Building in the Salt River Valley with a stone hoe held in the hand without a handle. These were the original engineer, the true pioneers who built, used and abandoned a canal system when London and Paris were a cluster of wild huts.

FORM 14-9144

Figure 13. Photograph showing Hohokam canal berms preserved at Park of
the Four Waters. Photograph taken November 4th, 1986 by the
author.
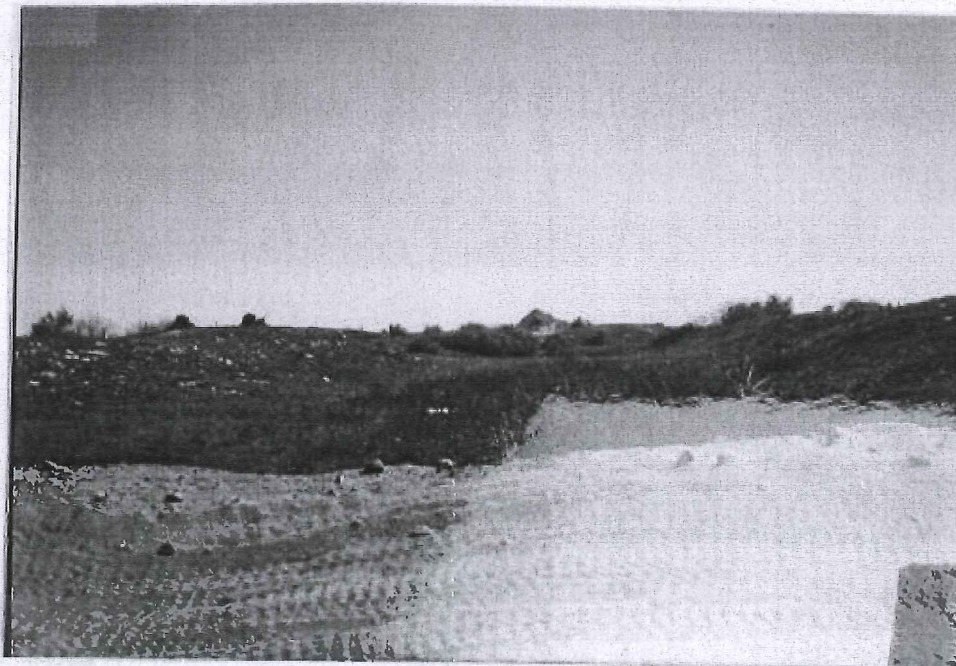
(Woodbury, 1960) attributed canal fill to normal silting-in while the
canals were in use. However, more recent investigations have shown that
the silt layers deposited in the canals are the direct result of Salt
River overbank flooding (Schulten, Bales, and Péwé, 1979; Péwé, 1982).
The following evidence supports this interpretation. Sedimentological
analysis of the silts, including size, sorting, and mineralogy (Péwé,
1982), as well as organic content (Means, 1902; Schulten, 1979; Masse,
unpublished data), points to an upper Salt River source. Thickness and
uniformity of silt layers indicate rapid flood deposition. Paucity of
archaeologic artifacts within silts also suggests rapid emplacement
(Masse, 1976; Nials et al, in press). Fining upward sequences within
individual units are usually found in slackwater deposits rather than in
deposits formed by steady canal flow. Finally, in places were the
original berms remain, the canal fill is deposited to an elevation above
that of the surrounding floodplain, indicating that the flood flow
covered the entire floodplain, but was trapped between the berms, causing
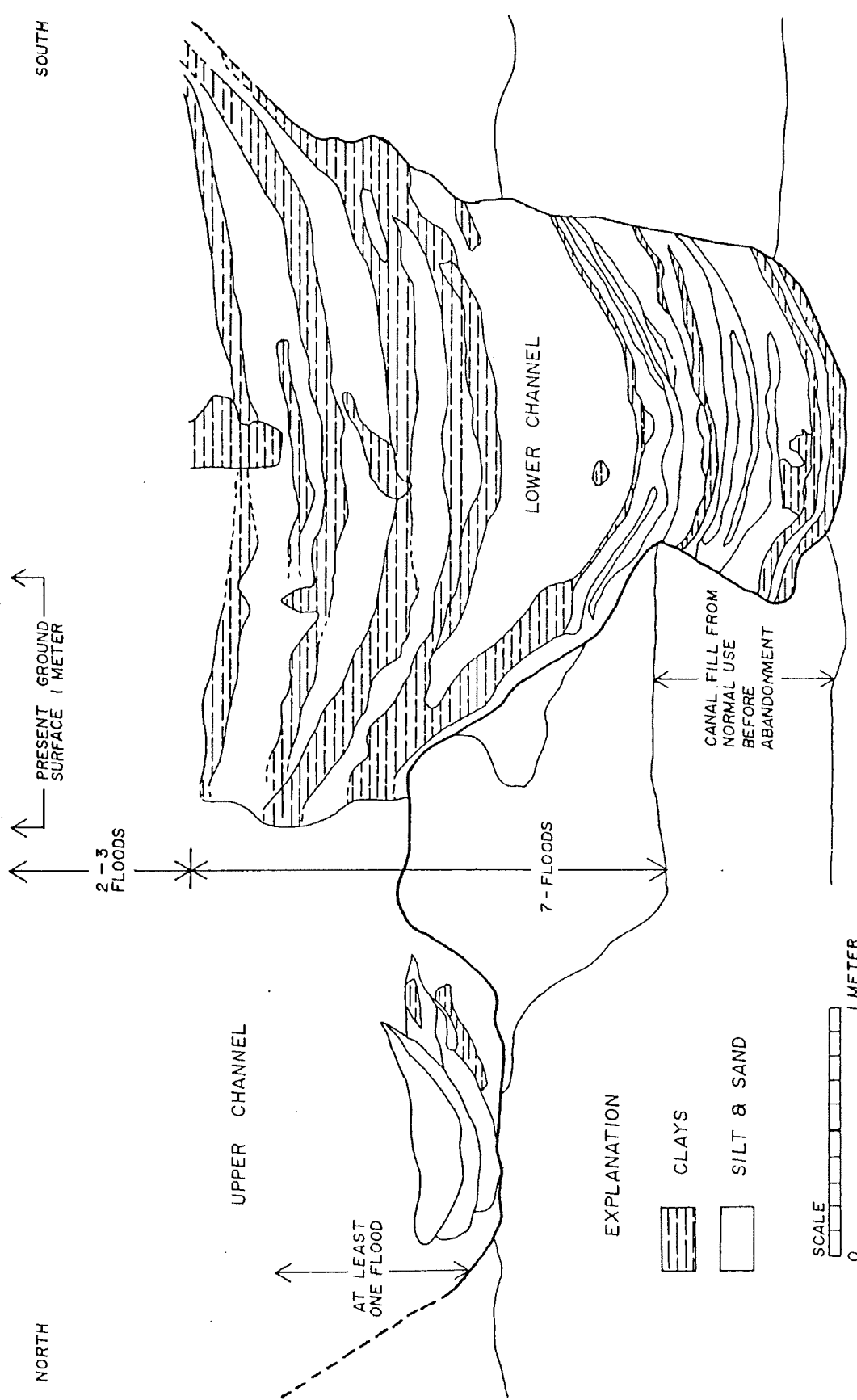deposition.

The manner of deposition of slackwater silts in Hohokam canals has
been described by Nials et al (in press). Hohokam Indians used rock and
brush "burro" dams to divert river water into their canals. Moderate
flooding washed away these fragile diversion dams, preventing flood water
from being directed at the canal. Canal headgates were closed during
flooding to prevent flood damage to the canal itself. Extreme flood
events destroyed the headgate as well as the burro dam, allowing flood-
water to enter the canal. Breaching of the headgates caused slackwater
deposition as the sediment-charged floodwaters were stilled in the back-

water environment of the canal. If the canals were abandoned after such a flood, only overbank floodwater could pass the blocked canal head and leave slackwater sediments further down the canal. Therefore, silt deposits within the canals represent sediment dropped out of suspension from floodplain flows, rather than from water coursing down the canal from its head. Nials et al (in press) estimated a recurrence interval of 50 to 100 years for flood years which emplaced canal slackwater sediments. Paleoflood discharge modelling of this study indicates that a minimum (bankful) discharge of 175,000 cfs (5000 cms) was required to overtop the high-flow channel banks.

Descriptions of the stratigraphy (Figure 14) of slackwater sediments infilling Hohokam canals at Park of the Four Waters were available from the field notes of Masse and Woodbury (Arizona State Museum Archives). While these investigators did not specifically seek to distinguish individual flood units within the canal fill, such analysis was made possible by the quality of their investigations, and by my experience describing slackwater sediments found elsewhere on the Salt River. Multiple canal sites from several periods of Hohokam occupation (Table 1) provided flood information for more than 1000 years of record (Table 2).

Individual flood units were identified by the presence of one or more of the following characteristics (Figures 11, 14): (1) intervening clay layers between silt units, often showing evidence of subaerial drying; (2) manganese discoloration lines between silt units; (3) abrupt textural or sedimentological differences between adjacent units; and (4) relative thickness of individual silt layers. Thin silt layers between gravel or clay lenses near the base of the canal could not be

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Figure 14. Example of canal sediment stratigraphy from canals described
           at Park of the Four Waters. This cross section shows Masse's
           description of Woodbury's South canal (Masse, 1976) and flood
           unit interpretation.

NORTH

UPPER CHANNEL

AT LEAST
ONE FLOOD

2 - 3
FLOODS

PRESENT GROUND
SURFACE 1 METER

7 - FLOODS

LOWER CHANNEL

CANAL FILL FROM
NORMAL USE
BEFORE ABANDONMENT

SOUTH

EXPLANATION

CLAYS

SILT & SAND

SCALE

0   1 METER

WOODBURY'S SOUTH CANAL

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Table 2. Summary of Canal Data

Canal	Investigator	Location	Number of Flood Units Described*	Approx. Date of Abandonment	Maximum Age of Youngest Flood Deposit	Years of Record	Dating Based On
North Canal	Woodbury (1960)	Park of the Four Waters, Phoenix	4 1 3 8	1350 A.D. younger than South Canal	1960 A.D.	660	Archaeological artifacts*
South Canal	Woodbury (1960)	Park of the Four Waters, Phoenix	8	1350 A.D. older than North Canal	1960 A.D.	760	Archaeological evidence
Canal #11 Woodbury's North Canal	Masse (1976)	U:9:2 Hohokam Expressway	4 5 1	1350 A.D.	pre-1930	630	Archaeological evidence and historic photos
Canal #3 Woodbury's South Canal	Masse (1976)	U:9:2 Hohokam Expressway	8 11 3	1350 A.D. Early Classic	pre-1930	730	Archaeological evidence and historic photos
Canal #7A Hagerstad	Masse (1976)	U:9:2 Hohokam Expressway	3 2 9 4	900? A.D.	1150	250	Archaeological and stratigraphic evidence – buried by #11 relation with canals #11, #3

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Table 2--Continued

Canal	Investigator	Location	Number of Flood Units Described*	Approx. Date of Abandon- ment	Maximum Age of Youngest Flood Deposit	Years of Record	Dating Based on
Canal #8	Masse (1976)	U:9:2 Hohokam Expressway	3 2 3	900?	1150	250	Archaeologic artifacts, radiocarbon - hearth stratigraphic - truncated by 7A
Hayden (San Francisco) Canal	Masse (1976)	U:9:2 Hohokam Expressway	4	1900	1976	76	Historical
East Canal Profile	Bradley (n.d.)	U:9:28N (44th & Grand Canal)	8	1100	?	?	Archaeologic artifacts

*Numbers of flood units at multiple canal sites reported as the number of units per individual canal at that site, see Figure 14, and total number of floods recorded.

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conclusively regarded as flood-emplaced, and thus were not considered as such.

On the basis of the criteria outlined above, the number of flood deposits was identified in each canal (Table 2). The number of estimated floods for each canal was then compared with the number of flood units found in other canals known to have been abandoned at the same time. This comparison provided a cross check on my reconstruction of the flood stratigraphy developed from Masse's and Woodbury's field notes.

Dating of canal sediments was based primarily on the archaeological investigations of Masse (1976), Bradley (unpublished manuscript in the Arizona State Museum Archives), Woodbury (1960), and Nials et al (in press). These researchers used archaeological artifacts found within, or related to, canal sediments to determine the dates of first use and of abandonment for each canal. Because canal abandonment was caused by flood damage, the time of abandonment was used as the age of the lowest silt unit comprising the canal fill. The age of the stratigraphically highest flood deposit in the canal was constrained by the date of its description (Woodbury, 1960), the date of historic cultivation in the cases where the canal berms were no longer preserved (Masse, 1976; Bradley, unpublished manuscript), or by historic trash deposits found in the uppermost layers (Masse, 1976). Two radiocarbon dates from organic material entrained within the silt layers also helped constrain the timing of flooding. The significance of these dates will be discussed in Results section below.

The third type of highwater marks used in this report were actual measurements of the extent and elevation of the February 1891 flood

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waters. Such measurements were available from USGS flood maps and from a map prepared by Bales (1981), as well as from historical documents and photos. These highwater marks were available along the entire length of the study reach and define an excellent water-surface profile with which to compare computer-generated profiles for a known discharge.
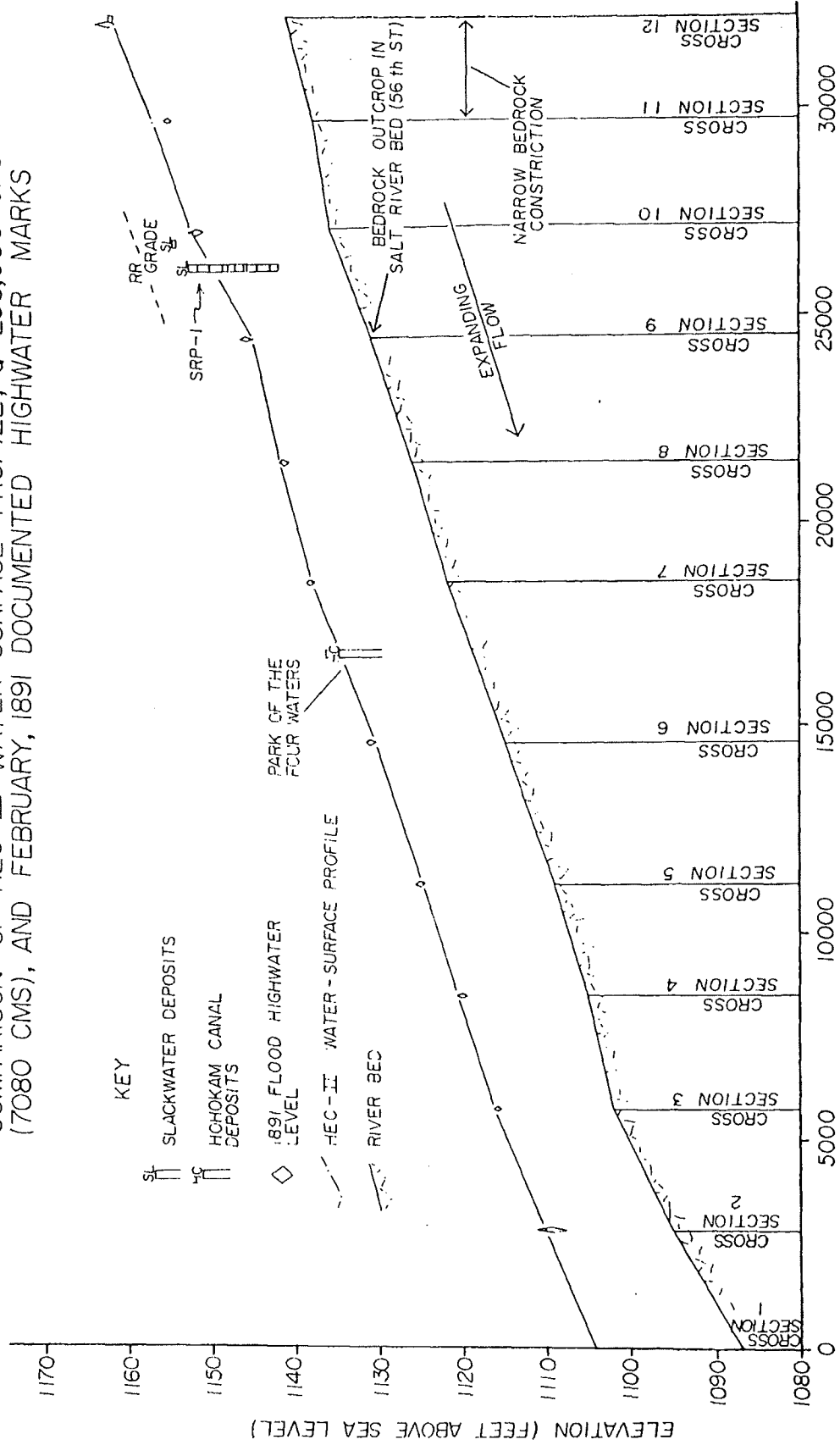
RESULTS

Calibration of the HEC-II Model

Actual measurements of the extent of the February 1891 flood provided a useful index for calibrating the HEC-II model. Extensive analysis of the 1891 flood has established its magnitude in Tempe at approximately 260,000 cfs (7400 cms). Stage information for each cross section was then compared to water-surface profiles generated by routing known discharges through the HEC-II computer program. These historic highwater marks fall in a range of HEC-II discharges between 250,000-257,000 cfs (7000-7400 cms) for the 1891 event (Figure 15). The greatest degree of overlap between highwater marks and water-surface profiles was obtained in the bedrock-controlled part of the reach, cross sections #7-11 (Figures 3, 10). Note that this part of the reach contained all the slackwater deposits used to reconstruct paleodischarges.

The close fit of HEC-II generated water-surface profiles and historic stage information justifies the use of cross-section data obtained from Davis' (1904) topographic map. Accurate correlation of the known and computed discharge estimates for the 1891 event indicates that slackwater elevations tied into the 1904 map would produce accurate reconstructions of the slackwater deposit emplacing paleodischarges. This accuracy may also indicate that significant scour and fill does not occur within the study reach, since such activity would make accurate reconstruction impossible.

Figure 15. HEC-II generated water-surface profiles which match known highwater marks of the February 1891 flood on the lower Salt River.

COMPARISON OF HEC-II WATER-SURFACE PROFILE, Q=250,000 CFS
(7080 CMS), AND FEBRUARY, 1891 DOCUMENTED HIGHWATER MARKS

KEY

SL ‖ SLACKWATER DEPOSITS

HC ‖ HOHOKAM CANAL DEPOSITS

◇ 1891 FLOOD HIGHWATER LEVEL

--- HEC-II WATER-SURFACE PROFILE

⌐⌐ RIVER BED

RR --- GRADE

SRP-1 →

PARK OF THE FOUR WATERS

BEDROCK OUTCROP IN SALT RIVER BED (56th ST)

EXPANDING FLOW

NARROW BEDROCK CONSTRICTION

DISTANCE FROM LOWER END OF STUDY REACH (FT)

ELEVATION (FEET ABOVE SEA LEVEL)

CROSS SECTION 1
CROSS SECTION 2
CROSS SECTION 3
CROSS SECTION 4
CROSS SECTION 5
CROSS SECTION 6
CROSS SECTION 7
CROSS SECTION 8
CROSS SECTION 9
CROSS SECTION 10
CROSS SECTION 11
CROSS SECTION 12

Once the accuracy of the HEC-II model was assured, water-surface profiles for a range of discharges were generated. Figure 16 shows computed water-surface profiles for discharges of 50,000 cfs to 450,000 cfs (1400-12,700 cms) in increments of 50,000 cfs (1400 cms). Large channel conveyance and broad, gently sloping overbank areas create a poor stage-discharge relationship. These factors limit the precision of paleoflood discharge estimation, especially at higher discharges. Hence, the accuracy of discharge estimates over 150,000 cfs (4200 cms) is essentially ± 25,000 cfs (700 cms) on this reach of the lower Salt River.

Slackwater Site SRP-1

At least eight flood units are preserved at slackwater site SRP-1 (Figures 11, 16). These units are represented by the deposits of the upper slackwater sequence. The layers of the inset slackwater deposit record local tributary flooding, rather than Salt River flooding, as shown by radiocarbon dating.

Three radiocarbon dates were obtained from organic material entrained within slackwater sediments at SRP-1 (Figure 16, Table 3). Two radiocarbon dates of material from the inset deposit yielded ages of 14,000 years B.P. (before present) and A.D. 1956 (ultramodern C-14; see Baker, Pickup, and Pollach, 1985). The 14,000 years B.P. date was the result of oil and tar contamination (Valastro, personal communication, 1986), probably due to fluid spillage by railroad maintenance crews. The presence of railroad material in the deposit indicates a true age of less than 100 years, the date of railroad construction at the site. The 1956 radiocarbon date records a period well after the site was isolated from

Figure 16. HEC-II generated water-surface profiles for a range of dis-
            charges and the elevation of slackwater sediment units used
            as highwater marks. Slackwater units at Park of the Four
            Waters are not distinguished here because bankful discharge
            was required to emplace sediment. Compare to bankful
            discharge as noted on the diagram.

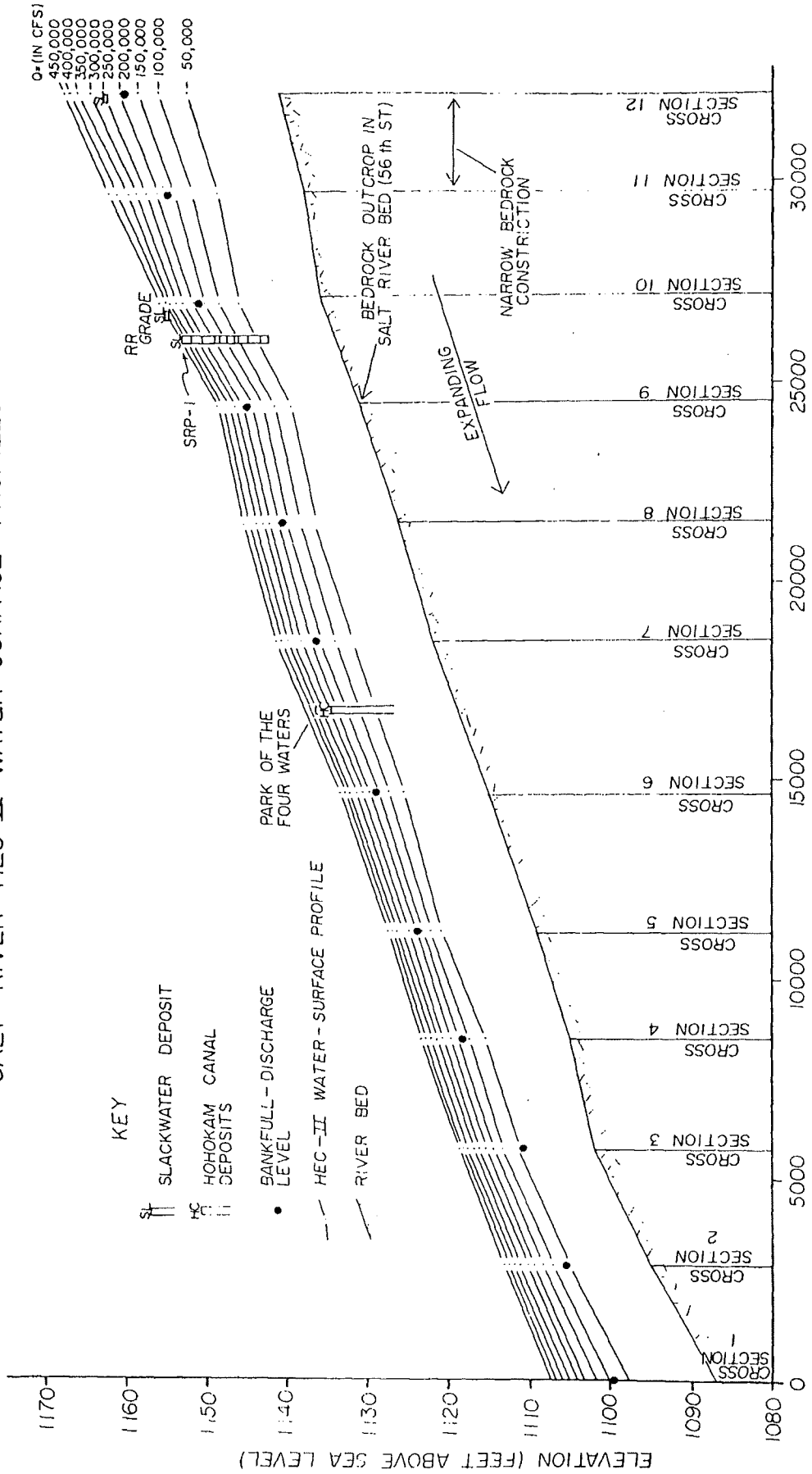# SALT RIVER HEC-II WATER-SURFACE PROFILES

KEY

Q (IN CFS)
- 450,000
- 400,000
- 350,000
- 300,000
- 250,000
- 200,000
- 150,000
- 100,000
- 50,000

SL — SLACKWATER DEPOSIT

HC — HOHOKAM CANAL DEPOSITS

• — BANKFULL-DISCHARGE LEVEL

— HEC-II WATER-SURFACE PROFILE

— RIVER BED

PARK OF THE FOUR WATERS

RR GRADE

SRP-1

BEDROCK OUTCROP IN SALT RIVER BED (56th ST)

NARROW BEDROCK CONSTRICTION

EXPANDING FLOW

DISTANCE FROM LOWER END OF STUDY REACH (FT)

ELEVATION (FEET ABOVE SEA LEVEL)

Table 3. Carbon-14 Dates from this Report

Site		Date	Type	Comment	Source
SRP-1	layer A (pit)	1956 (107.5 ± 1.6% modern carbon)	charcoal (maximum date)	C-14 gas proportion counter	Univ. of Arizona Lab #4589
	layer C/B (pit)	14,000 yrs B.P.	peat, organic layer (minimum date)	Liquid scint. (Contaminated by tar and oil from railroad?) Ballestra (1986, pers. comm.)	Univ. of Texas - Austin
	layer 4 - trench	410 ± 100 yrs B.P.	charcoal (Ponderosa Pine)	C-14 gas proportion counter	Univ. of Arizona Lab #4614
AZ:U:9:2.5-17	Canal 1 (Masse, 1976)	1100 ± 160 yrs B.P.	charcoal (mixed wood)	C-14 gas proportion counter	Univ. of Arizona Lab #4501
AZ:U:9:2.16-4	Canal 8-Hearth (Masse, 1976)	660 ± 90 yrs B.P.	charcoal	C-14 gas proportion counter	Univ. of Arizona Lab #4502

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Salt River flooding by construction of the railroad grade. Thus, the inset deposit cannot be the result of Salt River flooding. More likely, the inset slackwater layers were deposited as local tributary flooding caused arroyo headcuts to retreat through previously emplaced slackwater deposits. Older slackwater silts were reworked by the local runoff and then redeposited as the tributary flood ponded behind the railroad grade.

A third radiocarbon date of 410 ± 100 years B.P. was obtained for a piece of charcoal found in unit 4 of the upper deposit at SRP-1 (Figure 16, Table 3). Further age constraint was placed on the upper deposit by the development of Stage I+ carbonate in slackwater units 1, 2, and 3, indicating an age of 200-7000 years (Gile and others, 1981). Also, soil development, including C-horizon formation (clay illuviation) in units 4-8, and blocky soil texture in units 6 and 7 indicate at least 100 years since deposition. Finally, construction of the Southern Pacific Railroad grade in the 1880's to an elevation six feet (2 m) above the highest slackwater unit at SRP-1 implies a minimum age of 100 years B.P. for the youngest unit at the site.

Slackwater sediments at SRP-1 record two floods larger than the February 1891 flood (Figure 14, Table 4a). The minimum discharges for these two floods were 350,000 cfs (9900 cms) and 425,000 cfs (12,000 cms). Radiocarbon dating places the timing of these floods between 410 and 100 years B.P. The February 1891 flood is not preserved at SRP-1 due to the railroad grade which was constructed prior to that event. Also occurring within the same time period of the past 400 years, but earlier than the two largest floods of record, was a flood of equal magnitude to

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Table 4a. Paleoflood Information for SRP-1

Slackwater Unit	Flood Q (cfs)	Flood Q (cms)	Date (years B.P.)	Other
8	400,000-450,000	(11,300-12,700)	410 > Age > 1890 A.D.	Isolated slackwater deposits within reach (Figure 10)
7	300,000-350,000	(8500-9900)	410 > Age > Unit 8	
6	200,000-250,000	(5700-7100)	410 > Age > Unit 7	
5	200,000	(5700)	410 > Age > Unit 6	
4	150,000	(4200)	410	Significant erosion may have occurred
3	100,000	(2800)	1000 > Age > 410	Lower than bankful, may show depth of floodplain aggradation
2	75,000	(2100)	1000 > Age > 410	
1	50,000	(1400)	1000 > Age > 410	

the 1891 flood, 250,000 cfs (7100 cms), and a 200,000 cfs (5700 cms) flood.

Four floods from the time period before 410 years B.P. are recorded at SRP-1. All four of these floods are less than the bankful discharge of 175,000 cfs (5000 cms), and must therefore represent backwater deposits formed within a floodplain tributary. Thick accumulations of coarse sediments above units 3 and 4 may indicate erosion of the slack-water deposits to an elevation much lower than the actual flood stage. The presence of these colluvial layers probably indicates a significant time gap between emplacement of adjacent slackwater silts.

Park-of-the-Four-Waters Slackwater Site

Analysis of canal sediments at Park of the Four Waters and adjacent areas revealed slackwater sediments deposited throughout the past 1100 years. Irrigation canals abandoned during different periods of Hohokam occupation (Tables 2, 4b; Figure 17) preserved different periods of the flood record, creating a continuous record.
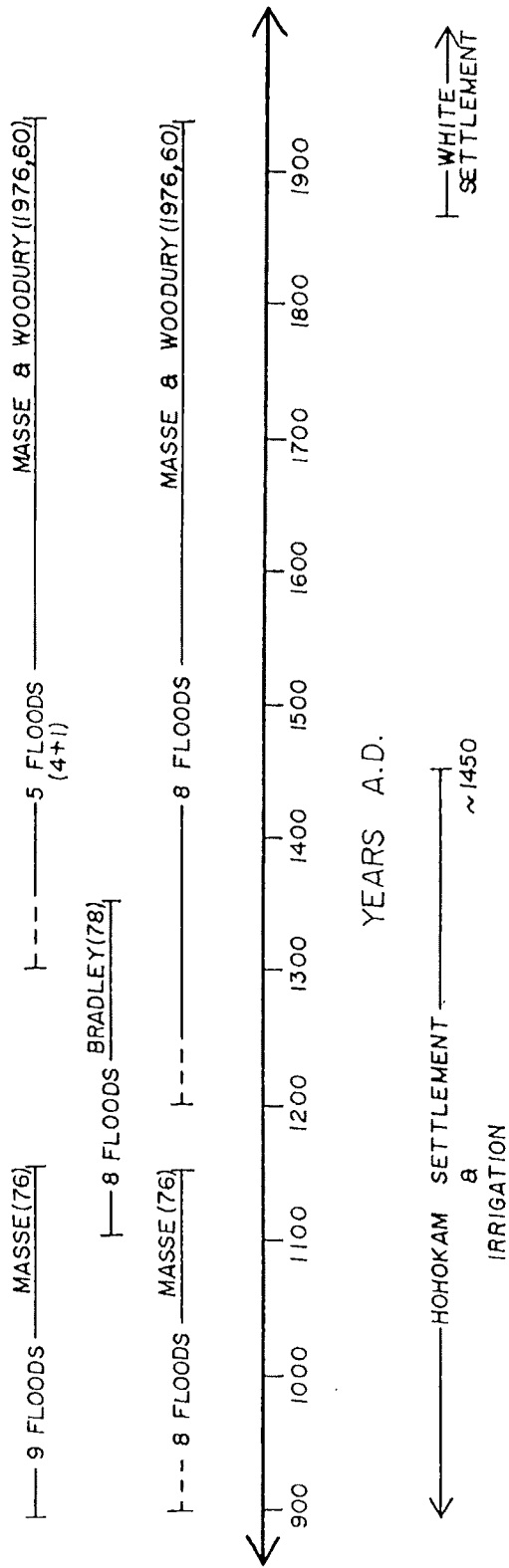
Nine floods greater than the Salt River bankful discharge of 175,000 cfs (5000 cms) occurred during the first period of the canal sediment record, A.D. 900 to A.D. 1150 (1100-850 years B.P.). Archaeologic evidence confirms that this period was one which experienced great flooding (Nials and others, 1986). Up to three more floods may be preserved above the actual canals sediments described by Masse (1976), but were regarded by archaeologists as overburden on top of the archaeo-logically interesting canals (Figure 14). These three additional units were tentatively identified from photographs published by Masse (1976)

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Table 4b. Paleoflood Information for Hohokam Canals (see Table 3)

Number of Floods	Time Period	Exceedance Threshold	Source of Information
9 - 11	900 A.D. - 1150	greater than 175,000 cfs	SRP-1 and HEC-II modelling
8 - 11	1200 A.D. - 1930	but less than 400,000 cfs	
4	1900 - 1976		
1	1100 B.P. (radiocarbon) C-14 date	400,000 (reached Lehi? Terrace) in Phoenix Townsite)	Nials et al (1986), Cable and Doyel (1983)
1	660 B.P. (radiocarbon) C-14 date	Unknown, probably destroyed Hohokam canals 175,000-400,000 cfs	Nials et al (1986)

Figure 17. Time-line of flood deposits preserved in abandoned Hohokam canals.

TIME LINE OF PREHISTORIC AND
HISTORIC FLOODS AS EVIDENCED
BY CANAL SEDIMENTS

|——— 9 FLOODS ——— MASSE(76)|

|– – – 8 FLOODS ——— MASSE(76)|

|–– 8 FLOODS ——— BRADLEY(78)|

|–– 5 FLOODS ——— MASSE & WOODURY (1976,60)|
(4+1)

|– – 8 FLOODS ——— MASSE & WOODURY (1976,60)|

900   1000   1100   1200   1300   1400   1500   1600   1700   1800   1900

YEARS A.D.

|——— HOHOKAM SETTLEMENT ———|
&
IRRIGATION

~1450

|——— WHITE
SETTLEMENT

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and from additional photographs of the dig found in the Arizona State Museum Archives. Slackwater canal sediments record eight floods over 175,000 cfs (5000 cms) from A.D. 1150 to A.D. 1370 (850-600 years B.P.). At least eight and at most eleven floods which exceeded the bankful threshold are recorded during the period between A.D. 1370 and A.D. 1960.

The largest flood recorded by canal slackwater sediments at Park of the Four Waters had a minimum peak discharge of 350,000 cfs (9900 cms) and occurred in the past 600 years. Maximum discharge for any of the floods preserved in the canal slackwater record is 420,000 cfs (11,900 cms), as defined by the maximum discharge which would not inundate the Lehi Terrace in the lower portion of the study reach. Because Hohokam canals on the Lehi Terrace do not show the same sequences of flood deposits like those on the lower terrace at Park of the Four Waters, the Lehi Terrace slope contained all but the largest floods. A larger, more extensive flood is implied by widespread canal destruction and subsequent reconstruction around A.D. 890 (1100 years B.P.). This flood did overtop the Lehi Terrace, as shown by flood deposits in Lehi Terrace canals, and by flood damage to Hohokam pueblos on the terrace.

In summary, the bankful discharge of 175,000 cfs (5000 cms) was exceeded 27 times in the past 1000 years (Table 4, Figure 18). Slack-water sediments at SRP-1 record minimum discharges of 200,000 cfs (5700 cms), 275,000 cfs (7800 cms), 350,000 cfs (9900 cms), and 420,000 cfs (11900 cms) for four floods which occurred in the past 410 years. The largest floods of record had a minimum peak magnitude of 420,000 cfs (11,900 cms). This threshold was exceeded once in the past 410 years, and once approximately 1100 years ago (Figure 18).

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Figure 18. The flood record of the lower Salt River as preserved in
            slackwater sediments according to minimum and maximum
            thresholds.

FLOOD THRESHOLDS ON THE LOWER SALT RIVER
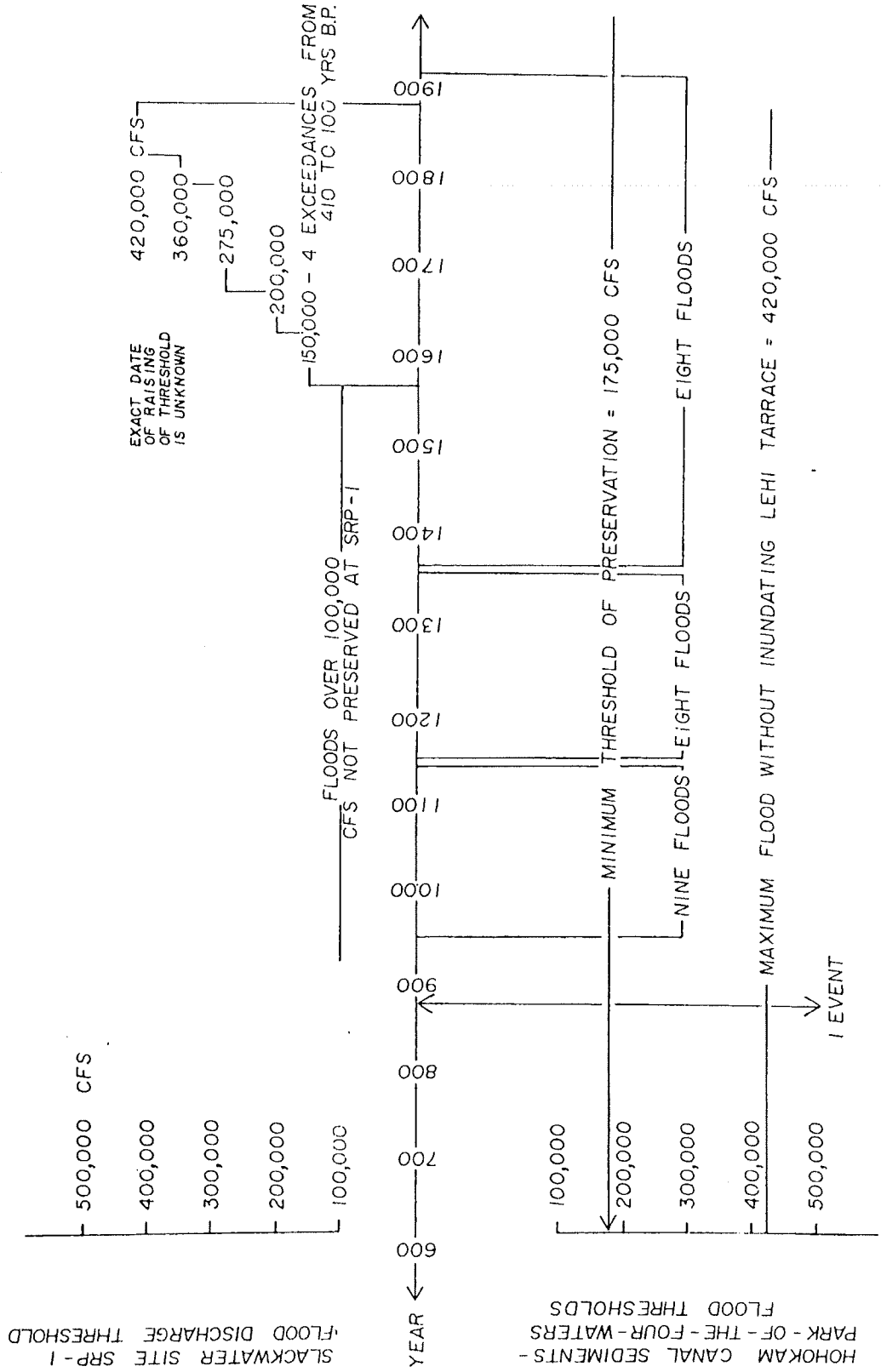
DISCUSSION OF RESULTS

Accuracy of Paleodischarge Estimates

The results of this study are meaningful only if paleodischarge estimates made from HEC-II modelling of the prehistoric Salt River are accurate. A poor overbank stage-discharge relationship, partial alluvial control within the study reach, and use of a 1904 topographic map for cross-section data are potential sources of error. Quantification of potential errors put paleoflood discharge estimates in their proper context.

Broad, shallow-sloping overbank topography and a wide flood channel create a poor stage-discharge relationship. That is, flood discharge may increase dramatically with only a small increase in flood stage. Thus, the reconstruction of flood magnitudes on the lower Salt River from known highwater marks, such as slackwater deposits, is subject to greater error than in the narrow, bedrock canyons upstream.

The effect of the poor stage-discharge relationship is shown in Figure 16. At the upper end of the range of modelled water-surface profiles, only a 0.5 foot (0.15 meter) rise in water surface elevation accompanies a 50,000 cfs (1400 cms) increase in discharge. Thus, these minimum discharge estimates should be reported as within ± 25,000 cfs (± 700 cms) of the true minimum discharge. However, such error, compared to the magnitude of the floods studied in this report, results in a relative error of only ±5% for the largest flood of record, and 14% for bankful discharge.

Error resulting from using the 1904 topographic map rather than direct survey data can be estimated by considering a worst-case scenario. Cross-section station information was taken from the 1904 map in 100-foot (30-m) increments. Thus, the total high-flow channel width could be off by, at most, 200 feet (60 m). Cross-section elevation error resulting from topographic irregularities not detected by the 5-foot (1.5-m) contour interval of the 1904 map presumably balances out over the length of the cross section, and hence, would not affect conveyance estimates. For this analysis, a liberal estimate of 1 foot (0.3 m) of consistent elevation error over the length of the channel cross section was assumed. Thus, the total error possible for both cross-section elevation and station data, results in an increase or decrease in discharge of 6100 cfs (170 cms). This translates to a relative error of 3% to 1% over the range of reconstructed flood discharges.

Error from the measurement inaccuracies discussed above are small compared to the potential error resulting from scour or fill, if it were to occur. In contrast to errors in measurement, relative inaccuracy from scour would increase as discharge (and sediment transport capacity) increased. Scour depths of only 3 feet (1 meter) across an entire cross section would result in relative error of 21% at bankful discharge. However, evidence presented in the Methodology section of this paper demonstrates the improbability of significant scour occurring during flooding.

Potential error from the aforementioned sources are well within the accuracy range of the HEC-II model. Because the HEC-II model assumes one-dimensional, gradually-varied flow, and fails to account for the

effects of sediment transport on discharge, the model's accuracy has been

estimated at 20% (Simon Ince, 1986, personal communication) to 40%

(Thomas Maddock, Jr., 1986, personal communication). Thus, mathematical

relative error for this study area is well within the HEC-II model's

theoretical limits. Therefore, reconstructed paleodischarge estimates

can be regarded as accurate, and can be used for planning and flood-

hazard analysis.

Comparison with Previous Paleoflood Studies

The results of this report should be considered in light of the

findings of previous paleohydrologic studies of the Salt River watershed.

Previous research has taken several forms: slackwater studies (Ely,

1985; Partridge, 1985; O'Connor and Fuller, 1986), statistical analyses

of historic flood data (USGS gage data, 1947; Malvick, 1980), and

dendrochronologic reconstruction of annual flow (Smith, 1981). A summary

of the flood data from these studies is shown in Tables 5 and 6. There

is great similarity between the results of previous studies and the

results of this project.

Earlier slackwater studies in the Salt River Basin concentrated on

reaches well above the confluence of the Salt and Verde Rivers. Dis-

charge information obtained for tributary rivers cannot simply be added

together for comparison with the discharges reconstructed for this study

reach downstream. Even if precise dating were available, flood peak

timing differences, transmission losses, and other hydrologic factors

would make absolute flood magnitude comparisons difficult. Rather,

information regarding relative flood magnitudes and their approximate

Table 5. Comparison of Prehistoric Flood Data from Paleohydrologic Studies of the Salt River Watershed

Source	River	Type of Study	Date of Floods (yrs B.P.)	Discharge Estimate (cfs)	Discharge Estimate (cms)	Largest Flood of Record	C-14 Dates
Ely (1985)	Verde	Slackwater technique	93 185 ± 89 223 ± 70 380 ± 320 1010 ± 95	124,000-134,000 124,000-134,000 177,000-191,000	3500-3800 3500-3800 5000-5400	177,000-191,000 cfs (5000-5400 cms) $\geq$ 1000 yrs B.P.	see dates of floods
Partridge (1985)	Salt	Slackwater technique	200 600 >600 (1000?)	102,000-113,000 113,000 145,000	2900-3200 3200 4100	145,000 cfs (4100 cms) $\geq$ 1000 yrs B.P.	1542 A.D. 1200-1400 A.D.
O'Connor and Fuller (1986)	Salt	Slackwater technique	<120 170 ± 60 1060 ± 90	88,000-106,000 106,000-127,000	2500-3000 2 floods - 3000-3600	1224,000-127,000 cfs (3500-3600 cms) 1952	1640 A.D. 1640-1950
	Verde		122 ± 135 210 ± 160 539 ± 125	56,000- 70,600	3 floods 1600-2000	77,700-85,000 cfs (2200-2400 cms) 1891	1450 A.D.
	Tonto Creek		190 ± 15	17,700- 24,700	4 or 5 floods 500-700	35,000 cfs (1000 cms) 1980	1670-1955

Table 6. Years of Major Prehistoric Flooding on the Lower Salt River

Sources	Period of Reconstruction	Flood Years
DENDROCHRONOLOGIC STUDIES		
Nials and others[1]	740 – 1370 A.D.	6 years R.I. 50-100 6 years R.I. 100+ (798, 802, 805, 822, 888, 899, 928, 1052, 1086, 1129, 1202, 1259, 1358 A.D.)
Smith[1] (1981)	1580 – 1979	1617, 1719, 1763, 1791, 1825-1870 (5 events)
HISTORIC ACCOUNTS PRIOR TO 1891 A.D.		
Newspaper Accounts	1800 – 1891	1833, 1862*, 1869, 1874*, 1880, 1884
Bartlett (1854)	pre-1854	1 flood left debris
McClatchie (1902)	pre-1891	1 flood = 1891 event

1 Annual floods = total annual flow

* Reported as large floods

years of occurrence for upstream and downstream paleoflood series should be compared.

The similarity between reconstructed flood series for the upper and lower Salt River is notable (Table 5). Each slackwater study documented major floods around the years A.D. 890 (1100 years B.P.), A.D. 1370 (600 years B.P.), A.D. 1750 (200 years B.P.), and, with the exception of Partridge's (1985) work, A.D. 1550 (440 years B.P.). Slackwater deposits which record flood discharge greater than the 1891 event were reported by Ely (1985) and Partridge (1985). The largest flood of record reported by Ely (1985) and Partridge (1985) occurred approximately 1000 years ago. Archaeologic evidence from Hohokam canal sites also documents the occurrence of an extremely large flood approximately 1100 years before present. It is interesting to note that slackwater studies of other Arizona and Utah river systems also record a single, large flood which occurred approximately 1100 years ago (O'Connor, 1985; Webb, 1985; Roberts, in preparation).

Flood sediments at SRP-1 show that a flood equaling the largest flood of record, 420,000 cfs (11,900 cms), occurred within the last 410 years. No record of such a large flood during this time period was found by earlier research in upstream reaches, although slackwater deposits from moderately large floods were reported. This anomaly is not necessarily a contradiction. Moderate sized floods on all the tributaries above the study reach in Tempe may have been appropriately timed so that a single, very large flood peak was produced downstream. Conversely, large, single tributary floods caused by localized precipitation would

Probably not produce large peak discharges below the Salt-Verde con-
fluence in Tempe.

There is some historical confirmation for very large discharges
occurring in the nineteenth century prior to the 1891 flood (Table 7).
Early Phoenix residents recall local Indian stories about a flood at
least as big as the February 1891 event (McClatchie, 1902). The first
explorers (Bartlett, 1854) and surveyors (Ingalls, 1868) report finding
flood debris high in the trees lining the Salt River high-flow channel.
Newspaper accounts from the old Southwest report large floods on the Salt
River in 1833, 1862, 1869, 1874, 1880, and 1884 (Durrenberger and Ingram,
1978; Newton, 1957; US Army Corps of Engineers, 1957, 1982). The floods
of 1862 and 1874 were noted as especially large events (Dobyns, 1981; The
Phoenix Gazette, 1978). Flood stages of up to 17 feet (5.2 m), which
would correspond to discharges of 100,000-150,000 cfs (5600-7000 cms),
were reported at Tempe Narrows.

Comparison of the slackwater record preserved in abandoned Hohokam
canals with upstream slackwater records is difficult. Because a constant
threshold (bankful discharge) was maintained throughout the period of
record at the canal sites, a more complete inventory of flooding was
preserved. Also, because canal sediments were buried in the floodplain,
they were absolutely preserved from erosion. Thus, in terms of numbers
of floods, more were recorded at the canal sites than in the typical
slackwater sites upstream. Since few age constraints beyond date of
abandonment and age of the youngest deposit were available for canal
sediments, no comparison to the ages of flood deposits in the upstream

Table 7. Historic Flood Discharges on the Salt River near Phoenix, AZ

Date[+]	Actual discharge (gaged or estimated) cfs	Estimated discharge without dams upstream[*] cfs
Feb. 1980	180,000	241,000
Mar. 1979	67,400	
Jan. 1979	88,000	235,000
Dec. 1978	140,000	
Mar. 1978	122,000	260,000
Feb. 1973	22,000	
Jan. 1966	67,000	85,000
Mar. 1941	40,000	170,000
Mar. 1938	85,000	115,000
Feb. 1932	86,000	117,000
Feb. 1927	70,000	123,000
Feb. 1920	130,000	155,000
Jan. 1916	120,000	164,000
- - - - - - - - - Completion of Roosevelt Dam, Salt River - - - - - - - - -		
Nov. 1906	200,000	220,000[**]
Apr. 1905	115,000	115,000[**]
Apr. 1895	115,000	
Feb. 1891	260,000	277,100[**]
Feb. 1890	143,000	145,500[**]
1884 1880 1874 1869 1862 1833	see Newton (57) Bartlett (1854)	magnitudes not determined, at least one flood equal to scale as Feb. 1891 (McClatchie, 1902)

+ Note that all these discharges are winter floods.
* US Army Corps of Engineers CAWCS Study (1982)
** Simulated in HEC-II Study

NOTE: For conversion to metric units, divide by 35.3.

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reaches is possible. However, there are no conflicts between flood data recovered from the two types of sites.

Dendrochronologic records also provide some confirmation for the high number of flood deposits uncovered in abandoned Hohokam irrigation canals within the study area (Table 6). Two tree-ring series from trees in the headwater regions of the Salt River were used for comparison with the slackwater record. Nials and others (in preparation) used tree-ring data to reconstruct the total annual flow of the Salt River for the years A.D. 740 to A.D. 1370. Smith's (1981) series of tree rings extends from A.D. 1580 to A.D. 1797. The relationship between tree rings and annual flow is described by Stockton (1975) and Smith (1981).

While total annual flow can only partially relate to the incidence of single, catastrophic floods, there is strong correspondence between the two variables, especially on semi-arid region rivers (Smith, 1981). Due to the paucity of normal rainfall over the Salt River watershed, total annual runoff can be doubled or tripled by the occurrence of a single, large, cyclonic winter storm and its ensuing flood. Thus, years with above average total runoff are likely to be years which experienced large winter floods. As long as runoff data have been collected on the Salt River, all of the years with summer peak discharges had below average annual flows. It is not the intent of this study to prove a valid relationship between tree-ring thickness and incidence of major floods. However, some correspondence between the two variables (Nials and others, in preparation) indicates that years of high annual flow may be years of major flooding. Thus, some confirmation can be made from tree-ring records for the number of floods preserved in Hohokam canals.

Nials et al (in preparation) report 12 years with annual floods of recurrence interval 50 years or greater during the time from A.D. 740-1370. They regard these years as ones with the potential to deposit sediment in Hohokam canals or to force the canal's abandonment. Smith reports high annual flow during 9 individual years from A.D. 1580 to 1879. Surely some lower annual recurrence interval years or lower total annual flood years emplaced slackwater deposits, while some predicted years did not. However, the total number of floods recorded by tree rings and by slackwater sediments comprising land fill is not dissimilar. Table 6 presents the data summarized above.

Analysis of the actual flood record preserved as slackwater sediments reveals a serious dichotomy between flood peak estimates made from rainfall-runoff models and from actual flood records (Tables 7, 8). The US Army Corps of Engineers' estimate of the probable maximum flood (PMF) is 925,000 cfs (26,200 cms). Geologic evidence indicates that a flood of at least 420,000 cfs (11,900 cms) occurred twice in the last 1100 years. No flood close to the PMF has occurred.

Comparisons of the results of this study with modern gage (estimated for this study reach) records are surprisingly accurate. The US Army Corps of Engineers (1982, Table 8) predicted a 500-year recurrence interval flood magnitude of 400,000 cfs (11,300 cms). Indeed, two 420,000 cfs (11,900 cms) floods are recorded in the geologic record over the past 1100 years. Estimates from a variety of methods predict a 100-year flood magnitude of about 260,000 cfs (7400 cms; Table 7). This is the size of the largest flood to occur within the last 100 years. However, further analysis of the results of this study using threshold

Table 8. Discharge Data for the Lower Salt River Near Phoenix, AZ

	Q_{min}	Date
GEOLOGIC EVIDENCE		
This Study	420,000 cfs	410-120 yrs B.P. and 1000 yrs B.P.
OBSERVATIONAL RECORD		
Largest gaged flood	260,000 cfs	February, 1891
Statistical		
- US Army Corps of Engineers		
100-year recurrence interval	300,000 cfs	
500-year recurrence interval	400,000 cfs	
- Malvick (1980)	260,000 cfs	
- USGS Q_{100}	217,000 cfs	
RAINFALL-RUNOFF		
US Army Corps of Engineers Probable Maximum Flood	925,000 cfs	
Standard Project Flood*	390,000+ cfs	

* Tempe Bridge

+ Assuming no dams upstream

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exceedance information (Stedinger and Cohn, 1986) will determine the accuracy of previous statistical analyses.

Applicability of the Slackwater
Technique to Alluvial Rivers

This study represents the first attempt to apply the slackwater technique to an alluvial river. The following unique characteristics of the study reach, described earlier in this report, allow the slackwater technique to be used: (1) partial bedrock control, (2) preservation of slackwater deposits within the alluvial floodplain in buried canals, (3) location of the study reach at the equilibrium point between erosional and depositional reaches of the lower Salt River, and (4) long-term stability of the flood channel.

Many alluvial rivers in the arid Southwest exhibit features that would prevent successful application of the slackwater technique. Most alluvial rivers in Arizona underwent a series of arroyo cutting episodes coincident with the onset of settlement by cattle-farming pioneers. Such deepening of a river channel would not allow paleodischarge modelling using its modern channel dimensions. Unless accurate topographic information were available, extensive estimation of the pre-arroyo channel dimensions would limit the accuracy of paleoflood reconstruction.

The Salt River near Phoenix did not exhibit a flood response typical of many other Arizona rivers. Burkham (1972) documented a cyclical pattern of channel widening and narrowing in response to flooding and periods of normal flow on the Gila River. Such patterns of changing channel morphology would significantly vary channel conveyance through time, making paleoflood modelling impossible.

Finally, the existence of datable slackwater deposits is not common along alluvial rivers. The typical alluvial floodplain does not have enough areas of ineffective flow large and stable enough to accumulate a long-term slackwater sediment sequence. Usually there is no shelter from erosive processes which would rapidly destroy a sandy-silt deposit. Often, the few areas that might have been suitable sites for slackwater accumulations have been significantly altered by farming and floodplain development.

Thus, the slackwater technique is probably not applicable to many alluvial rivers. Such application was made possible on the Salt River near Phoenix due to the presence of bedrock control, unique prehistoric canal deposits, rich historic and prehistoric flood records, pre-development topographic and land use information, and hydraulically stable channel morphology. Undoubtedly, other alluvial rivers in the Southwest have reaches which would be suitable sites for slackwater analysis. Such reaches should be sought out in order to further expand the use of the slackwater method to supplement historic and stream-gage records.

CONCLUSION

Analysis of slackwater sediments and HEC-II modelling of prehistoric flooding places recent flooding on the Salt River near Phoenix, Arizona into perspective. While the timing of several large-magnitude floods within the short time span of 1978-1980 may be somewhat unusual, neither the magnitude nor the overall frequency of such floods is rare in any sense. Slackwater analysis of sediments from the past 1100 years reveals that at least 27 floods overtopped the banks of the Salt River in Tempe. Two of these floods exceeded 420,000 cfs (11,900 cms). Much worse flooding than that recently experienced can and has happened within the geologically recent past.

The Salt River near Phoenix provides an opportunity for a new application of the slackwater technique. While the technique is not easily applied to alluvial rivers, several factors provide the stability and information needed to use the method successfully. Historical, archaeological, and geological data were used as input for reconstructing paleodischarges in the study area.

Geological analysis of the flood record combined with modern gage information provides the most balanced approach for predicting potential flood peaks. Extension of the flood record reduces statistical skewness caused by inclusion of outlying large events, decreases the probability of non-stationarity, and does not rely on climatologically improbable rainfall-runoff models. Slackwater sediments represent a source of flood information which should not be ignored.

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