ELSEVIER

Geomorphology 19 (1997) 203–226

GEOMORPHOLOGY

Extracting Holocene paleohydrology and paleoclimatology information from modern extreme flood events: An example from southern California

Yehouda Enzel [a,*], Stephen G. Wells [b]

[a] *Institute of Earth Sciences and Department of Geography, Hebrew University, Givat Ram, Jerusalem 91904, Israel*
[b] *Quaternary Sciences Center, Desert Research Institute, P.O. Box 60220, Reno, NV 89506-0220, USA*

Revised 18 September 1996; accepted 2 October 1996

Abstract

The extraction of paleohydrological and paleoclimatological information from a modern hydrological system, shown to represent unique and extreme hydroclimatological conditions, is illustrated by an example from the Mojave River drainage basin in southern California. The Mojave River allows only the most extreme floods to reach its terminal basin in the Silver Lake playa and to form ephemeral lakes. All the other floods are lost by transmission into the alluvial aquifer along its 200 km channel. This filtering out of regular floods by the river provides an essential tool in establishing a physical link between atmospheric and hydrologic conditions. We demonstrate such a link between anomalous, present-day atmospheric circulation patterns over the North Pacific Ocean, extreme storms in southern California that produced the heaviest precipitation on record, the largest floods of record in the Mojave River watershed, and ephemeral lakes in its terminal playa. This physical link determines the possible cause of the formations of perennial, short-duration, shallow lakes in Silver Lake playa during the late Holocene and characterizes the hydroclimatic conditions that prevailed during these lacustrine episodes. Hydrological simulations of this river and its filtering character demonstrate that these lakes could have formed only if the most extreme modern storms and floods were more frequent in at least an order of magnitude during specific time episodes. We conclude that such extreme hydroclimatic conditions occurred more frequent in past episodes during which the Holocene lakes formed. In turn, this conclusion indicates that the cause of these storms and floods, i.e. the anomalous atmospheric circulation pattern, must have been more frequent. This research outlines a way to extract information on Holocene climates in hydrologic settings that demonstrate a unique cause and effect relationship. © 1997 Elsevier Science B.V.

Keywords: Holocene; paleohydrology; floods; Mojave Desert; hydroclimatology

1. Introduction

Paleohydrology of lakes provides insights into paleoclimatic conditions through the identification of patterns in local and regional lake-level fluctuations (Bradley, 1985). It is also a useful tool in connecting observed geomorphic responses and regional paleoclimatic conditions of similar temporal resolution. Accurate paleoclimate reconstructions based upon lake-level fluctuations require a clear relationship between the climatic conditions and at least one of

---

[*] Corresponding author. Tel.: +972 (2) 658-4210; Fax: +972 (2) 566-2581; E-mail: yenzel@vms.huji.ac.il

0169-555X/97/$17.00
PII S0169-555X(97)00015-9

the components of the lacustrine hydrological cycle. A physical link must be established between the cause (the climatic conditions), and the response of the hydrological system, through paleoclimatic parameters (such as temperature, evaporation, precipitation, runoff, snow melt) that can be reliably inferred from sediments (Anderson, 1986; Wohl and Enzel, 1995; Baker et al., 1995). The common inference of the paleoclimate from paleohydrology is usually the most problematic stage.

Evidence for the occurrence of shallow, short-duration, middle to late Holocene lakes in the terminal playas of the Mojave River in southern California (Fig. 1) is presented. Then we analyze and model the hydrology of the river and the playa/lake and reveal the anomalous synoptic climatology which causes regional extreme storms. These analyses direct us to the essential physical link between the observed geomorphic and geologic data, fluvial and lacustrine hydrological processes, and the possible climatic forcing conditions. Through the analyses and understanding of basin and regional hydroclimatology we determine the nature of the hydroclimatic change that must have occurred in the region to produce these lakes and geomorphic responses in a wide range of environments in the region. This methodology extracts climatic data from extreme events and can be used elsewhere, especially in hydrologic systems which are sensitive to unique hydroclimatology (see also Enzel et al., 1989; Ely et al., 1993a).

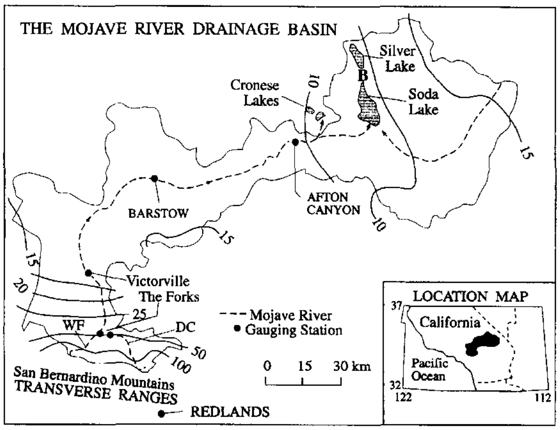

Fig. 1. Map showing the Mojave River drainage basin and average annual rainfall in cm (modified from Enzel, 1990, 1992). *B* = Town of Baker, California. Deep Creek (*DC*) and West Fork Mojave River (*WF*) form the headwaters of the river, joining at The Forks.

2. Regional setting and climatic conditions

The Mojave River heads on the northern flanks of the San Bernardino Mountains in southern California (Fig. 1). During large floods, the river flows from the headwaters about 200 km downstream without additional tributaries, across the Mojave Desert to Silver Lake playa (Fig. 1), the latest Pleistocene to present-day terminus (Wells et al., 1989; Enzel et al., 1992). The climatic conditions of the region consist of relatively hot, dry summers and a winter precipitation maximum with a weak but distinct secondary rainfall maximum from local summer storms in the area downstream of Barstow (Fig. 1; Enzel, 1990). The precipitation in the headwaters exceeds 1000 mm/year but, 90% of the watershed area draining into Silver Lake playa (total of 9500 km^2) typically receives 150 mm/year or less. The playa area itself receives about 75 mm rainfall per year (Fig. 1; Enzel, 1990). The lack of rainfall in the lower portion of the watershed is associated with very high temperatures and potential lake evaporation rates (> 2000 mm/year; Blaney, 1957). These hot, dry conditions form one of the most arid environments in North America.

In these terminal playas, the remnants of the Pleistocene and early Holocene Lake Mojave (Thompson, 1921, 1929; Antevs, 1937; Muessig et al., 1957; Ore and Warren, 1971; Wells et al., 1987, 1989), we identified middle and late Holocene lakes as well as historical ephemeral lakes, which lasted for various durations and had various depths. Understanding the hydrological processes of each of these different types of lakes assists us in interpreting the paleohydrology and paleoclimatology of the region.

3. Holocene lakes

Two types of geological evidence support the existence of late Holocene lake stands in the hyperarid Silver Lake playa (Fig. 2). One type is preserved in the stratigraphy of the shore environment and is most complete at the northern end of the playa (Fig. 3), and the other type is in lacustrine deposits from drilled cores and a pit near the southern end of the playa (Fig. 4). We cannot provide direct evidence that these shore and lacustrine sediments were deposited by the same lake stand.

3.1. Holocene beach complex

A sequence of five beach ridges exists at the northern edge of Silver Lake playa (Ore and Warren, 1971; Wells et al., 1989; Enzel et al., 1992; Figs. 2 and 3). The highest three beach ridges (morphostratigraphic units BR-I, BR-II, and BR-III in Fig. 3) all exhibit a well-developed stone pavement overlying an early to middle Holocene eolian unit which is approximately 1 m thick (Wells et al., 1987, 1989; Enzel et al., 1992; McFadden et al., 1992). Radiocarbon dates on shells (*Anadonta californesis*) from the northern beach complex (Fig. 3) (Ore and Warren, 1971; Wells et al., 1989; Enzel et al., 1992) become progressively older with increasing height and distance from the playa. The upper three ridges contain shells dated from 13,640 ± 120 yr B.P. (Beta-26456) to 10,330 ± 120 yr B.P. (Beta-21200).

The lowest two beach ridges lack the early to middle Holocene eolian mantle (McFadden et al., 1992). Pelecypod shells from the near-shore equivalent of the older beach ridges underneath BR IV and BR V provide a maximum age for the two lowest beach ridges and a minimum age of about 9300 yr B.P. for the earliest Holocene lake (Enzel et al., 1992; McFadden et al., 1992).

Beach features covered by the eolian unit are older than lower beach features which lack this unit. The source for the eolian sediments was the playa

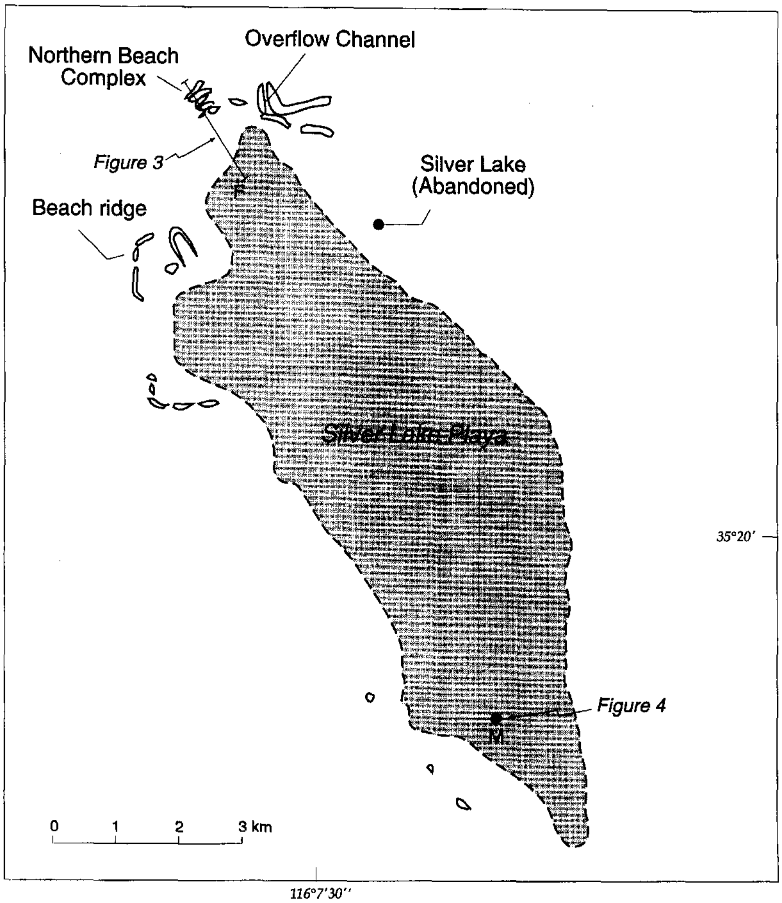

Fig. 2. Selected late Quaternary shoreline features surrounding Silver Lake playa, location of drill holes, and soil and topographic profiles discussed in text.

itself (Wells et al., 1987), and implies that the eolian event occurred after about 8500 yr B.P., when the lake dried (Ore and Warren, 1971; Wells et al., 1987, 1989). Thus, the two lower beach ridges formed after the middle Holocene eolian event that covered the upper three beach ridges with sandy deposits. McFadden et al. (1992) concluded that the soils on these lower two beach ridges are middle to late Holocene in age. These age estimations of the BR IV and BR V morphostratigraphic units were the first indication of lake stands, in the Silver Lake playa that postdate 8000 yr B.P.

3.2. Evidence from the playa / lake environment

Two 6.4 m cores (SIL-M and SIL-N) were drilled in the southern end of Silver Lake playa 1 m apart. A pit was dug to a depth of 1.6 m about 10 m away from the cores. All are marked as site SIL-M in Fig. 2. The composite lithology and the interpreted depositional environments are presented in Fig. 4. Wells et al. (1989) summarized the sedimentologic characteristics of the upper 2 m recovered from the cores and exposed at the pit.

The deposits recovered from site SIL-M are divided into three zones (Fig. 4). Zones 1 and 2 correspond to earlier phases of the lake and Zone 3, which is the main interest of this study, comprises the upper half of the cores. In addition to massive, oxidized brown silt, sand, and clay playa deposits, Zone 3 contains a few beds with tens to hundreds of very fine, millimeter-scale, laminated couplets. The couplets differ slightly from bed to bed. The sedimentologic characteristics indicate a shallow lacustrine depositional environment with estimated water depth of only a few meters. Five such thin lacustrine sequences occur within the upper 2.2 m of the cores. The uppermost one and the third one from the top (Fig. 4) contain *Phacotus* (J.P. Bradbury, pers. commun., 1988), which supports the lacustrine origin of these type of deposits; the other sequences were not analyzed. The thickness and sedimentologic characteristics of the deposits indicate that several Holocene lacustrine episodes in Silver Lake playa lasted from several years to decades. It is impossible to determine the precise duration of these episodes. For comparison, modern ephemeral lakes in Silver Lake playa that lasted up to 18 months (see below) were

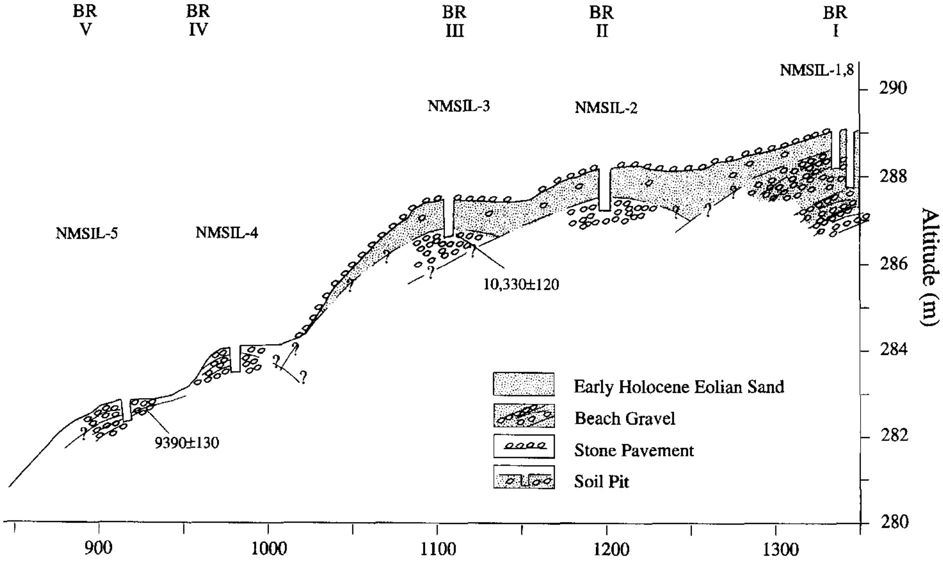

Fig. 3. Schematic cross section illustrating the topography, soil–geomorphic relations, and position of radiocarbon dates in the northern beach complex (see Fig. 2) in Silver Lake playa. *NMSIL* = location of soil pits (McFadden et al., 1992) on top of beach ridges (morphostratigraphic units *BR-I* to *BR-V*). Present-day playa elevation is 275.5 m (modified from Enzel et al., 1992).

not able to produce enough lacustrine deposits to be preserved in the sedimentologic record. These deposits were incorporated into the homogeneous, shrinking-and-swelling playa deposits within a very short time since their deposition and left no indication about the occurrence of the ephemeral lakes. Therefore, we think that thicker deposits which survived the processes of the playa that are able to destroy the primary sedimentary structure represent longer duration of lake stands.

Organic matter in the bulk samples from the two uppermost lacustrine deposits are dated to 390 ± 90 yr B.P. (Beta-25634) and 3620 ± 70 yr B.P. (Beta-25341 and ETH-3989). These dates probably represent the mean ages of the deposition of these units and are essentially identical to the dates presented by Drover (1978) from the Cronese Lake playas, two small terminal playas which receive naturally diverted water from the Mojave River (Fig. 1). The lake episode at about 3620 ± 70 yr B.P. was apparently of longer duration than any of the other Holocene lake stands.

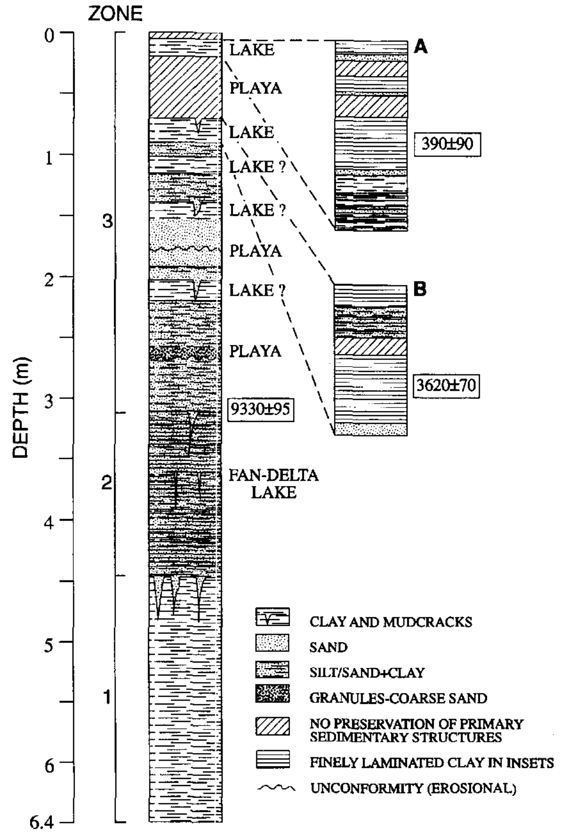

Fig. 4. Composite lithology and depositional environments of sediments recovered in cores SIL-M and SIL-N. Note the enlargement *A* and *B* of the complexes of the two youngest lake deposits.

3.3. *Geometry of the Holocene lakes*

We emphasize that the lakes that occupied the basin during these episodes were much shallower and shorter lived than the earlier, Late Pleistocene to early Holocene phases of Lake Mojave. This conclusion is based on detailed study of the thickness and other characteristics of the Late Pleistocene and the Holocene lacustrine deposits and sedimentation during and since Lake Mojave (Wells et al., 1989). The large reduction in volume/area ratio between Lake Mojave conditions and the late Holocene lakes increases the sensitivity of the more recent lakes to evaporation (Fig. 5; Enzel, 1990, 1992; Enzel et al., 1992). The smaller the ratio, the larger the evaporative area relative to the volume. The late Holocene curves (Fig. 5) indicate that at a water-surface elevation of about 282 m, a one- to two-meter increase in elevation causes a doubling of the lake surface area and thus increases the water volume that can be evaporated. This geometric buffering on the water accumulation may have prohibited the Holocene lakes from rising above the observed elevations of the Holocene beach ridges (below 284 m; Fig. 5). Field observations indicate that overflow at the north end of Silver Lake playa (Fig. 2) did not occur during the middle to late Holocene and support the idea that the geometric configuration of the lake basin limits the amplitude of the minor lake-level fluctuations during the Holocene in Silver Lake playa. The inability of the Holocene lakes to overcome such a small geometric control implies that the formation of the Holocene lakes in Silver Lake playa reflects the minimum change needed to fill the earlier, larger and deeper pluvial Lake Mojave.

What could have caused these shallow lakes in the Mojave River terminus only a few centuries ago and even a few thousands years ago when the assumption can be made that the physiography is not much different than that of the present-day? This question is emphasized when the present-day arid climatic conditions at the terminal playa are considered. What is the magnitude of change in the Mojave River hydrology and regional climatology needed to produce the late Holocene lakes? In the next part we characterize the present-day hydrology of the basin and later we use it as a basis for hydrologic modeling in an effort to answer these questions.

Storage capacity, areal extent, and depth of the late Holocene lake are needed for paleohydrological calculations (see below) and they are derived from the geologic and geomorphologic evidence (Enzel et al., 1992; Enzel, 1992). The lacustrine and beach deposits from Silver Lake playa, which were discussed above, provide information on the possible minimum and maximum depths of the late Holocene lake (Enzel, 1992). The volume of water stored was estimated by determining the boundary conditions

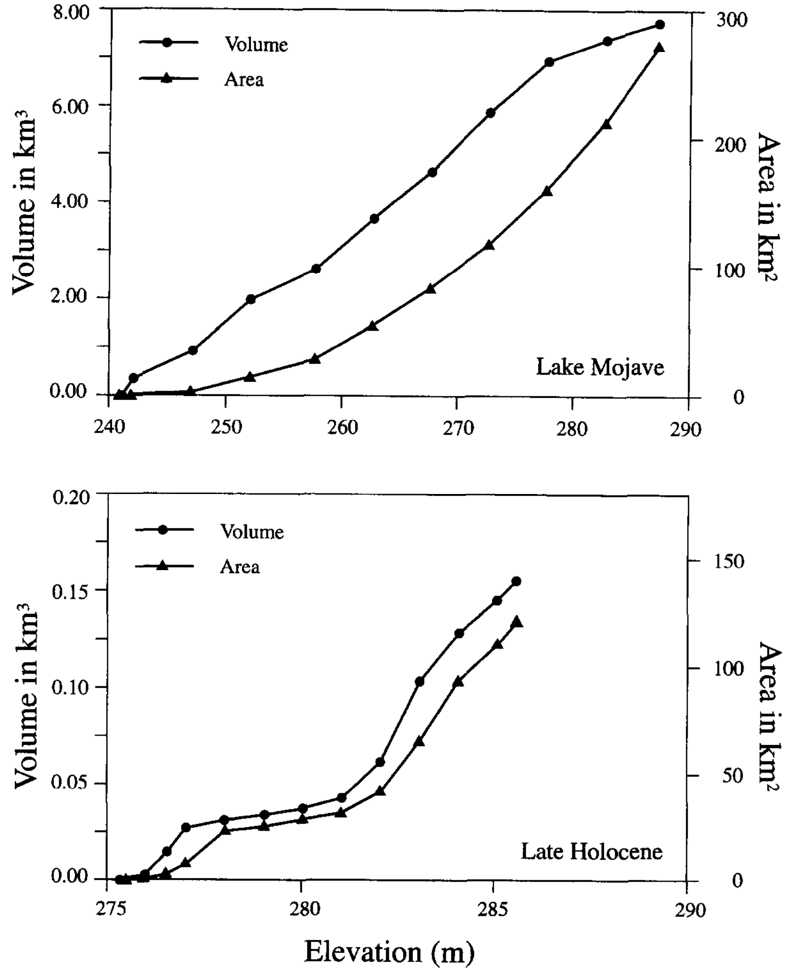

Fig. 5. Lake elevation (m) versus lake volume (km^3) and lake surface area (km^2) during the youngest, latest Holocene lake and the earliest phase (approximately 22,000 yr B.P.; Wells et al., 1989) of pluvial Lake Mojave. A relatively small volume is needed to bring the lake to elevation of 282 m during the youngest lake stand. Increases in volume and surface area are not associated with a substantial change in water-surface elevation between 282 and 284 m, making the youngest configuration of the lake very sensitive to evaporation at that range of elevation. The present-day overflow spillway is at an elevation of 285.5 m but probably was not reached during the middle and late Holocene.

for the depth of the lake and using the constructed area–volume–elevation curves (Fig. 5).

4. The basin hydrology and historical lakes

4.1. The hydrologic record

Annual discharge records (Fig. 6) demonstrate that a large amount of water is lost along the Mojave River and that significant flow reaches Afton Canyon (Fig. 1) only during those years with large discharge at The Forks. A similar pattern is evident from seasonal and single flood hydrographs (Fig. 7). It is also evident from the data that the extreme 'wettest' seasons in the record, such as the winters of 1969 and 1978 (Figs. 6 and 7), are comprised of distinct individual heavy storms and extreme floods. Hydrological and historical records indicate that significant stream flow is recorded in the Afton station only during extreme floods, and this flow has reached Silver Lake playa and produced ephemeral lakes during only 8 years between 1894 and 1990 (Table 1, Figs. 8 and 9; Enzel, 1990). Virtually all of the discharge in these events originated in the headwaters, and most of it was lost through infiltration along the river bed (e.g., Fig. 7; Hardt, 1969; Buono and Lang, 1980; Mojave Water Agency, 1982; Enzel et al., 1989; Enzel, 1990). The floods that reached the playa and produced ephemeral lakes were the result of very large storms (Fig. 10). Several of the rainfall amounts and intensities recorded in these storms were (a) the largest recorded in California, (b) lasted up to two days, and (c) occurred only during the winter (Fig. 11). The same storms produced an order of magnitude less rainfall in most of the area downstream of the Forks. It seems that only flood events with high peak discharge at The Forks are able to exceed the loss by infiltration along the river and to reach Afton Canyon. Larger floods in The Forks (> 500 m^3 s^{-1}; Table 1; Enzel et al., 1989) are needed to continue further downstream and to reach Silver Lake playa. The filtering of small and medium floods and reaching of only the largest floods to the playa, the 'recorder' of rare events, suggest a mechanism which explains the cause of a past lake in the terminal basin.

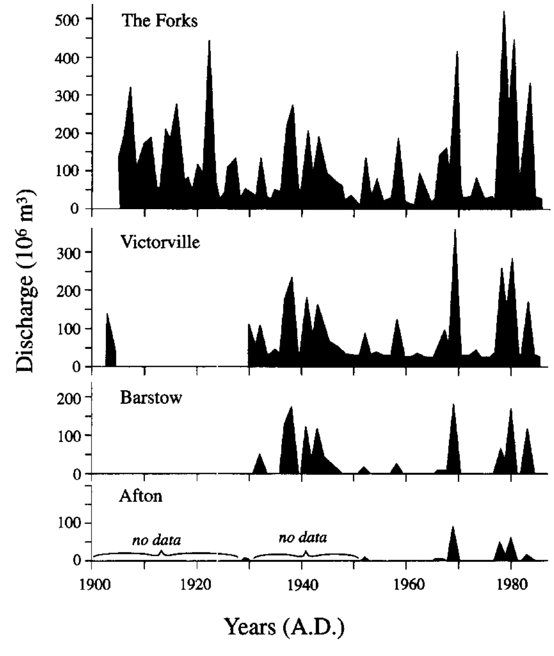

Fig. 6. Annual discharge in downstream direction (from top to bottom): The Forks (1905–1985)—the combined discharge of Deep Creek and West Fork (Fig. 1); Lower Narrows near Victorville (1903–1904 and 1929–1985); Barstow (1930–1985); Afton (1930–1931 and 1952–1985).

From a hydrologic modeling point of view the configuration of the separated headwaters, channel, and terminus portions allows for the relatively simple simulation of the Mojave River hydrological system (Fig. 12). The availability of detailed hydrologic and historical records of rainfall, stream flow, lake-building floods, and ephemeral lakes makes it possible to quantify this hydrologic system.

4.2. The underlying concepts of the simulation

Three major components are used in the simulation of the Mojave River hydrological system (Fig. 12): (a) the source of the floods, consisting of Deep Creek and the West Fork at the headwaters of the Mojave River; (b) the long channel of the Mojave River downstream of The Forks, where discharge is lost by infiltration and there is no addition of tributaries; and (c) the sink, which under modern and late Holocene conditions consists of the Silver Lake playa.

Storm precipitation over the headwaters is transformed in the simulation into a flood hydrograph at

The Forks. The flood is routed along the Mojave River channel, through Victorville and Barstow, to Afton (Enzel, 1990, 1992). Daily and hourly precipitation data (e.g., Fig. 10) of the largest storms in the Mojave River headwaters were analyzed to construct a 24-h unit hydrograph (e.g., Bedient and Huber, 1988) at The Forks. A 24-h unit hydrograph was selected because all available rainfall and stream flow data of the storms that reached the playas show a common duration of 12–36 h (Fig. 11).

The storm hydrographs at the Afton gauging station were used to estimate the discharge input into the playa. The volume of water in the Silver Lake playa during historical lakes is the only available data related to flood waters downstream of Afton. The volumes of the historical lakes are estimated from the known depth and constructed curves of volume and surface area versus elevation (Fig. 5) and are used to estimate the discharge loss between Afton Canyon and Silver Lake playa (Enzel, 1990).

The procedure for the water balance of the lake was modified for this specific hydrological basin from a computerized procedure written by M.T. Gerety (R.Y. Anderson, written commun., 1989).

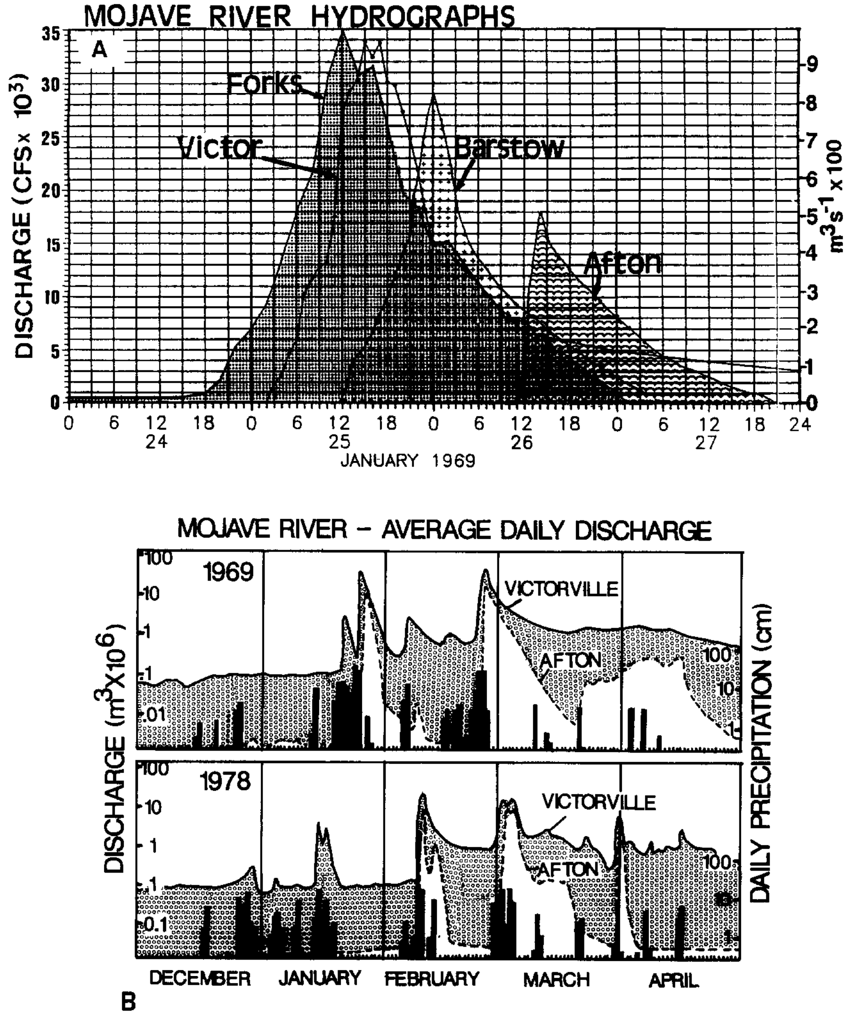

Fig. 7. (A) Storm hydrographs for the January 24–27, 1969 flood as recorded in four locations along the Mojave River (see Fig. 1). (B) Average daily discharge during December–April 1968–1969 (upper) and 1977–1978 (lower) for Victorville (solid line) and Afton (dashed line) in response to daily precipitation (solid bars) in the San Bernardino Mountains (modified from Buono and Lang, 1980).

Table 1

Headwaters and lower basin monthly precipitation and magnitude and discharge of Mojave River floods associated with documented historical lakes in Silver Lake playa [a]

Date	Peak discharge [b]	Average daily flow [c]	Precipitation [d]		Lake	
	(m^3 s^{-1})	(m^3 s^{-1})	A (cm)	B (cm)	depth [e] (m)	duration (months)
31/12/1909	1745 (F)		46.9		> 1	> 6
	1073 (D)	19.4 (D)				
18/01/1916	$\sim$ 1010 (F)		127.7		2.5–3.2	18
	651 (D)	51.8 (D)				
21/12/1922	880 (F)	23.9 (D)	77.9		2	?
03/03/1938	$\sim$ 1000 (A)		73.7		2.7–3.2	18
	1821 (B)	55.6 (B)				
	2060 (F)					
	1320 (D)	42.8 (D)				
25/01/1969	510 (A)	9.8 (A)	87.3	3.0		
	840 (B)	21.2 (B)				
	1025 (F)					
	651 (D)	33.1 (D)				
25/02/1969	500 (A)	20.0 (A)	76.5	3.0	2.2–2.5 [f]	< 12
		36.4 (B)				
	$\sim$ 1000 (D)	33.4 (D)				
03/03/1978	395 (A)	11.8 (A)	70.1	2.6	< 1	> 2
	290 (B)?	14.2 (B)				
	702 (D)	43.6 (D)				
17/02/1980	93 (A)?	3.9 (A)?	61.6	4.6	< 1	> 2
	323 (B)	45.0 (B)				
	464 (D)	47.7 (D)				
02/03/1983	152 (A)	5.6 (A)	34.8	6.6	< 1	$\sim$ 3
	348 (B)	35.8 (B)				
	470 (D)	29.5 (D)				
22/01/1862 [g]	$\sim$ 4100 (F)					
xx/12/1867 [g]	$\sim$ 2210 (F)					
07/03/1884 [g]	$\sim$ 1130 (F)					
23/02/1891 [g]	$\sim$ 2120 (F)					

[a] See Wells et al. (1989) and Enzel (1990) for sources of data.

[b] A = Afton, B = Barstow, F = The Forks, D = Deep Creek (see Fig. 1).

[c] Discharge during the month of lake-producing flood.

[d] Precipitation during month of lake-producing flood; A = either at Lake Arrowhead or at Squirrel Inn No. 2, two stations at the Mojave River headwaters with $R^2 = 0.96$ and average annual precipitation of 109.1 cm; B = at Baker station with average annual of 7.8 cm (see Fig. 1).

[e] Not all observations were made relative to the topographically lowest point.

[f] The lake is the outcome of both the January and the February floods.

[g] A possible lake. No evidence except the relatively large peak discharge.

The calculations are based upon the hydrological balance of the lake (e.g., Smith and Anderson, 1982; Smith and Street-Perrott, 1983; Bradley, 1985; Allen and Anderson, 1993; Wohl and Enzel, 1995), which in this study, as the result of the specific characteristics of the Mojave River, also includes an input of flood discharge.

Local runoff from rainfall around the playa does not usually reach the playa; when it does, the water evaporates within a day. This and other supportive evidence listed by Enzel (1990) imply only a small percentage of the rainfall over the area draining directly into the playa. In the simulation, a value of up to 2% of the rainfall over the lower Mojave River watershed is used as the local runoff input to the playa. Even when a larger percentage of runoff is used with twice the modern precipitation, the local runoff is a relatively insignificant input when compared with the precipitation in the headwaters and the resulting flood discharge of the Mojave River. The rainfall data for Baker, California (75 mm/year), at the southern end of Silver Lake playa (Fig. 1, Table 1) are taken to represent the local rainfall although Baker is situated at a low elevation relative to the entire lower Mojave River basin. The local precipitation was separated into winter and summer seasons (Enzel, 1990). Similar values for the annual, winter, and summer rainfall are used for the direct rainfall on the playa/lake itself. This rainfall will evaporate when it falls on a simulated dry playa and will contribute to the depth of an existing lake.

Little is known about the subsurface components of the hydrological balance. Blaney (1957) concluded that during the formation of the 1938 ephemeral lake (the largest in the historical record) in Silver Lake playa; however, all of the loss was from evaporation and not through infiltration into the playa bed. Furthermore, the lake dried out at a rate similar to other modern evaporation rates (after correction for pan evaporation) in the Mojave Desert,

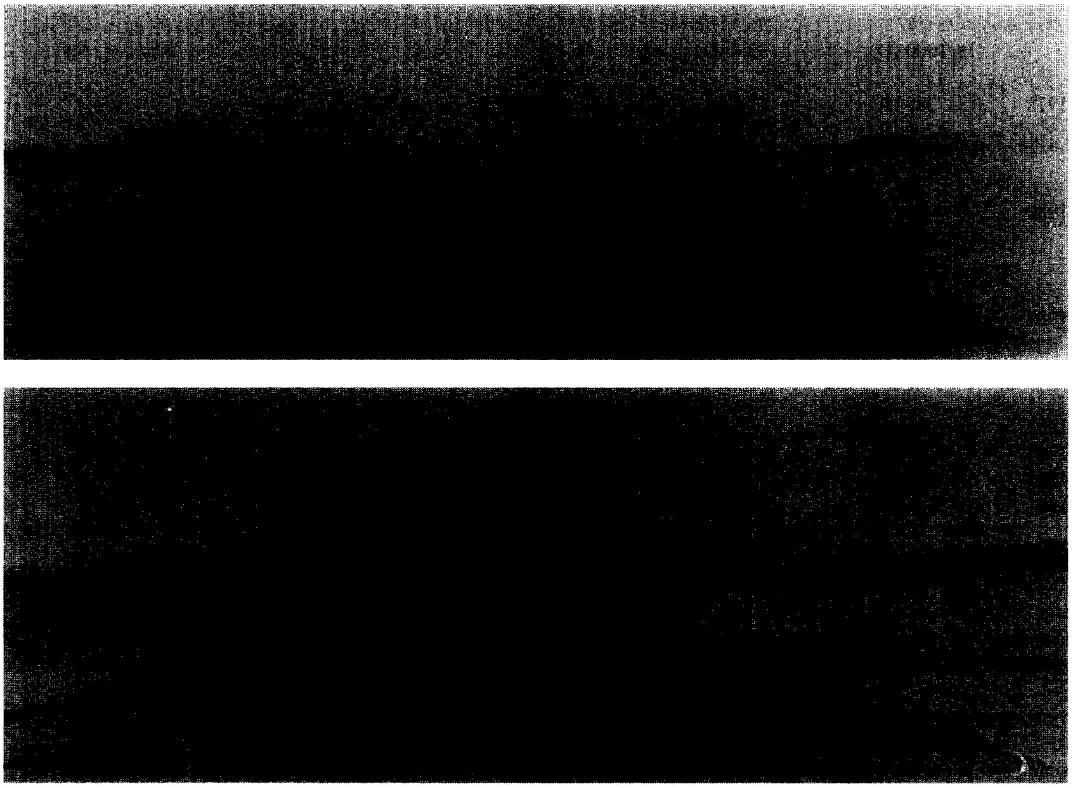

Fig. 8. The lake of January 1916 covered Silver Lake playa, Silver Lake town, and the T&T railroad. In the reference to this photograph, Myrick (1963) noted that this was the second time the railroad was flooded in this playa since its construction in 1906; the other year was 1910. The two photographs were taken about six months apart and the water depth is different. (W.C. Hendrick Collection.)

indicating no additional water input to or output from the playa. This and other evidence reviewed by Enzel (1990) indicate that the subsurface components are not necessary for the simulation of a short-duration shallow lake. The simulation presented here is, therefore, not applicable for the Late Pleistocene hydrologic conditions. The measurements by Blaney (1957) of the 1938 lake provide an unusually rare type of evaporation data, and are valuable in any water-balance calculation. Incremental reductions in lake evaporation, starting with his measured values of 1400 mm for summer and 630 mm for winter (Blaney, 1957), were used in this simulation.

4.3. Simulation results and present-day flood frequency

In the simulation, the storm precipitation input to the headwaters is transformed into a flood hydrograph and routed to the terminal playas. During each winter season, a few storms, each with a different duration and intensity, can be simulated. The combined discharge from all of these floods is the water input to the lake/playa. The water balance is calculated for the terminal lake. If water is left in the lake at the end of the summer, subsequent floods during the following winter will increase the depth and areal extent of the lake. In turn, this will increase the evaporative area and the area for direct rainfall. A lake which after 5 to 10 years reaches a depth between the minimum and maximum bounds previ-

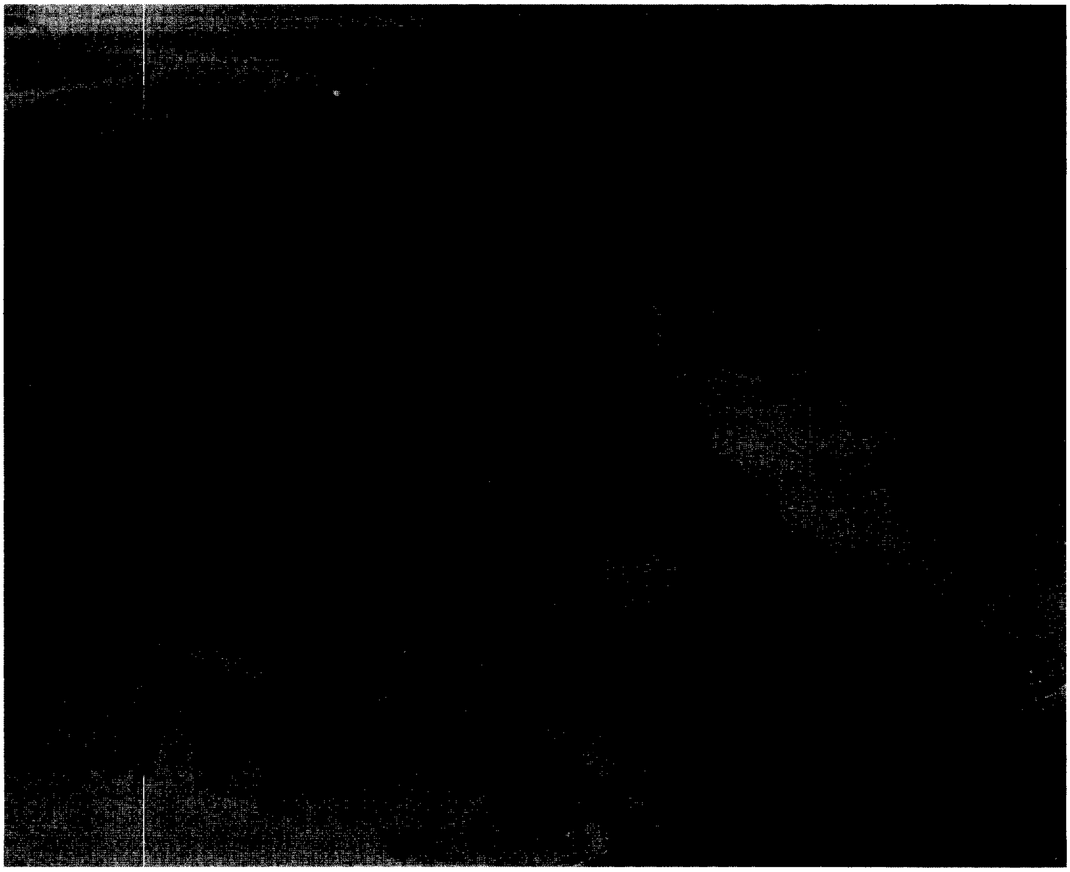

Fig. 9. The Silver Lake playa flooded after the March 1938 flood. The water backfilled into the northern portion of Soda Lake playa but did not reach to the prehistorical shorelines (photo by Spence Air Photos, courtesy of Department of Geography, University of California, Los Angeles).

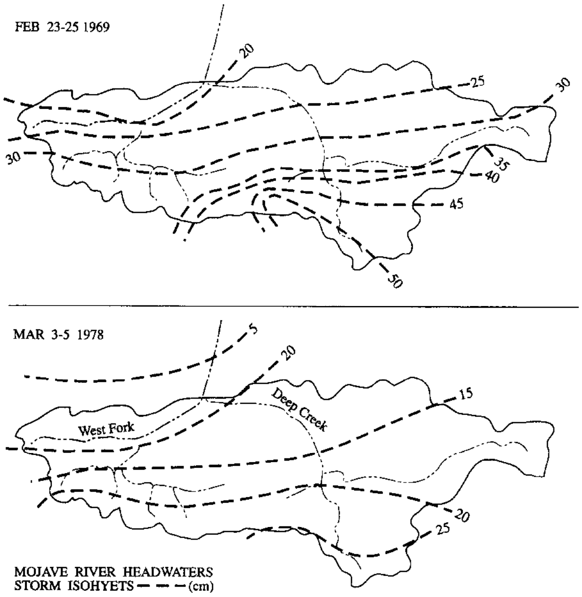

Fig. 10. Isohyetal maps (precipitation expressed in cm) for 1969 and 1978 storms in the Mojave River headwaters (see Fig. 1).

ously discussed indicates a combination of hydrologic conditions under which the late Holocene lake could have formed.

The simulated conditions included (in different runs): (a) one to five storms per year with storm precipitation incrementally increased over the head-

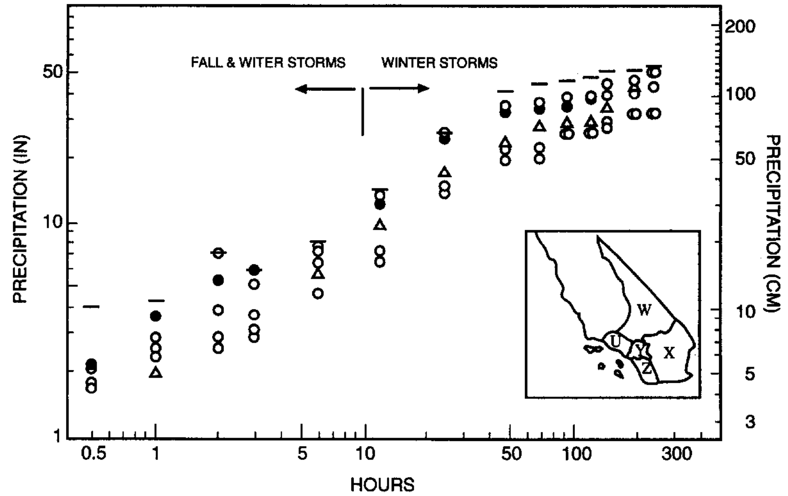

Fig. 11. Maximum precipitation recorded in southern California hydrographic regions (*U*, *W*, *X*, *Y*, and *Z* in inset map) over time intervals from 0.5 h to 10 days (240 h). The specific markers are: dash, the maximum precipitation recorded anywhere in California; solid circle, when the maximum precipitation event in region Y occurred in the Santa Ana headwaters (the Santa Ana River shares a waterdivide with the headwaters of the Mojave River); triangle, when the maximum precipitation event in region W occurred in the Mojave River headwaters. Regions are drainage provinces as defined by Department of Water Resources (1980a,b). *U* = Los Angeles, *W* = South Lahontan (southern Great Basin), *X* = Colorado River and Salton Sea, *Y* = Santa Ana, *Z* = San Diego. All maximum values for rainfall duration above 3 h in the Great Basin are from the Mojave River headwaters. All the data points for time intervals greater than 6 h from regions W and Y are from the high elevations of San Bernardino Mountains and occurred during the winters of 1969, 1938, 1916, and 1891. Based on data from Visher (1941); Department of Water Resources (1976, 1980a,b, 1981); Goodridge (1986).

waters; (b) winter and summer evaporation separately and incrementally reduced to 50% of the modern values; and (c) winter and summer precipitation incrementally increased over the playa region up to 200 mm/year (> 200% of modern values), which is probably a large overestimation for the late Holocene rainfall. The results indicate that even if the modern precipitation is doubled, the contribution from the direct rainfall and the runoff from the local rainfall to the formation of a lake are insignificant relative to the input from the Mojave River floods. When the cumulative flood discharge input produced a lake that exceeded the known maximum elevation of the beach ridges, the incremental increases of precipitation over the headwaters stopped. The depths of the Holocene lakes were such that even at the maximum, they would have dried out after 2 to 4 years of no flood input.

The results presented in Fig. 13 are of the simulation of the most simple combinations and include (a) one flood per year with the discharge increasing as the simulated rainfall over the headwaters was increased, (b) 100% to 50% of the modern evaporation from the lake, and (c) 25% increase above modern rainfall over the lower Mojave River watershed. Results of simulations of two and three events per year with a similar range of local precipitation and evaporation are tabulated in Enzel (1990, appendix M). The geometric body in Fig. 13 envelopes all the combinations of the simulated hydrological conditions listed above under which a perennial lake within the geological and physical boundary conditions of the late Holocene lake would form. Changes in the simulated hydrological conditions will only slightly shift the surfaces of the geometric body.

The combinations of hydrologic conditions presented in Fig. 13 show that a large discharge from the Mojave River into the playa is a prerequisite for the formation of the lake, and that no lake would form solely from a reduction in evaporation. The minimum input of discharge needed annually to form and maintain even the shallowest lake is about 40 × 10^6 m^3. This discharge is equal to or greater than the total measured or estimated annual discharge recorded in the Afton station during most of the years with the largest floods; e.g., 1969 (two large floods), and 1978 (one large and three smaller floods). In the historical and systematic hydrological record, only the lakes formed by the March, 1938 flood (Hardt, 1969) and probably the January, 1916 flood were large enough to overcome the annual evaporation (Fig. 13) and persist for more than one year (Table 1), both in reality and in a two-year simulation. The two 1969 floods together did not produce a large enough volume of water to survive the summer evaporation (Fig. 13).

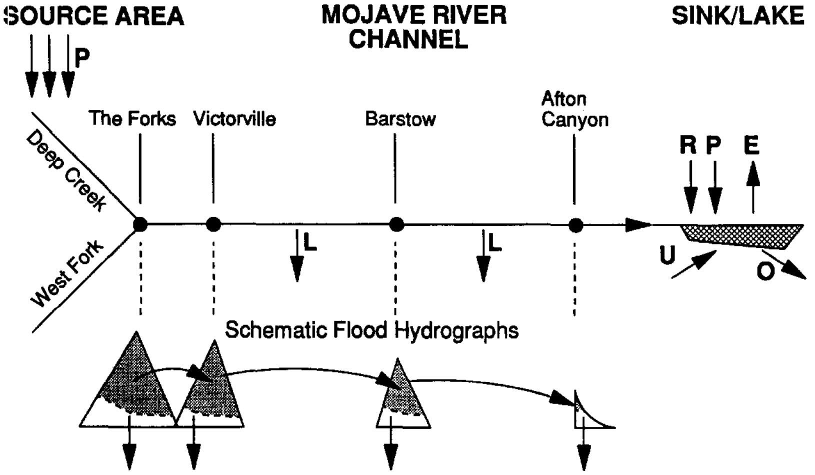

Fig. 12. Schematic diagram of the simulation model of the Mojave River hydrological system. L = discharge loss by infiltration along the Mojave River channel, E = evaporation, P = precipitation, R = local runoff. O and U represent the subsurface water output and input, respectively. The shaded portion of each hydrograph represents the discharge that reached a downstream reach after the losses (dashed and curved lines). From Enzel (1992).

The simulation results indicate that three to four floods per year with discharges similar to one of the 1969 floods are needed to produce a late Holocene lake which would stabilize within the observed range of depth. Smaller flows are not able to reach the playa. These results suggest that to produce a perennial lake during the late Holocene, a flood discharge of the magnitude of the two largest floods in the systematic hydrologic record must occur almost every year. A reduction in evaporation would not produce a lake in Silver Lake playa, and it only slightly shifts the boundaries of the zone that marks the possible combinations in Fig. 13. If the evaporation rate used in the simulation for either the winter or the summer is too low and if a lake already exists, a very slight increase in the flood discharge input will result in a lake that overtops the known maximum elevation. This implies that either floods much larger than the 1938 flood rarely occurred or that 50% reduction in evaporation during the lake episodes of the late Holocene is a large overestimation, or both. A reduction of 50% in the annual evaporation is greater than any value suggested even for the Late Pleistocene in the southwestern United States (e.g., a list by Smith and Street-Perrott, 1983). An annual discharge that is too great (> 175 × 10^6 m^3) produces a lake too deep for the geological evidence under all evaporation rates used, and indi-

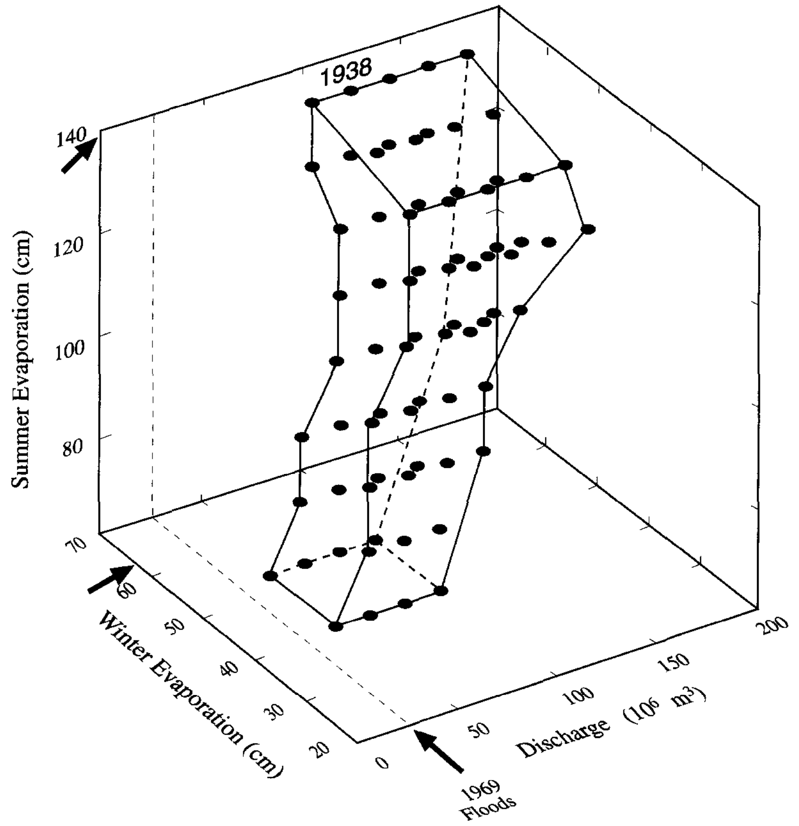

Fig. 13. Three-dimensional representation of the combination (dots) of hydrological conditions for the formation of a perennial lake in the simulation using one flood per year, a constant +25% increase in rainfall over the lower Mojave River watershed, and incremental increases in storm rainfall over the headwaters to determine the discharges (10^6 m^3) into the Silver Lake playa, and incremental and independent decreases in summer and winter evaporation rates (cm). The zone delineated by the dark solid lines in the middle of the diagram represents the hydroclimatic conditions that could have produced the late Holocene lake with the observed geological boundaries. Winter and summer evaporation rates were simulated within the range of 100% and 50% of modern evaporation (modern value from Blaney, 1957 are marked by thick arrows). *1938* = the conditions for the 1938 flood and lake—the largest modern gaged flood and a historical lake; *1969* = the total discharge of the January and February 1969 floods.

cates a possible upper bound to the floods during the late Holocene. Combinations of hydrological conditions marked in the upper, left, and back portion of the geometric body in Fig. 13 are, therefore, the most probable.

Flood frequency analyses performed on the annual series of peak discharges at two gaging stations along the Mojave River (R.H. Webb, written commun., 1989) indicate that the recurrence intervals of the 1969 and 1938 floods are > 30 years at Barstow and > 18 years on the West Fork (Enzel, 1992). Floods with smaller magnitudes than either the 1938 or the 1969 floods and that reached the terminal playas during the modern record have recurrence intervals greater than 8 years at all of the Mojave River gaging stations analyzed (Enzel, 1990). The simulation results which were presented earlier indicate a recurrence interval of 0.25 to 2 years for floods of this magnitude to produce and maintain the late Holocene lakes. This emphasizes that different hydroclimatic conditions prevailed in the Mojave River watershed during the formation of the late Holocene lakes.

The simulation of the Mojave River watershed hydrology indicates that only a persistent repetition of floods with the magnitude of the largest modern floods over a period of several years can form even a shallow lake in Silver Lake playa. Increased summer precipitation and reduced winter and/or summer evaporation could have played only a marginal role in the formation of these lakes. We conclude that the hydrologic processes that control the Mojave River indicate the nature of the change needed. A step further will lead to the conclusion that Holocene hydroclimatic conditions are characterized by an increased number of heavy storms and flooding during short episodes. As during historical times the effects of such storms cannot be limited to the Mojave River alone, but must be recorded in other basins and environments in southern California, in the Mojave Desert, and perhaps even outside of these regions.

5. Other evidence from the region

Evidence for more 'wet' conditions which were synchronous with the two most recent lakes in the Mojave River basin were identified by other researchers. Furthermore, the evidence does not contradict our inference that more frequent events with the magnitude of the modern extremes formed the average wetter conditions. Several observations support such characteristics of the paleoclimatic conditions.

In addition to evidence from glaciated areas in the western United States (e.g., Burke and Birkeland, 1983; Grove, 1988), the episode around 3620 ± 70 yr B.P. is reported also to affect non-glacial environments in the southwestern deserts of the United States. A 150-m lowering of the woodland boundary (Spaulding, 1985) and the only significant recharge into the groundwater aquifer since about 9000 yr B.P. (Benson and Klieforth, 1989) occurred in southwestern Nevada between 4000 and 3000 yr B.P. A 10-m deep lake probably occurred in Death Valley sometime between 4000 and 2000 yr B.P. (Hunt, 1975), and less arid conditions prevailed in Lucerne Valley in the western Mojave Desert sometime between 4300 and 1600 yr B.P (King, 1976).

Mehringer and Warren (1976) dated peat deposits and dune stabilization at 4000 to 3600 yr B.P. in Ash Meadows in the Amargosa Desert in southwestern Nevada. The dates of the peat deposits and dune stabilization correlates very well (Fig. 14) with the Silver Lake lacustrine episodes. More recently, Wintle et al. (1994) and Lancaster (1997) presents a chronology of variation in the stability of the Kelso Dunes, which are located only 25 km southeast of Soda Lake playa. It is hypothesized that the sand comprising these dunes is derived from the Mojave River (Sharp, 1966). The timing of the dune stabilization here is also in good agreement with the chronology of the lacustrine episodes in Silver Lake playa. In Searles Lake, an age of 3520 ± 190 yr B.P. was obtained from wood within deposits of a saline lake that rose about 45 m above the present-day playa (Smith, 1979). Other evidence from non-glacial environments for moister climatic conditions in the southwestern United States during that period includes: (a) a tree-line shift in the White Mountains of California between 3500 and 2500 yr B.P. (LaMarche, 1974); (b) a higher lake level in Mono Lake at about 3500 yr B.P. (Lajoie and Robinson, 1982 in Forester, 1987) with a high stand approximately 3770 calibrated yr B.P. (Stine, 1990); (c) increased debris flow activity in the San Gabriel

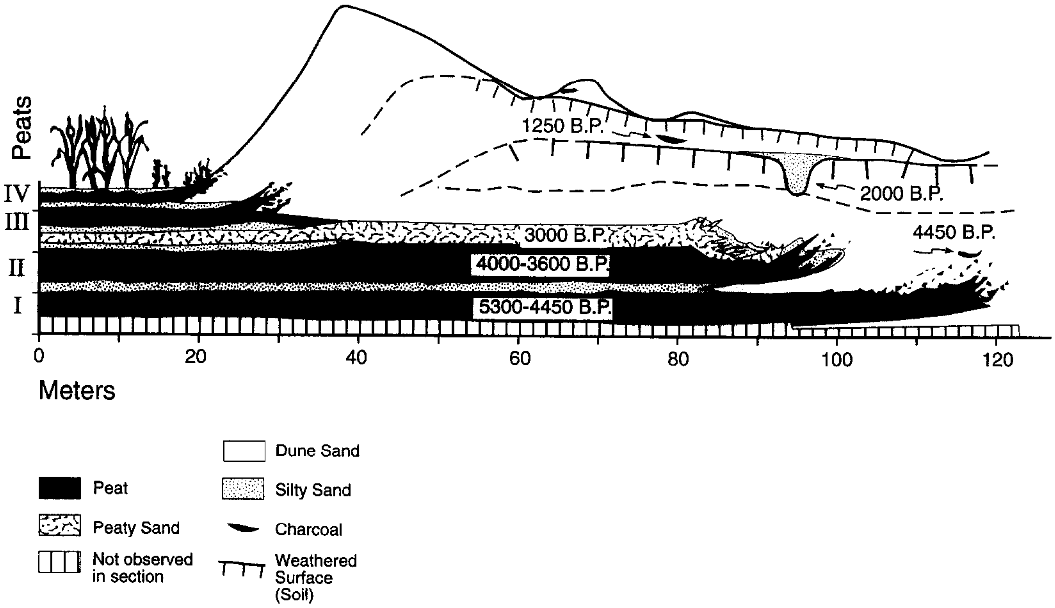

Fig. 14. Schematic representation of peat and dune deposits and the ages, Ash Meadow, Carson Slough, Nevada. Modified from Mehringer and Warren (1976). Remarkable agreement between the ages of the peat deposits and the ages of the lacustrine events in Silver Lake.

Mountains between 5000 and 3500 yr B.P. (R. Weldon, written commun., 1990); (d) a lacustral event in the Wilcox Playa in southeastern Arizona, sometime around 4000 to 3000 yr B.P. (Waters, 1989;, and (e) a brief period of fresh water evident from pollen assemblages in San Joaquin Marsh in Newport Bay, southern California (Davis, 1992). Wetter conditions also dominated the San Juan Basin in northwestern New Mexico (Wells et al., 1990).

Evidence from such diverse environments of wetter and stormier climatic conditions in the southwestern United States at 4000–3000 yr ago implies a change in the main features of the atmospheric circulation patterns. These patterns had to increase the moisture transported into the region and to produce heavy precipitation, compared to the present. Based on quantitative analysis of radiolaria in varved sediments in the Santa Barbara Basin, Pisias (1978) demonstrated increased winter sea-surface temperatures (SST) off the shore of southern and central California during the time of the wet climatic episode observed in the above continental records, implying different oceanic circulation in the eastern North Pacific. During modern times, such increased SST temperatures are associated with large precipitation events in southern California (Namias, 1980). Winter storms that affect southern California also affect other regions in the southwestern United States (Ely et al., 1993a). The clustering of paleofloods during such episodes is reported by Ely et al. (1993b) and Ely (1997). Thus, past climatic conditions that increased winter sea-surface temperatures off the shore of California may have also caused the observed wetter conditions in the southwestern United States.

Analyses of tree-ring data from southern and central California (e.g., Schulman, 1947; Michaelsen and Haston, 1988) indicate that more frequent wet conditions occurred in the late 1500s and early 1600s, at the same time that the youngest lake was maintained in Silver Lake basin. Further, when the 390 ± 90 yr B.P. date is calibrated and plotted on tree-ring chronologies from southern and central California, it is centered at the largest positive anomaly in the tree-ring width (Enzel, 1990; Graumlich, 1993). The high-frequency, high-magnitude annual precipitation and stream flows that Schulman (1947) and Michaelsen and Haston (1988) interpreted for that period in southern California support the inference of increased frequency of the high-magnitude runoff events during the youngest lake stand in Silver Lake playa. Reconstructions of North Pacific sea-level pressure from tree-ring chronologies (Fritts et al.,

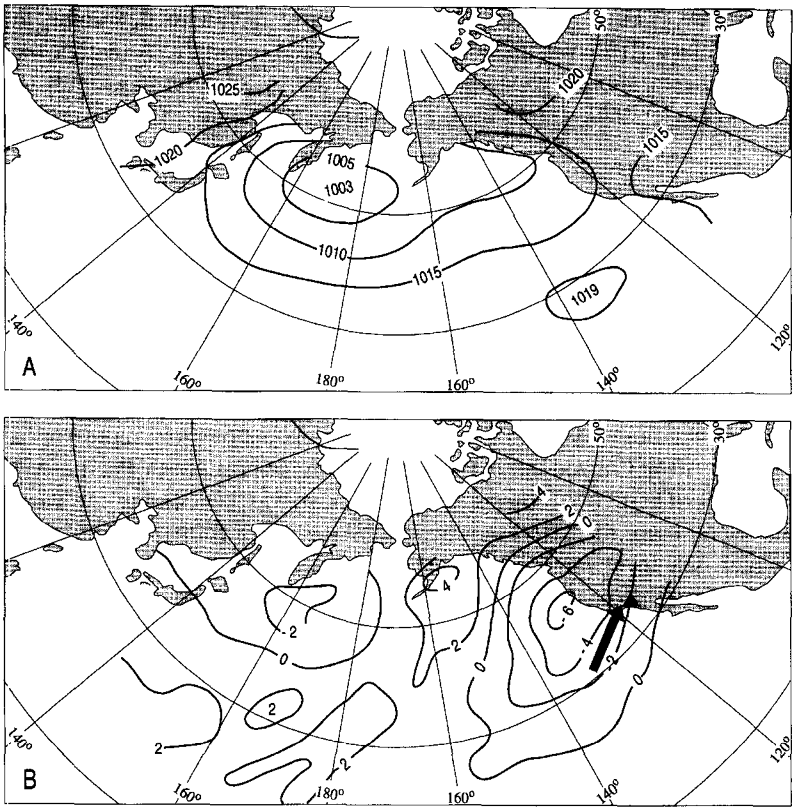

Fig. 15. Composite North Pacific sea-level pressure (A) and anomaly (B) for the eight months with lake-building events. ▲ = location of the San Bernardino Mountains. The arrow shows the anomalous component of the mean wind direction that results from the anomalous sea-level pressure. The enhanced southwesterly wind advects moist warm Pacific air over the San Bernardino Mountains and the negative pressure anomalies indicate the necessary vorticity for extreme precipitation events (from Enzel et al., 1989).

1979) show that the early 1600s had a high frequency of North Pacific sea-level pressure patterns that were similar to the 1978 winter sea-level pressure pattern. The winter of 1978 was one of the wettest in the instrumented record and produced some of the largest recorded floods in central and southern California and Arizona. Based on regional paleoflood records, Ely and Baker (1990) and Ely et al. (1993b) concluded that rivers in central Arizona and southern Utah experienced large floods between 1400 and 1600 A.D. At present, large floods on some of these rivers occur primarily during the winter (Ely et al., 1993a).

Other indications of the climatic patterns during that period that supported Holocene lakes include: (a) moraines in the Sierra Nevada from the early 1600s (Curry, 1971; Burke and Birkeland, 1983); (b) tree-line fluctuation in the White Mountains of eastern California (LaMarche, 1974); (c) episodes of marsh growth in Panamint Valley from 1550 to 1650 A.D. and peat in Ash Meadows at ~ 1550 A.D. (Fig. 14; Mehringer and Warren, 1976); (d) increased human occupation in Cronese Lake playas (Drover, 1978); (e) two high stands separated by a low stand in Mono Lake between about 500 and 300 calibrated yr B.P. (about 1450–1650 A.D.; Stine, 1990); and (f) a downward shift in vegetational communities between 1435 and 1795 A.D. in the northern Mojave Desert (Cole and Webb, 1985).

With the limitations of the age-dating techniques used, these observations indicate concurrent snow accumulation in the Sierra Nevada of central California, high precipitation and stream flow in southern California, and high lake stands in the Mojave River basin sometime around 1600 A.D. Historical, lake-producing floods in the Mojave River watershed are also associated with concurrent similar phenomena during a single season (Enzel, 1990; Enzel et al., 1990).

6. Synoptic climatology of the lake-building floods

To characterize the climate associated with the late Holocene lake stands we have analyzed the synoptic climatology associated with the eight most intense storms and the lake-building floods (Table 1) as well as the synoptic climatology associated with the 29 floods which passed Afton Canyon up to 1987 (Enzel, 1990, appendix N). These two criteria for defining large floods were used for selecting the group of floods to which sea level pressure (SLP) and 700 mbar height composite anomaly maps were produced. This is part of a set of methods to extract connections between various characterization of river flow and patterns of atmospheric circulation (Hirschboeck, 1985, 1988; Cayan and Peterson, 1989). Because extreme floods are rare, the statistical significance of such analysis is reduced. The anomalous climatic patterns, however, are extracted. This methodology directs us to the specific atmospheric circulation pattern that is responsible for large floods in a specific drainage basin/region and to the larger-scale necessary climatic conditions.

To overcome the filtering mechanism of the river and to form a lake in the lower part of its watershed requires a vigorous storm, which is unusual for southern California but a characteristic borne out in every case examined. The mean meteorological pattern associated with these storms and lakes is constructed to identify distinct characteristics in the climatology of these unusual storms. Composite monthly values of sea-level pressure and the sea-level pressure anomalies over the North Pacific and western North America are calculated for the months which included the eight lake events listed in Table 1 (Fig. 15). Values of sea-level pressure are employed because of availability over a Northern Hemisphere grid since 1899 (Trenberth and Paolino, 1980). The values of sea-level pressure for each month with a lake event are subtracted from the long-term mean sea-level pressure (1947–1972; Namias, 1975) of the specific month to determine the monthly sea-level pressure anomaly. Although the actual flooding occurred on specific days with more intense sea-level pressure features than was produced from the monthly mean, several of the floods were associated with a persistent succession of storms that conform to a particular pattern. The monthly patterns of sea-level pressure provide an overall indication of the large-scale pattern that produced the particular storm or storm sequence.

During months when lakes formed, the eastern North Pacific subtropical high weakened, giving way to anomalously low pressure along the west coast. The anomalous low represents a southeastward shift of the central North Pacific winter low, with vigorous storms penetrating the west coast of the United States much further south than normal. These storms produced the heavy precipitation observed in the San Bernardino Mountains.

The composite pattern of sea-level pressure (Fig. 15) shows a tendency for a 'split' Aleutian Low with higher-than-normal sea-level pressure in the Aleutians and anomalously low sea-level pressure over Kamchatka. The blocking high pressure in the eastern Aleutian region during this type of event is also borne out by inspection of daily maps. This synoptic pattern has been diagnosed as a potent flood-producing condition in California (U.S. Weather Bureau, 1962). The Mojave River flood and lake events are symptoms of this very same pattern.

The strong negative anomaly of −6 mbar at 40°N, 130°W (Fig. 15) represents 1.5 to 3.0 standard deviations from the long-term monthly mean (depending on the specific winter month during which the flood has occurred). Other studies of winter and monthly average precipitation and storm flow have shown this condition to favor heavy precipitation and stream flow in California and Arizona (Namias, 1980; Hirschboeck, 1985; Kline and Bloom, 1987; Cayan and Peterson, 1989). The composite sea-level pressure and sea-level pressure anomaly of the 29 months with floods that passed Afton Canyon show similar atmospheric circulation patterns (Fig. 16). The detected anomaly is centered further away from the shore than the anomaly associated with the eight lake-building events. One underlying observation is common to both cases: a major shift in the North Pacific pressure system to the south and east during

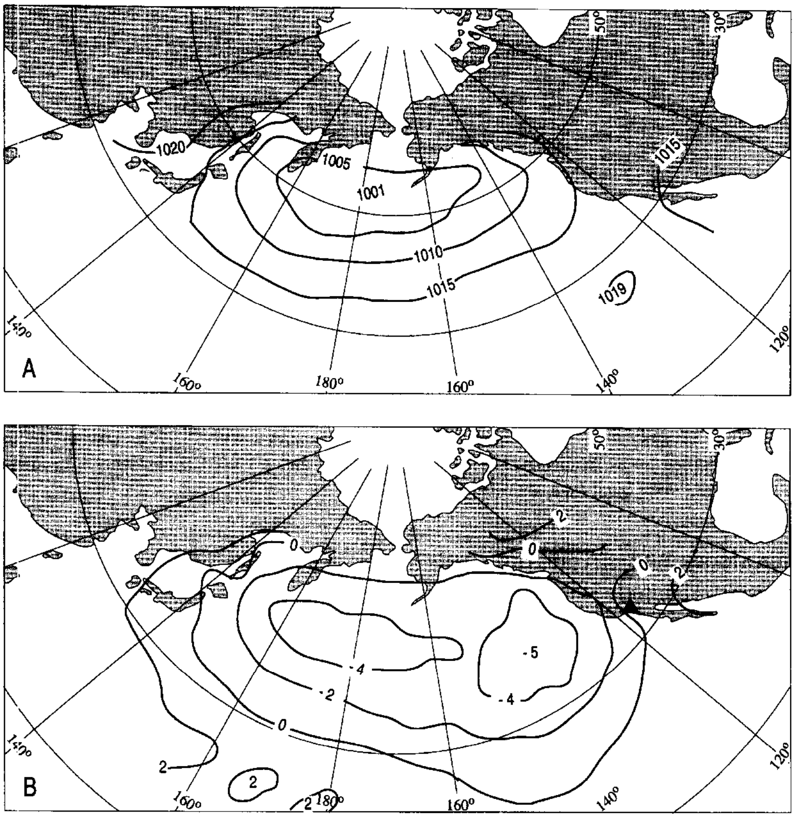

Fig. 16. Same as Fig. 15 but for the 29 months with Mojave River floods that reached Afton Canyon.

all floods that reach Afton Canyon. It seems that the 8-cases group represents the extreme conditions within the larger, 29-cases group.

Upper-air data cover even smaller numbers of lake-producing floods, a problem which is common to any study of extreme hydroclimatic phenomena (Hirschboeck, 1987, 1988; Ely et al., 1993a,b; Ely, 1997). Such data are limited to only four of the eight events. Fig. 17 shows the daily 700 mbar height anomaly associated with these four events. The monthly anomaly in the SLP mirror the anomaly observed in the upper-air data. This indicates that the atmospheric circulation is so anomalous that it is evident even in the monthly data. This is similar to the conclusion of Ely et al. (1993a).

Individual maps of 500- and 700-mbar height, satellite images, and previous studies (e.g., Wagner, 1969; Namias, 1980) for the months of the floods in the winters of 1969, 1978, 1980, and 1983, reveal two common patterns. The most frequent pattern featured an unusually deep trough or cut-off low pressure offshore from California, and a blocking high pressure in the Gulf of Alaska with a southerly displaced storm track entering California. In some of these cases, moisture and strong winds of these storms were assisted by the activity of the subtropical jet. This was indicated during the 1969 storm (Bonner et al., 1971). A second pattern that emerged was a sequence of storms imbedded in strong southerly-displaced westerlies that spanned the entire eastern North Pacific. This pattern occurred during the 1980 and 1983 events. Inspection of the high clouds on satellite images indicates that most of the moisture is of subtropical origin and the atmospheric circulation is directing it into southern California in general and to the San Bernardino Mountains in particular. During such interactions between the subtropics and the mid-latitude atmospheric circulation, the subtropical jet was in a more northern position (Enzel et al., 1990). Similar interaction was observed

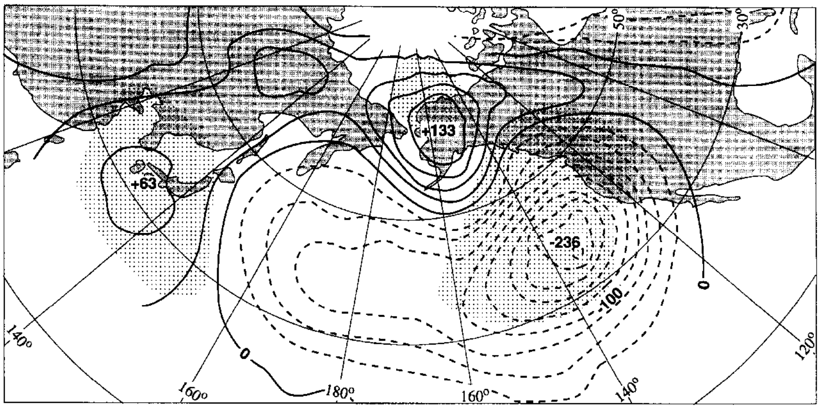

Fig. 17. Composite anomaly map of daily 700-mbar height values (in m) associated with the four lake-producing floods of 1969, 1978, 1980, and 1983. Hatched and stippled areas, respectively, mark the negative and positive zones where the difference from the mean is significantly greater than zero at the 90% level (see also Ely et al., 1993a).

for the largest winter floods and stream flow volumes in the southwestern United States and was associated with a negative Southern Oscillation Index (Cayan and Peterson, 1989; Ely et al., 1993a).

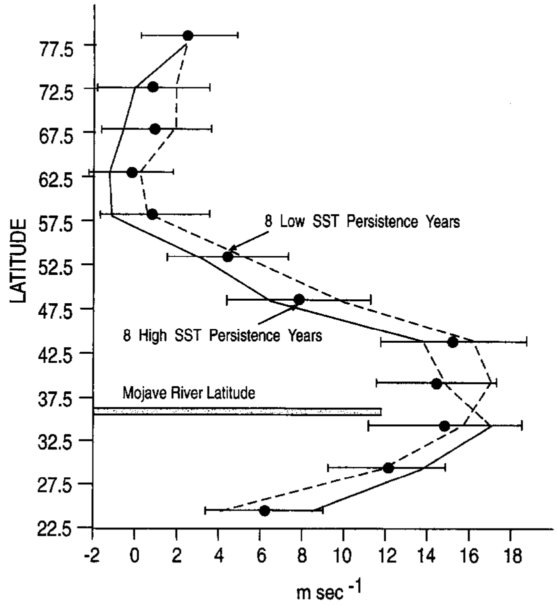

Fig. 18. Composite and range of North Pacific 700-mbar zonal wind velocity profiles (m/s) for 33 months of January (dots). Modified from Namias et al. (1988). Dashed line = the same for the eight years with the lowest persistence of January SST anomalies; solid line = the same for the eight years with highest persistence of January SST anomalies. The shift to the south of the maximum zonal wind occurs during years of high SST persistency, to the latitude of the Mojave River headwaters.

Evidence suggests (Namias et al., 1988) that the ocean surface boundary conditions may have played a role in the development of these storms. Namias et al. (1988) divided 33 years of SST records in the eastern North Pacific into three groups according to the persistency of the winter SST anomalies. Three of the winters with lake-building floods (the winters of 1969, 1978, and 1980) were included in their analyses. All of these three winters were included in the group of persistent high seasonal SST anomaly. During these years with high SST persistency, the maximum zonal winds along the eastern North Pacific were further south than the normal position and were located over the latitude of the Mojave River (Fig. 18). This is perhaps not a necessary condition, but such winter SST anomaly patterns can increase the frequency of extreme storm episodes in southern California in general and in the San Bernardino Mountains in particular. Indications of similar elevated winter SST characterized the area offshore California in the past (Pisias, 1978) during the time periods of the Holocene lakes in Silver Lake playa (Enzel et al., 1992).

7. Summary

The physical link between modern anomalous atmospheric circulation patterns over the North Pacific Ocean, extreme storms in southern California, the largest floods of record in the Mojave River, and lake stands in the Mojave River terminal playas is demonstrated by analyzing the hydrologic and climatic data.

The Mojave River filters out small to medium floods from the lake record by discharge losses through infiltration into the alluvial aquifer and allows only the large floods to pass Afton and the largest floods to reach the terminal playa. Storms that produced the large floods lasted one to two days and the precipitation intensities in the headwaters of the river were extremely high relative to the California records. These extreme precipitation events resulted from the orographic effect of the San Bernardino Mountains on storms from the west and southwest that direct moisture from the subtropical Pacific Ocean into southern California.

During 8 years in the 20th century, storms were vigorous enough to produce large floods that were able to overcome the filtering-by-infiltration mechanism of the river. These floods reached the terminal playa and produced the eight documented lakes. The vigorous storms occurred in response to extremely southerly displacement of both the winter storm activity and the Polar jet over the eastern North Pacific, directing subtropical moisture into southern California. Analyses of SLP for the eight months with lake-building floods revealed: (a) that the eastern North Pacific subtropical high weakened, giving way to an anomalously low-pressure system along the west coast of the United States; (b) a shift to the east and south of the central North Pacific winter low; and (c) a tendency for a 'split' Aleutian Low with higher-than-normal SLP in the Aleutian and an anomalously low SLP over Kamchatka. The historical lake-building storms and floods are relatively rare; however, they control the daily to decadal hydrological records of the Mojave River hydrologic system and probably indicate a different subgroup of extreme events within the data.

Simulations of late Holocene lakes recorded in sediments in and around Silver Lake playa are carried out based on the present-day hydrology of both the Mojave River and its terminal playas and also on geological boundary conditions. The geological boundary conditions are based on the elevation of middle to late Holocene beach ridges surrounding the Silver Lake playa and the late Holocene lake deposits recovered from drilled cores in this playa. This geological evidence provides the information needed to construct the geometry of the Holocene lakes. The results of this simulation reveal that the two largest floods in the systematic record, which presently have recurrence intervals > 18 years, have to occur each year in order to build a perennial lake in the terminal playa. The necessary increase in the number of floods relative to the present is found to be insensitive to reduction in evaporation. The two youngest Holocene lake episodes that occurred 390 ± 90 and 3620 ± 70 yr B.P. are synchronous with evidence from various environments in southern California and nearby areas, all of which support the existence of such anomalous stormy and wet hydroclimatic conditions during these episodes. The understanding of the modern hydrology and the simulation results imply: (a) that during these periods the moisture input into the Mojave River headwaters was much greater than the present input; and (b) that this moisture was transformed into large floods that were able to reach the terminal playas to produce a perennial lake. This, in turn, implies that high-frequency, high-intensity storms occurred in southern California, southern Nevada and Arizona during these late Holocene episodes. Atmospheric circulation patterns over the North Pacific, similar to the modern anomalous ones, were very frequent and may have persisted during the winter season in order to cause these storms and thus the perennial Holocene lakes.

From this study it is further concluded that modern extreme climatic and hydrologic conditions that influence hydrological systems can serve as useful analogues for earlier periods that experienced different hydroclimatic events than the present. This type of study can also provide information about the response of regional hydrological systems to scenarios of future climatic change.

7.1. Epilogue

During the winter of 1992–1993, a vigorous storm affected southern California and central Arizona. It was the result of atmospheric circulation anomalies similar to those documented above and produced floods in both regions. Several of these floods were described as the largest in the historical record or

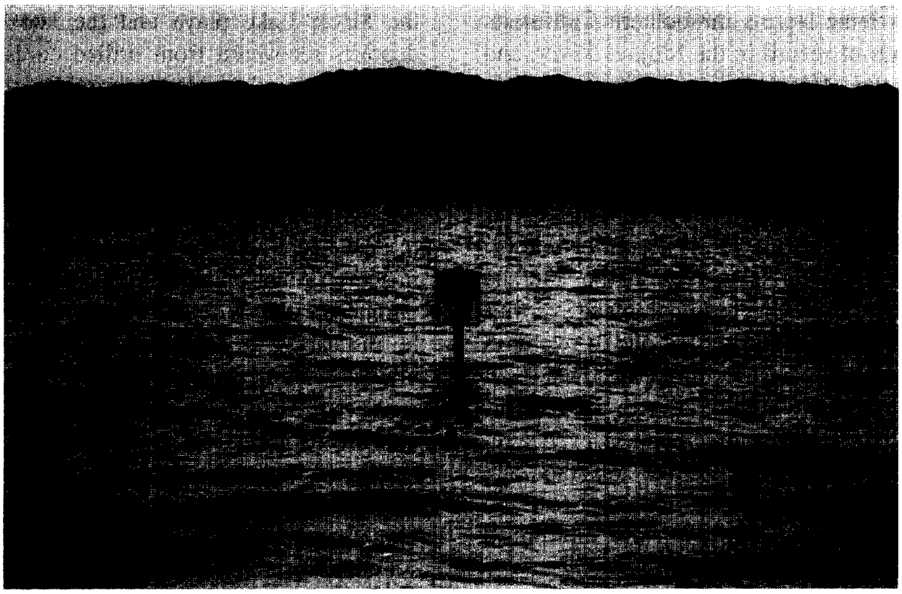

Fig. 19. Photograph of the ephemeral lake which was formed in Silver Lake playa following an extreme storm during the winter of 1992–1993.

even as the floods of the century. The storm and flood in the Mojave River produced an ephemeral lake in Silver Lake playa (Fig. 19). It is the ninth lake documented in this playa since the 1890s. This flood is even more impressive than most of the earlier events because by now the river is heavily regulated to reduce the amount of water reaching below Afton Canyon and to increase recharge into the alluvial aquifer in the upstream reaches. This hydroclimatic event, which has followed the sequence of the specific anomalous atmospheric circulation pattern and caused a lake-building flood in the Mojave River, supports our inferences about the conditions that must have had to occur in the basin to produce the perennial lakes.

Acknowledgements

We thank Bruce Allen, Roger Anderson, Bob Balling, Bill Brown, Dan Cayan, Lisa Ely, Bruce Harrison, Richard Heggen, Les McFadden, Jean-Luc Miossec, and Bob Webb who helped to accomplish this research. Anat Altman and Miri Shmida, Department of Geography, Hebrew University, helped with the drafting. We appreciate the efforts of the anonymous reviewers. This paper is dedicated to our late colleague Jean-Luc Miossec.

References

Allen, B.D., Anderson, R.Y., 1993. Evidence from western North America for rapid shifts in climate during the last glacial maximum. Science 260, 1920–1923.

Anderson, R.Y., 1986. The varved microcosm: propagator of cyclic bedding. Paleoceanography 1, 373–382.

Antevs, E., 1937. Age of Lake Mohave culture. In: Crozer-Campbell, W.E., Campbell, H.W., Antevs, E., Amsden, A.C., Barbierry, A.G., Bode, D.F. (Eds.), The Archaeology of Pleistocene Lake Mojave, Symposium. Southwest Museum Papers, No. 11, Los Angeles, Calif.

Baker, V.R., Bowler, J.M., Enzel, Y., Lancaster, N., 1995. Late Quaternary paleohydrology of arid and semi-arid regions. In: Gregory, K.J., Starkel, L., Baker, V.R. (Eds.), Global Continental Paleohydrology. Wiley, New York, pp. 203–232.

Bedient, P.B., Huber, W.C., 1988. Hydrology and Floodplain Analysis. Addison-Wesley, Reading, Mass.

Benson, L.V., Klieforth, H., 1989. Stable isotopes in precipitation and ground water in Yucca Mountain region, southern Nevada: paleoclimatic implications. In: Peterson, D.H. (Ed.), Aspects of Climate Variability in the Pacific and the Western Americas. Am. Geophys. Union, Geophys. Monogr. 55, 41–59.

Blaney, F.H., 1957. Evaporation study at Silver Lake in the Mojave Desert, California. Am. Geophys. Union Trans. 38, 453–463.

Bonner, W., Pyke, C., Hickey, R., 1971. A Study of The California Rainstorm of January 1969, Final Report. National Environmental Satellite Center, National Oceanographic and Atmospheric Administration, Contract E-3270(N). Department of Meteorology, University of California, Los Angeles, 29 pp.

Bradley, R.S., 1985. Quaternary Paleoclimatology. Allen and Unwin, Boston, Mass., 472 pp.

Buono, A., Lang, D.J., 1980. Aquifer discharge from the 1969 and 1978 floods in the Mojave River basin, California. U.S. Geol. Surv. Water Resour. Invest. Open-File Rep., 80-207, 25 pp.

Burke, R.M., Birkeland, P.W., 1983. Holocene glaciation in the mountain ranges of Western United States. In: Wright, W.E. (Ed.), Late Quaternary Environments of The United States—The Holocene. Minneapolis University Press, Minneapolis, Minn., pp. 3–11.

Cayan, D.R., Peterson, D.H., 1989. The influence of North Pacific atmospheric circulation on streamflow in the west. In: D.H. Peterson (Editor), Interdisciplinary Aspects of Climate Variability in the Pacific and Western America. Am. Geophys. Union, Geophys. Monogr. 55, 375–398.

Cole, K.L., Webb, R.H., 1985. Late Holocene changes in Greenwater Valley, Mojave Desert, California. Quat. Res. 23, 227–235.

Curry, R.R., 1971. Holocene climatic and glacial history of the central Sierra Nevada, California. In: Schuman, S.A., Bradley, W.C. (Ed.), United States Contribution to Quaternary Research. Geol. Soc. Am. Spec. Pap. 123, 1–47.

Davis, O.K., 1992. Pollen analysis of San Joaquin Marsh: Rapid climatic change in coastal southern California. Quat. Res. 37, 89–100.

Department of Water Resources, 1976. Rainfall for Drainage Design. Vol. I, Short Duration Precipitation Frequency Data. Vol. II, Long Duration Precipitation Data, Sacramento, California. State of California, Department of Water Resources Bulletin, 195 (three volumes).

Department of Water Resources, 1980a. California rainfall summary, monthly total precipitation 1849–1979, Sacramento, California. State of California, The Resources Agency, Department of Water Resources, Division of Planning, 55 pp.

Department of Water Resources, 1980b. Maximum daily precipitation by months, Sacramento, California. State of California, Department of Water Resources, 21 pp.

Department of Water Resources, 1981. Index to sources of hydrologic data, Sacramento, California. State of California, Department of Water Resources Bulletin 230-81, 23 pp.

Drover, C.E., 1978. The Early Prehistoric Ecology of The Northern Mojave Sink, San Bernardino County, California. Unpublished Ph.D. Diss., University of California, Riverside, 255 pp.

Ely, L.L., 1997. Response of extreme floods in the southwestern United States to climatic variations in the late Holocene. In: Kochel, R.C., Miller, J.R. (Eds.), Geomorphic Responses to Short-Term Climatic Change. Geomorphology 19, 175–201 this issue.

Ely, L.L., Baker, V.R., 1990. Large floods and climate change in the southwestern United States. In: French, R.H. (Editor), Hydraulics and Hydrology of Arid Lands. American Society of Civil Engineers, New York, pp. 361–366.

Ely, L.L., Enzel, Y., Cayan, D.R., 1993a. Anomalous North Pacific atmospheric circulation and large winter floods in the southwestern United States. J. Climatol. 7, 977–987.

Ely, L.L., Enzel, Y., Baker, V.R., Cayan, D.R., 1993b. 5000-year record of extreme paleofloods and associated atmospheric circulation patterns, southwestern United States. Science 262, 410–412.

Enzel, Y., 1990. Hydrology of a Large, Closed Arid Watershed as a Basis for Paleohydrological and Paleoclimatological Studies in The Mojave River Drainage System, Southern California. Unpublished Ph.D. Diss., University of New Mexico, Albuquerque, 316 pp.

Enzel, Y., 1992. Flood frequency of the Mojave River and the formation of late Holocene playa lakes, southern California, USA. Holocene 2, 11–18.

Enzel, Y., Cayan, R.D., Anderson, R.Y., Wells, S.G., 1989. Atmospheric circulation during Holocene lake stands in the Mojave Desert: evidence of a regional climatic change. Nature 341, 44–48.

Enzel, Y., Anderson, R.Y., Brown, W.J., Cayan, D.R., Wells, S.G., 1990. Tropical and subtropical moisture and southerly displaced North Pacific storm Track: factors in the growth of late Quaternary lakes in the Mojave Desert. In: Betancourt, J.L., MacKay, A.M. (Eds.), Proc. 6th Annual Pacific Climate (PACLIM) Workshop, March 5–8, 1989, California Department of Water Resources. Interagency Ecological Studies Program Report, 23, pp. 135–139.

Enzel, Y., Brown, W.J., Anderson, R.Y., McFadden, L.D., Wells, S.G., 1992. Short-duration Holocene lakes in the Mojave River drainage basin, southern California. Quat. Res. 38, 60–73.

Forester, R.M., 1987. Late Quaternary paleoclimate records from lacustrine ostracodes. In: Ruddiman, W.F., Wright, H.E. (Eds.), North America and Adjacent Oceans During the Last Deglaciation. Geological Society of America, Boulder, Colo., pp. 261–276.

Fritts, H.S., Lofgern, G.R., Gordon, G.A., 1979. Variations in climate since 1602 as reconstructed from tree rings. Quat. Res. 12, 18–46.

Goodridge, J.D., 1986. On Going to the Extremes in California Rainfall. 31 Rondo Court, Chico, CA 95928, 35 pp.

Graumlich, L.J., 1993. A 1000-year record of temperature and precipitation in the Sierra Nevada. Quat. Res. 39, 249–255.

Grove, M.J., 1988. The Little Ice Age. Methuen, New York.

Hardt, W.F., 1969. Mojave River basin ground-water recharge with particular reference to the California flood of January and February 1969. U.S. Geol. Surv. Water Resour. Div., Open-File Rep., 13 pp., December 17, 1969.

Hirschboeck, K.K., 1985. Hydroclimatology of Flow Events in the Gila River Basin, Central and Southern Arizona. Ph.D. Diss., Univ. of Arizona, Tucson, 335 pp.

Hirschboeck, K.K., 1987. Catastrophic flooding and atmospheric circulation anomalies. In: Mayer, L., Nash, D. (Eds.), Catastrophic Flooding. Binghamton Symp. Geomorphol. Int. Ser., 18, Allen and Unwin, Boston, Mass., pp. 23–56.

Hirschboeck, K.K., 1988. Flood hydroclimatology. In: Baker, V.R., Kochel, R.C., Patton, P.C. (Eds.), Flood Geomorphology. Wiley, New York, pp. 27–50.

Hunt, C.B., 1975. Death Valley—Geology, Ecology, Archeology. University of California Press, Berkeley.

King, T.J., 1976. Late Pleistocene–early Holocene history of coniferous woodlands in the Lucern Valley region, Mojave Desert, California. Great Basin Naturalist 36, 227–238.

Kline, W.H., Bloom, H.J., 1987. Specification of monthly precipitation over the United States from the surrounding 700 mb height field. Mon. Weather Rev. 115, 2118–2132.

LaMarche, V.C., 1974. Paleoclimatic inferences from long tree-ring records. Science 183, 1043–1048.

Lancaster, N., 1997. Response of eolian geomorphic systems to minor climate change: examples from the southern Californian deserts. In: Kochel, R.C., Miller, J.R. (Eds.), Geomorphic Responses to Short-Term Climatic Change. Geomorphology 19, 333–347, this issue.

McFadden, D.L., Wells, S.G., Brown, J.W., Enzel, Y., 1992. Genesis of soils on beach ridges of pluvial Lake Mojave: Geomorphic controls and implications for lacustrine and eolian events during the Holocene in the Mojave Desert, southern California. Catena 19, 77–97.

Mehringer, P.J. Jr., Warren, C.N., 1976. Marsh, dune and archeological chronology, Ash Meadows, Amargosa Desert, Nevada. In: R. Elston and P. Headrick (Editors), Holocene Environmental Change in The Great Basin. Nev. Archeol. Surv., Res. Pap. 6, 120–150.

Michaelsen, J., Haston, L., 1988. Precipitation variability in coastal California: spatial and temporal components and relationships to atmospheric circulation patterns. Final Report for Water Resources Center, University of California, Project W-707.

Mojave Water Agency, 1982. Report on historic and present conditions, Newberry Groundwater Basin. Victorville, Calif.

Muessig, S., White, N.G., Byers, M.F., 1957. Core logs from Soda Lake, San Bernardino County, California. U.S. Geol. Surv. Bull., 1045-C.

Myrick, D.F., 1963. Railroads of Nevada and Eastern California, Vol. 2. Howell-North Books, Berkeley, Calif., pp. 545–675.

Namias, J., 1975. CalCOFI Atlas No. 22. Scripps Institution of Oceanography, La Jolla, Calif., 243 pp.

Namias, J., 1980. The heavy California winter rain of 1979–1980 as a manifestation of macroscale air/sea coupling. Proc. 5th Annual Climatic Diagnostic Workshop. National Oceanic and Atmospheric Administration, Silver Spring, Md., pp. 35–50.

Namias, J., Yuan, X., Cayan, D.R., 1988. Persistence of North Pacific sea surface temperature and atmospheric flow patterns. J. Climatol. 1, 682–703.

Ore, H.T., Warren, C.N., 1971. Late Pleistocene–early Holocene geomorphic history of Lake Mojave, California. Geol. Soc. Am. Bull. 82, 2553–2562.

Pisias, N.G., 1978. Paleoceanography of the Santa Barbara Basin during the last 8000 years. Quat. Res. 10, 366–384.

Schulman, E., 1947. Tree-ring hydrology in southern California. Lab. Tree-Ring Res. Bull. 4, 1–36.

Sharp, R.P., 1966. Kelso dunes, Mojave Desert, California. Geol. Soc. Am. Bull. 77, 1045–1073.

Smith, G.I., 1979. Subsurface stratigraphy and geochemistry of late Quaternary evaporites, Searles Lake, California. U.S. Geol. Surv., Prof. Pap. 1043, 130 pp.

Smith, G.I., Street-Perrott, A.F., 1983. Pluvial lakes of the Western United States. In: Porter, S.C. (Ed.), The Late Pleistocene. University of Minneapolis Press, Minneapolis, Minn., pp. 190–212.

Smith, N.L. and Anderson, Y.R., 1982. Pleistocene–Holocene climate of the Estancia basin, central New Mexico. In: Grambling, J.A., Wells, S.G. (Eds.), Albuquerque County II. New Mexico Geological Society Guidebook, pp. 347–350.

Spaulding, W.G., 1985. Vegetation and Climates of the last 45,000 years in the vicinity of the Nevada Test Site, south-central Nevada. U.S. Geol. Surv., Prof. Pap. 1329, 83 pp.

Stine, S., 1990. Late Holocene fluctuations of Mono Lake, eastern California. Palaeogr. Palaeoclimatol. Palaeoecol. 78, 333–381.

Thompson, G.D., 1921. Pleistocene lakes allonge the Mojave River, California. J. Wash. Acad. Sci. 11 (17), 423–424.

Thompson, G.D., 1929. The Mojave Desert region, California: A geographic, geologic and hydrologic reconnaissance. U.S. Geol. Surv. Water-Supply Pap. 578, 1–143, 371–572.

Trenberth, K.E., Paolino, D.A., 1980. The northern hemisphere sea-level pressure data set tends, errors, and discontinuities. Mon. Weather Rev. 108, 855–872.

U.S. Weather Bureau, 1962. Meteorology of hydrologically critical storms in California. U.S. Dep. of Commerce, Weather Bur. Hydrometeorol. Rep. 37, 207 pp.

Visher, S.S., 1941. Rainfall of 10 inches, or more, during 24 hours, in the United States. Mon. Weather Rev. 85, 353–356.

Wagner, A.J., 1969. The weather and circulation of January 1969. Mon. Weather Rev. 97, 351–358.

Waters, R.M., 1989. Late Quaternary lacustrine history and paleoclimatic significance of pluvial Lake Cochise, southeastern Arizona. Quat. Res. 32, 1–11.

Wells, S.G., McFadden, L.D., Dohrenwend, J.C., 1987. Influence of late Quaternary climate changes on geomorphic and pedogenic processes on desert piedmont, eastern Mojave Desert, California. Quat. Res. 27, 130–146.

Wells, S.G., Anderson, R.Y., McFadden, L.D., Brown, W.J., Enzel, Y., Miossec, J.-L., 1989. Late Quaternary paleohydrology of the eastern Mojave River drainage, southern California: quantitative assessment of the late Quaternary hydrologic cycle in large arid watershed. New Mexico Water Resour. Res. Inst. Rep. 242, 253 pp.

Wells, S.G., McFadden, L.D., Schultz, J.D., 1990. Eolian landscape evolution and soil formation in the Chaco dune field, southern Colorado Plateau, New Mexico. Geomorphology 3, 517–545.

Wintle, A., Lancaster, N., Edwards, S.R., 1994. Infrared stimulated luminescence (IRSL) dating of late-Holocene aeolian sands in the Mojave Desert, California, USA. Holocene 4, 74–78.

Wohl, E.E., Enzel, Y., 1995. Data for paleohydrology. In: Gregory, K.J., Starkel, L., Baker, V.R. (Eds.), Global Continental Paleohydrology. Wiley, New York, pp. 23–59.