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WALNUT CANYON AND WATER: CAPTURE, STORAGE,
AND USE OF WATER DURING THE SINAGUA PERIOD OF
OCCUPATION, CA. A.D. 1100 - 1300

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CONTENTS

The Setting: Environment and Prehistory of Walnut Canyon National Monument

Climate and Precipitation at Walnut Canyon: Limiting Factors for Water Procurement

Yearly Cycles of Precipitation

Summer Wet Season

Winter Wet Season

Drought Periods

Paleoclimatic Reconstructions

Prehistoric Capture, Storage, and Use of Water in the Southwest

Walnut Canyon and Water

Probable Sources of Surface and Near-Surface Water

Conversion of Snowpack into Water

Quantification of Water Use at Walnut Canyon

Estimating Sinagua Population at Walnut Canyon

Sinagua Water Consumption

Sinagua Use of Water for Agricultural Production

Archaeological Implications

Conclusion

FIGURES

- Figure 1. Walnut Canyon National Monument (to be drafted; after Baldwin and Bremer 1986:2).
- Figure 2. Seasonal distribution of precipitation for the Colorado Plateau, expressed as average monthly precipitation in inches (after Sellers and Hill 1974:8).
- Figure 3. Location of habitation sites, agricultural features, and potential water sources at Walnut Canyon National Monument (to be drafted at larger scale).
- Figure 4. Histogram showing dates of first frost, Flagstaff Airport weather station.
- Figure 5. Histogram showing dates of last frost, Flagstaff Airport weather station.
- Figure 6. Histogram showing dates for onset of summer rains, Walnut Canyon National Monument.
- Figure 7. Histogram showing dates for end of summer rains, Walnut Canyon National Monument.
- Figure 8. Average distribution of precipitation in inches at Walnut Canyon National Monument, by season.
- Figure 9. Histogram showing dates for beginning of snow season, Walnut Canyon National Monument.
- Figure 10. Histogram showing dates for end of snow season, Walnut Canyon National Monument.
- Figure 11. Average precipitation per day in inches, by season, Walnut Canyon National Monument.
- Figure 12. Percentage of days with measurable precipitation, by season, Walnut Canyon National Monument.
- Figure 13. Average length of periods without at least 0.10 inch of rain, by season, Walnut Canyon National Monument.
- Figure 14. Median values for length of periods without at least 0.10 inch of rain, by season, Walnut Canyon National Monument.
- Figure 15. Histogram showing lengths of periods without at least 0.10 inch of rain during spring dry season, Walnut Canyon National Monument.
- Figure 16. Histogram showing lengths of longest periods without at least 0.10 inch of rain during each year's spring dry season, Walnut Canyon National Monument.
- Figure 17. Precipitation values from dendroclimatic reconstructions from the Flagstaff, Arizona station, showing decade-level values expressed in standard deviations from the mean, A.D. 680-1970. The solid line represents the mean.

FIGURES, *continued*

Figure 18. Precipitation values from dendroclimatic reconstructions from the Flagstaff, Arizona station, showing yearly values expressed in standard deviations from the mean, A.D. 1060-1310. Solid line shows yearly departures from normal, dashed line represents average values.

Figure 19. Artist's conception of capturing water from canyon rim runoff (in preparation).

Figure 20. Plan and profile map of Cherry Canyon bedrock pools (to be drafted).

Figure 21. Estimates for peak population at Walnut Canyon, ca. A.D. 1250, using three methods of estimation and three assumptions regarding percentage of habitation rooms in use.

Figure 22. Estimated annual domestic water consumption by Sinagua residents of Walnut Canyon at peak of prehistoric occupation.

Figure 23. Estimated annual maize production by Sinagua residents of Walnut Canyon during peak of prehistoric occupation.

Figure 24. Postulated use of storage space in prehistoric pueblo rooms at Walnut Canyon during peak of Sinagua occupation.

TABLES

Table 1. Data for wet and dry seasons at Walnut Canyon National Monument.

Table 2. Dendroclimatic data from Flagstaff Station, by decade, A.D. 680-1970.

Table 3. Data for population estimates, peak of Sinagua occupation at Walnut Canyon National Monument.

Table 4. Estimated per-capita annual water requirements for Sinagua occupants of Walnut Canyon, ca. A.D. 1250.

Table 5. Estimated annual maize production at Walnut Canyon, ca. A.D. 1250.

One of the most baffling aspects of the prehistoric Sinagua culture (ca. A.D. 700 to 1450) involves water: Where and how did the Sinagua obtain sufficient water to sustain life and grow crops? The very name of the culture – an abbreviation of the Spanish designation *Sierra Sin Agua*, or "Waterless Mountains" (Colton 1939:34) – embodies the paradox. All around the Sinagua country, a sparse and uneven distribution of reliable water sources contrasts sharply with a widespread distribution of prehistoric sites. Literally thousands of prehistoric settlements seemingly have been located without regard for water, which is a basic, daily necessity of human existence.

At Walnut Canyon the mystery is heightened by the fact that prehistoric cliff dwellings and pueblos, dating to the 12th and 13th centuries A.D., are clustered along the sides and rim of a water-carved canyon. The form of this canyon and the abundant water-rolled geological deposits at its bottom suggest that water once was a powerful force here. However, today the canyon bottom is almost completely dry for most days of the year, and water flows only during heavy thunderstorms or when there is sufficient snow-melt (Brian 1992:36). Like the prehistoric Sinagua, the waters that carved Walnut Canyon seem to have abandoned the area sometime in the distant past. Modern observers are left to question whether both were ever present at the same time, and to wonder if their departures were linked. In many ways, Walnut Canyon is a quintessential Sinagua puzzle.

However, like many archaeological questions, the "mystery" of Sinagua water procurement is more apparent than real. In this study, we will discuss various issues surrounding how prehistoric inhabitants of the Southwest were able to survive in arid environments, and we will propose several models regarding the probable means by which the Sinagua procured their drinking water at Walnut Canyon. Finally, we will attempt to estimate the probable domestic and agricultural water needs of the Sinagua inhabitants of Walnut Canyon during the peak of their population. These estimates have important implications for interpreting the artifacts and architecture of the Walnut Canyon Sinagua, and they provide a tangible basis for

envisioning their lifeways and technological solutions they developed for living in a sometimes harsh and unpredictable environment.

THE SETTING: ENVIRONMENT AND PREHISTORY OF WALNUT CANYON NATIONAL MONUMENT

Walnut Canyon National Monument (Figure 1) was created in 1915, and expanded in 1938, primarily to preserve and interpret the prehistoric cliff dwellings and other archaeological remains clustered along a short stretch of the canyon (Colton 1932; Ritchie 1968; Stein 1986). The Monument lies about 6 mi. (9.6 km.) east-southeast of Flagstaff, Arizona at the southeastern edge of the San Francisco volcanic field, a relatively recent geological formation comprising more than 400 cinder cone volcanoes, lava flows, and other volcanic formations (Robinson 1913; Nations and Stump 1981:155-170). The dominant geological feature of the San Francisco volcanic field is the San Francisco Peaks, a name given to the four summits of an extinct volcano located just north of Flagstaff, Arizona. The San Francisco Peaks rise to an elevation of 12,670 ft. (3,861 m.), or nearly 6,000 ft. (1,829 m.) above the surrounding terrain. This mountain mass is a commanding presence in the region, and the immense relief of the Peaks has important influences on local patterns of wind, precipitation, and surface runoff (Colton 1958). The San Francisco Peaks are also a pre-eminent feature of the cultural landscape, and for a variety of reasons they are considered a sacred place to the many aboriginal groups who live in a broad surrounding area.

The San Francisco volcanic field is located at the southern edge of a much larger physiographic province called the Colorado Plateau. This province generally is made up of gently sloping, relatively soft sedimentary rock formations that are intermittently carved by local drainages into a series of deeply incised canyons. The Colorado Plateau thus forms a flat table land with relief provided primarily by wind and water erosion and occasionally, as in the case of the San Francisco Peaks, recent volcanic activity. The principal canyon of the Colorado Plateau is the Grand Canyon, carved

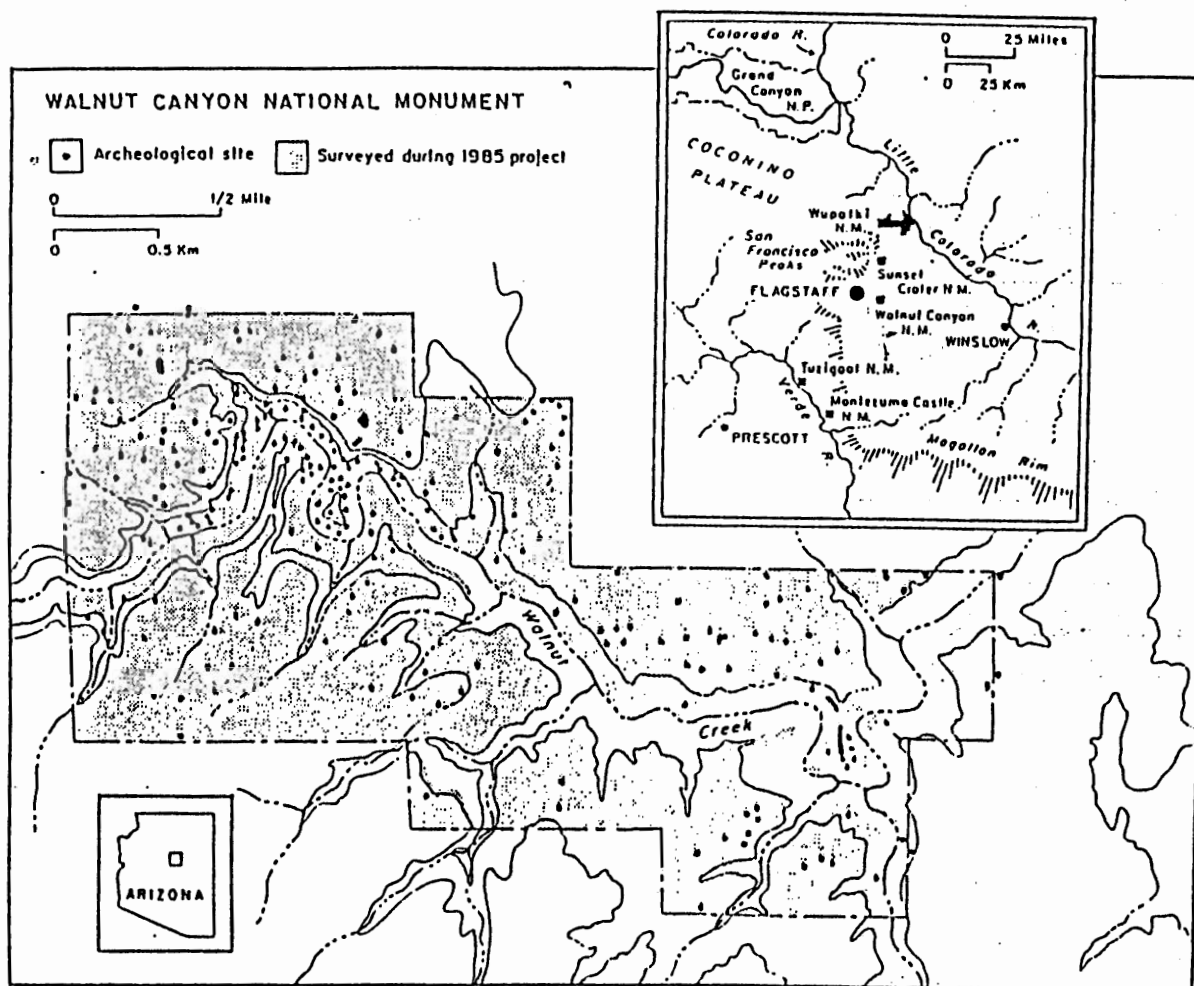


Figure 1. Walnut Canyon National Monument (to be drafted; after Baldwin and Bremer 1986:2).

by the major drainage of the province, the Colorado River. This canyon has been cut to a depth of more than 5,000 ft. (1,524 m.), and achieves a total width of more than 20 mi. (32 km.).

A principal tributary of the Colorado River in northern Arizona is the Little Colorado River, which flows northwest from its headwaters in the White Mountains of east-central Arizona. The Little Colorado River drains a very large portion of northeastern Arizona, encompassing the territory extending from the Mogollon Rim northward to the northern rim of Black Mesa. In the area surrounding Flagstaff, Arizona, several major washes flow east-northeast from the eastern slope of the San Francisco Peaks, and northeast from the uplift associated with the Mogollon Rim. Many of these drainages, including Walnut Canyon, have deeply incised but narrow canyons cut into limestone and sandstone formations.

Walnut Canyon itself was formed by the erosive action of Walnut Creek, a stream that flows across the northwestern portion of Anderson Mesa and empties into San Francisco Wash, a tributary of the Little Colorado River. The headwaters of Walnut Creek lie just north of Mormon Lake, a shallow, natural impoundment within the Mormon Mountain (el. 8,450 ft. [2,576 m.]) watershed (Brian 1992:2). In its upper reaches, Walnut Creek flows northwest along the west side of a steep basalt escarpment that forms the far western edge of Anderson Mesa. Within a short distance of its headwaters Walnut Creek turns to the east-northeast and descends into a steep-walled, meandering gorge known as Walnut Canyon. This canyon is cut through the Permian-age rock formations of Kaibab Limestone and Coconino sandstone. At its deepest point, a few miles upstream from the current boundaries of Walnut Canyon National Monument, the Canyon is about 440 ft. (134 m.) deep and 1,700 ft. (518 m.) wide. From the head of Walnut Creek to its confluence with the San Francisco Wash, some 17 mi. (27.2 km.) to the northeast, Walnut Creek drops from about 7,000 ft. (2,134 m.) to 6,100 ft. (1,859 m.). Within Walnut Canyon National

Monument, the bed of Walnut Creek drops from about 6,380 ft. (1,945 m.) to 6,280 ft. (1,914 m.), with the canyon rim descending a comparable distance, from 6,700 ft. (2,042 m) on the western end of the Mounument to 6,600 ft. (2,012 m.) on the east.

The flora, fauna, and natural environment of Walnut Canyon have been described in numerous publications (e.g., Spangle and Spangle 1954; Haldeman and Clark 1969; Salomonson 1973; Joyce 1974; Bremer 1988; Harper 1993; Brian 1992). The steep sides of Walnut Canyon provide dramatic changes in elevation, moisture, temperature, and sun exposure that are reflected in distinctive environmental zones. Generally, vegetation within or near the canyon bottom is denser than along the sides, and vegetation is more abundant along the south side of the canyon than on the north side. These patterns undoubtedly reflect soil moisture and temperature conditions, wherein the coolest and wettest environments are found in the canyon bottom and along its north-facing slopes.

The most comprehensive study of Walnut Canyon's vegetation is provided by Joyce (1974), who recognized four sharply-defined ecological zones. These zones consisted of (1) the north rim of the canyon, dominated by pinyon pine (*Pinus edulis*) and Utah juniper (*Juniperus osteosperma*); (2) the north slope of the canyon, featuring muttongrass (*Poe fendleriana*) and sagebrush (*Atremesia frigida*); (3) the canyon bottom, with box elder (*Acer negundo*) and Arizona walnut (*Juglans major*); and (4) the south slope of the canyon, dominated by Douglas fir (*Pseudotsuga menziesii*). Beyond the rim and sides of the canyon, vegetation communities vary largely with elevation. Bremer (1987:41) has observed that the pinyon/juniper zone near Walnut Canyon is located below the 6,700 ft. (2,042 m.) contour. Above the pinyon/juniper zone on both sides of the canyon, there is a transitional vegetation zone, consisting of a ponderosa/pinyon/juniper woodland, and above this at the western end of the National Monument, a limited ponderosa/oak woodland.

The natural hydrology of Walnut Creek

during the period of Sinagua occupation is difficult to assess due to modern alteration of the stream's watershed. Probably the most significant changes have been caused by dams built in the uppermost reaches of the drainage during the early 20th century. These dams, designed to assure a steady water supply for the city of Flagstaff, Arizona, currently impound reservoirs known as Lower Lake Mary (built in 1905) and Upper Lake Mary (built in 1941). Both reservoirs today capture the seasonal runoff that once flowed into Walnut Creek from the eastern side of Mormon Mountain. In order for Walnut Canyon to flow in its upper reaches, the reservoirs must fill and then overflow their dams, an event that happens only rarely. As a consequence, the bed of Walnut Canyon today is filled in places with fine-grained sediments that would in prehistoric times have been flushed out by periodic floods. Other changes since prehistoric times, including a thickening of brush growth due to fire suppression, groundwater pumping, and blocking or diversion of small tributaries, may also have changed the hydrology of Walnut Creek. Though the effects of such changes are difficult to assess, they probably are minor when compared to the impacts of Lake Mary.

The most comprehensive study of Walnut Creek is provided by Nancy Brian (1992), who has examined historic records, photographs, and changes in vegetation for the purpose of determining whether or not the stream was perennial prior to the construction of Upper Lake Mary in 1905. Her research established that historic accounts provide no definitive evidence that Walnut Creek was a permanent stream prior to 1905. In fact, several written documents and interviews support the opposite conclusion, i.e., that before 1905 this drainage was at best intermittent, flowing only when there was sufficient local rainfall or snowmelt, usually during middle to late summer and late spring. Photographic comparisons of vegetation in the creek bottom also lend support to this notion. Brian (1992:11-35) found that in the last few decades, a dense growth of riparian vegetation has arisen in the canyon bottom, evidently because periodic floods no longer scour the bed

of Walnut Creek. However, even the earliest photographs of the canyon available to Brian (ca. 1900) do not show vegetation characteristic of perennial streambeds (e.g., cottonwood), and there is no evidence in any of the photographs that such vegetation once existed. Brian therefore has concluded (1992:36) that Walnut Creek probably was not a perennial stream:

Due to the lack of evidence that proves Walnut Creek was a perennial stream prior to the construction of the Lake Mary Dams in 1905 and 1941, the drainage can only be considered intermittent. Water flows in the drainage only following heavy winter runoff or summer thunderstorms. No observers at the turn of the century testified that water ran year-round in the Walnut Canyon drainage.

Regarding the possibility of springs or other sources of permanent water that might be found within Walnut Canyon, it appears that the canyon's geology is not conducive to the formation of reliable springs. According to Bremer (1987:46):

No permanent springs or other water sources have been recorded along the canyon. The local geology is not well suited for forming aquifers to trap water which could extrude from local seeps.

However, this is not to say that subsurface moisture does not exist. The sand, silt, and gravel deposits within the canyon bottom have the ability to retain water for a limited period after Walnut Creek has experienced a flow, and such water can be obtained by digging below the surface. There are also fractures and contact zones within the walls of the canyon where small amounts of water seep out during times of heavy rainfall or snowmelt. During the spring of 1993, the authors observed several

small accumulations of water (probably on the order of a few gallons each) in the canyon bottom below such seeps (Figure 3; see also Harper 1993:1337-139). Another significant water source for the Sinagua would have been runoff that cascades over the canyon rim during heavy rains (Harper 1993:138). This water could have been captured directly by placing water jars in strategic locations below overhanging canyon walls (Schroeder 1944), and it is often captured naturally in small potholes or "tinajas" that exist on horizontal rock surfaces below the overhangs. The latter features do not retain large quantities of water (usually less than one gallon), but in the aggregate they probably offer several hundred gallons and therefore might be counted as a significant source of ephemeral water that would have been available to the Sinagua after a heavy rain or snow event. It should also be remembered that Walnut Canyon, located at an elevation of nearly 7,000 ft. (2,134 m.) experiences relatively cold winters with significant amounts of snowfall. Thus, in most years, the winter months provide important opportunities for obtaining drinking water from existing snowpack. As we will discuss below, some quantity of snow is usually available from about mid-November through mid-April.

Finally, in canyon bottoms the bedrock is sometimes eroded to such a degree that deep pools are formed. One such pool was observed by the authors and mapped as part of this project in July of 1993 in Cherry Canyon, a tributary of Walnut Creek (Figures 3 and 19). Here, water has carved a series of long, narrow holes into the bedrock at the bottom of Cherry Canyon, forming several pools capable of retaining water for extended periods of time. In fact, given the amount of water observed and the time during which the observation was made (at the end of a particularly dry spell during the late spring/early summer dry season of 1993), it appears that this catchment could have provided the Sinagua with a reliable water source during most years.

Such pools may have been found at the bottom of Walnut Canyon itself during the prehistoric period of occupation. Today, no

such bedrock pools can be observed, but this is probably due to the fact that the construction of Upper and Lower Lake Mary have resulted in the accumulation of fine-grained sediment deposits in the canyon bottom. These deposits have filled and obscured any potential bedrock pools that once existed. Photographs taken in the 1880s show that prior to the construction of the upstream dams, the bed of Walnut Creek was periodically flushed of fine-grained sediments, and the creek channel was quite rocky and held pools of water (Peter Rowlands, personal communication 1994). During a walk through the canyon bottom in 1993, several areas were observed that probably represent sediment-choked bedrock pools (Figure 3). These areas today have a substrate of fine-grained sediments such as sand and silt, are marshy during the wetter seasons of the year, and support hydrophilous vegetation types such as horsetail (*Equisetum* sp.). This vegetation type is an excellent indicator of near-surface moisture, and often can disclose the location of recently filled spring pools (Moore 1979:87). Though the volume and reliability of these pools cannot now be assessed, they appear to constitute a likely and important source of water for the prehistoric Sinagua of Walnut Canyon. Like the bedrock pool observed in Cherry Canyon, those of Walnut Canyon could have contained water at least during the wetter seasons of the year, and perhaps, if they were deep enough, for the full year.

In summary, although Walnut Creek is not now a perennial stream, and probably was not perennial during the period of Sinagua occupation, Walnut Canyon presented a number of potential water sources for its prehistoric inhabitants. These include the seasonal runoff that would have occurred on a more regular basis prior to the construction of Lower Lake Mary; subsurface water retained in sediments at the canyon bottom; limited seeps issuing from the bedrock walls of the canyon; water flowing off the canyon walls; snowpack; and relatively large pools of water retained in eroded pockets of the canyon bottom.

Although none of these sources alone could have provided all of the water needs of the Sinagua, their complementary distribution in

runoff
subsurface
water
seeps
water
flowing
off
rock pool

time and space probably assured that drinking water was available year-round. This is especially true if, as we will argue below, the Sinagua were able to collect water and store it in ceramic jars for later use.

In the next section, we explore the nature of water availability at Walnut Canyon by examining the modern record of precipitation. This examination provides the basis for considering strategies and scheduling of prehistoric water procurement at Walnut Canyon.

CLIMATE AND PRECIPITATION AT WALNUT CANYON: LIMITING FACTORS FOR WATER PROCUREMENT

Prehistoric water use at Walnut Canyon depended greatly on patterns of precipitation. By any standard, Walnut Canyon is an arid environment with sparse and unpredictable precipitation, and its prehistoric inhabitants certainly understood this and planned their water-gathering activities, water storage strategies, and agricultural efforts accordingly. One useful way to consider prehistoric water procurement and storage is to model the conditions of weather and climate that would have confronted Walnut Canyon's Sinagua populations. There are two major sources of data available for this purpose. The first consists of short-term weather records, gathered over the past several decades, and the second is the long-term climatic record encoded in tree-rings.

Modern weather records are available from Walnut Canyon and surrounding weather stations such as the Flagstaff airport. These records provide a glimpse at the general nature of precipitation in the area, and illustrate some of the weather extremes that would have confronted the Sinagua in their search for water. Although modern records are admittedly a small sample and do not precisely reflect weather conditions in the 12th and 13th centuries A.D., they are nonetheless useful. As we will discuss in more detail in a later section, general weather patterns probably have not changed radically in the past several centuries,

at least in their broadest outlines, and the modern observations provide the only available information on the day-to-day precipitation variability that characterizes the general area.

Weather data used in this report were obtained from the Western Regional Climate Center at the Desert Research Institute in Reno, Nevada. Data consisted of the daily weather observations from Walnut Canyon National Monument and the Flagstaff Airport, encoded in ASCII format on 5 1/4 in. floppy diskettes. Computerized data for Walnut Canyon spanned the period from October 9, 1950 to October 31, 1993, and the Flagstaff airport data set encompassed January 13, 1950 to October 31, 1993. Recorded variables for both data sets included the date and time of weather observation, 24-hour precipitation total (in hundredths of inches), 24-hour snowfall total (in tenths of inches), 24-hour maximum temperature, (in whole degrees Fahrenheit), and 24-hour minimum temperature. Information was also included on the quality of data for each observation. To perform our analyses, the data were first converted from the ASCII format to a DBASE IV data file. Summaries and analyses of weather data were accomplished on a microcomputer using the various reporting functions of DBASE IV and the statistical functions of the SYSTAT statistical package. Analyses were converted to graphic form using the QUATTRO PRO spreadsheet software.

In conducting analyses of modern weather records, several questions were posed:

- (1) What is the yearly cycle of precipitation in terms of "wet" seasons and "dry" seasons?
- (2) What is the duration of the most extreme drought periods?
- (3) When is snow available for conversion into water?

Results of our examinations are presented below, with special attention given to how the environmental conditions at Walnut Canyon would have affected prehistoric water procurement and agricultural pursuits.

general
weather
patterns have
not changed
significantly

Yearly Cycles of Precipitation

Like the Southwest region in general, the Flagstaff area is a dry environment. Precipitation is relatively sparse, and it usually comes during fairly well-defined wet seasons separated by prolonged dry periods. Because of low relative humidity, rates of surface evaporation can greatly exceed precipitation. At the Fort Valley weather station, just west of Flagstaff, it has been determined that the annual evaporation rate is approximately 42 in. (106.7 cm), a figure that is nearly double that of the average annual precipitation of 21.99 in. (55.85 cm.) (Sellers and Hill 1974:38, 222). Thus, while precipitation is scarce to begin with, any pools of water that are left after a rain usually dry up very quickly. This implies in turn that water procurement strategies were opportunistic and keyed to seasonal precipitation events.

The annual cycle of precipitation for the Flagstaff area is markedly "bi-seasonal." According to Sellers and Hill (1974:8):

There are two seasons of the year when precipitation is especially common in Arizona or, stated more correctly, two seasons of the year when drought conditions are less severe than usual. The best defined of these is summer, particularly July and August, which are the wetter months in all parts of the state. ...The second "wet" season extends from December through the middle of March.

There are several means of assessing the validity of these postulated wet and dry seasons. One is simply to plot the average rainfall during each month of the year in order to observe peaks and troughs in the mean monthly values. Figure 2 presents such a graph for the Plateau section of Arizona surrounding Flagstaff, which shows how average monthly precipitation values rise and fall on a seasonal basis. There are two clearly defined peaks of

precipitation. One is a higher peak that comes during the summer months of July and August, and the other is a lower and more prolonged peak lasting from December through March. Troughs, indicating "dry" seasons, are observed during two periods: a late spring dry season, extending from April through June, and a late fall dry season encompassing October and November.

Another and perhaps more informative way of considering the seasonal precipitation regime is to consider rainfall and snowfall in terms that might have been relevant to the prehistoric Sinagua. To do this, we examined two seasons presumed to have been of importance: (1) a summer "growing" season, beginning with the expected last frost of the spring, and ending with the expected first frost of the fall, and (2) a winter "snow" season, beginning with the first significant snowfall event in the late fall, and ending with the last significant snow in the late spring of the following calendar year. We chose these seasons because they were probably important to a wide range of Sinagua activities, especially water procurement. Each of the two wet seasons defined above punctuates a prolonged dry season during which the lack of available water would have presented potential challenges to survival.

Our scenario of the seasonal cycles of Sinagua water procurement is based on the following assumptions. The onset of summer rains probably meant that the Sinagua could have turned to a variety of readily available water sources, including flow within Walnut Creek and its major tributaries, seeps in the canyon bottom, water cascading from the canyon rim, and accumulations of water in deep potholes or cavities in the creek bottom. Essentially, with the first summer rains the Sinagua would have been freed from their reliance on stored water reserves or long-distance treks to the nearest source of permanent water. This liberation would have been especially welcome because the summer rains bring a number of labor requirements associated with agriculture.

The second major wet season, the winter snow season, marks the end of the late

PLATEAU

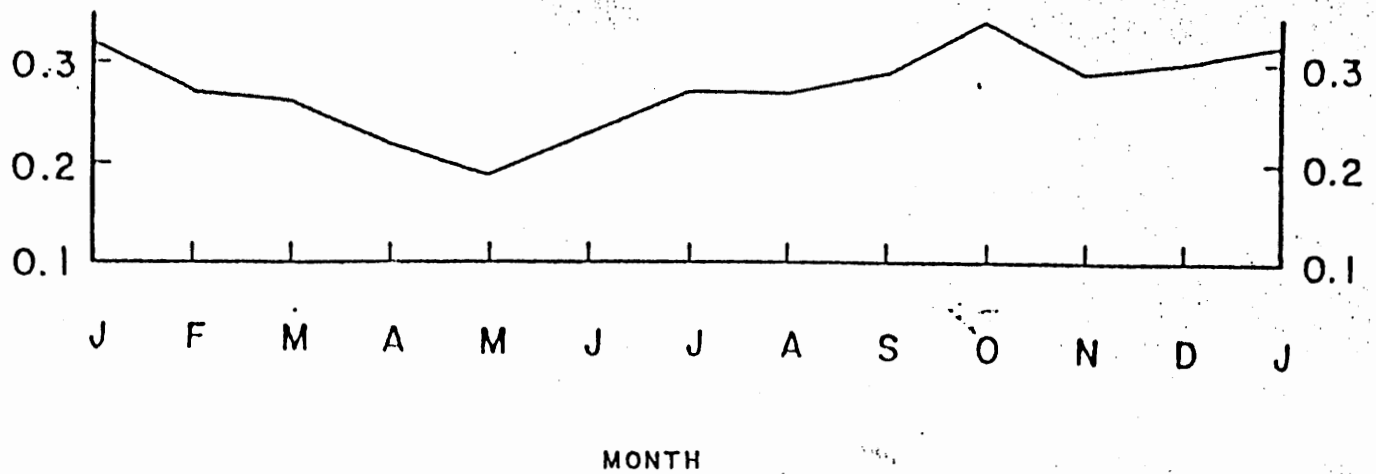


Figure 2. Seasonal distribution of precipitation for the Colorado Plateau, expressed as average monthly precipitation in inches (after Sellers and Hill 1974:8).

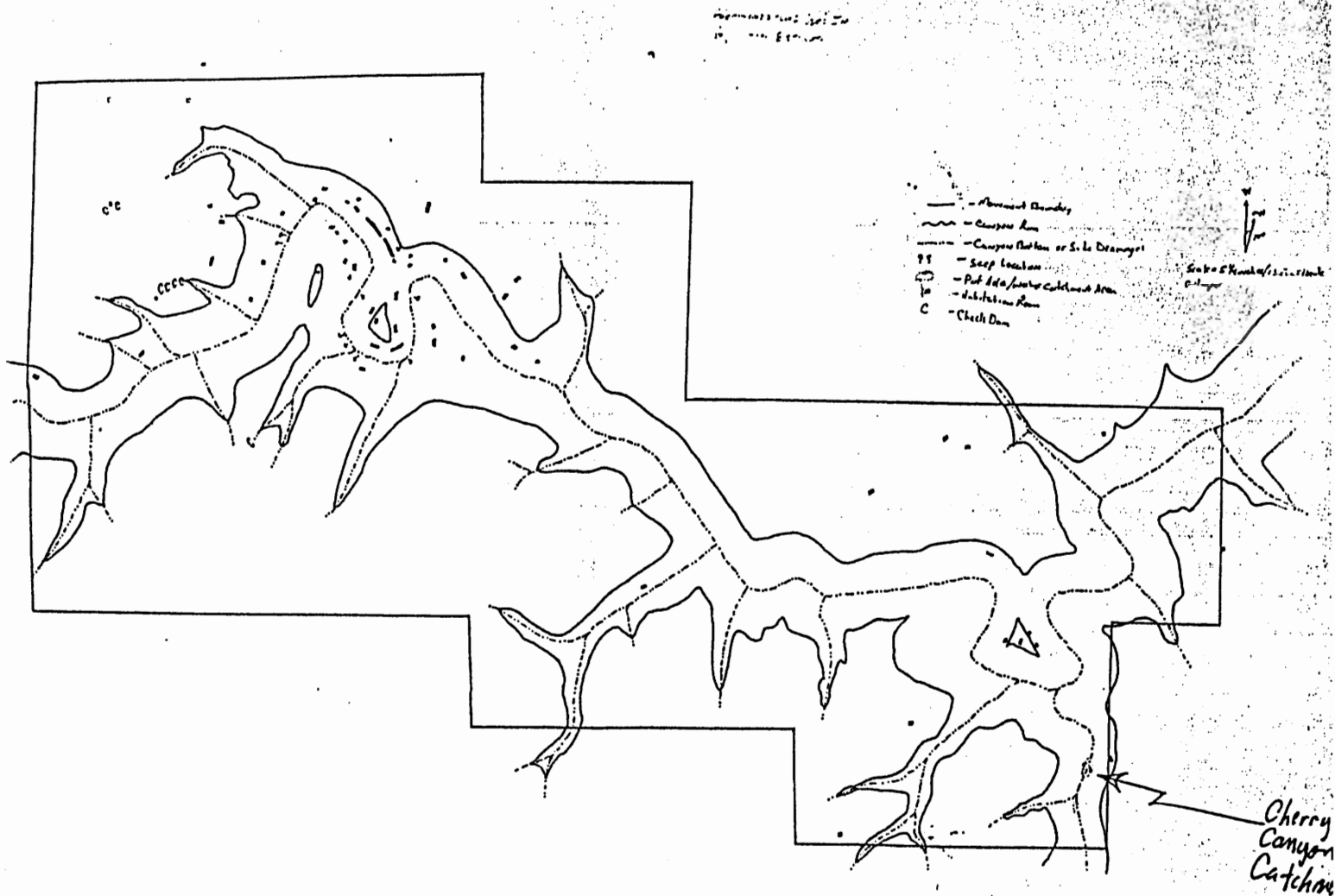


Figure 3. Location of habitation sites, agricultural features, and potential water sources at Walnut Canyon National Monument (to be drafted at larger scale).

fall dry season. With the first heavy snow comes a period of persistent snowpack, especially on the north-facing slopes of the canyon and in the shade of heavily forested areas on the canyon sides and rim. Harper (1993:133) has observed that the north-facing slopes at Walnut Canyon may retain the snow from a single snowstorm for more than four weeks. Like the summer rains, the accumulation of snowpack would have freed the Sinagua from dependence on stored water reserves or long water procurement trips. This too was probably a welcome event, since the winter season also brings important labor requirements, such as hunting and the gathering of firewood. In addition, walking long distances in the winter to obtain water was probably difficult and, at times, dangerous.

To aid our measurement of the annual precipitation cycles at Walnut Canyon, we developed empirical measures for determining the length of summer and winter wet seasons. The summer wet season was defined as follows. To ascertain the duration of the summer wet season, we calculated the average date of first and last frosts for the Flagstaff Airport weather station, which represents the data point nearest to Walnut Canyon with reliable records on temperature. The calculation was performed as follows. Each day of the year was assigned a numeric value, ranging from 1 (January 1) to 365 (December 31; for leap years, all days after February 29 were assigned their non-leap year value, plus 1). This operation was necessary to allow the calculation of the "average" onset and end of the frost season. The data set then was filtered to include only those cases for which the daily minimum temperature was less than or equal to 32 degrees Fahrenheit. The last frost for each year was considered to be the latest day in the period from January through July that exhibited a daily minimum of ≤ 32 degrees. The first frost for each year was considered to be the earliest day in the period from August through December that exhibited a daily minimum of ≤ 32 degrees. Average dates for the onset and end of the frost season were calculated by summing and averaging numeric values obtained for each year from 1950 through 1992.

Results of these calculations were as follows. The average date for the last frost at the Flagstaff Airport is June 12, and the average date for the first frost in the fall is September 22, with first and last frosts tightly distributed around these dates (Figures 4 and 5). Therefore, an average growing season in Flagstaff is approximately 102 days, extending from about mid-June through late September. Because the Flagstaff Airport lies at a slightly higher elevation than the rim of Walnut Canyon (7,006 ft. [2,135 m.] for the airport vs. 6,700 ft. [2,042 m.] for the canyon rim), the canyon's growing season may be slightly longer. Nonetheless, data from the Flagstaff Airport give a useful proxy measure of temperature conditions at Walnut Canyon, and the net difference between the two locations is probably only a few days.

Summer Wet Season

To calculate the duration of the summer wet season during this interval (approximately mid-June to mid-September), the following procedures were employed. The summer wet season was considered to begin only after the average last frost (June 12), and only when a daily precipitation total at Walnut Canyon met or exceeded 0.10 in. (0.25 cm.). The end of the summer wet season was defined as the last day prior to the average first frost (September 22) that had a precipitation total of ≥ 0.10 in. Thus, within the average frost-free interval from June 12 to September 22, the summer wet season spans the period between the first significant rainfall (≥ 0.10 in.) and the last significant rainfall (≥ 0.10 in.). Because crop growth generally cannot take place before the last spring frost or after the first fall frost, and because a rainfall event of less than 0.10 in. probably does not have a significant effect on soil moisture useful for crops or runoff that might be collected for drinking, it is argued that our empirically-defined measure probably represents a reasonable method for determining the duration of a summer "wet" season that would have had cultural relevance to the Sinagua.

Results of the analysis are provided in

Date of First Frost, Flagstaff Airport Weather Station

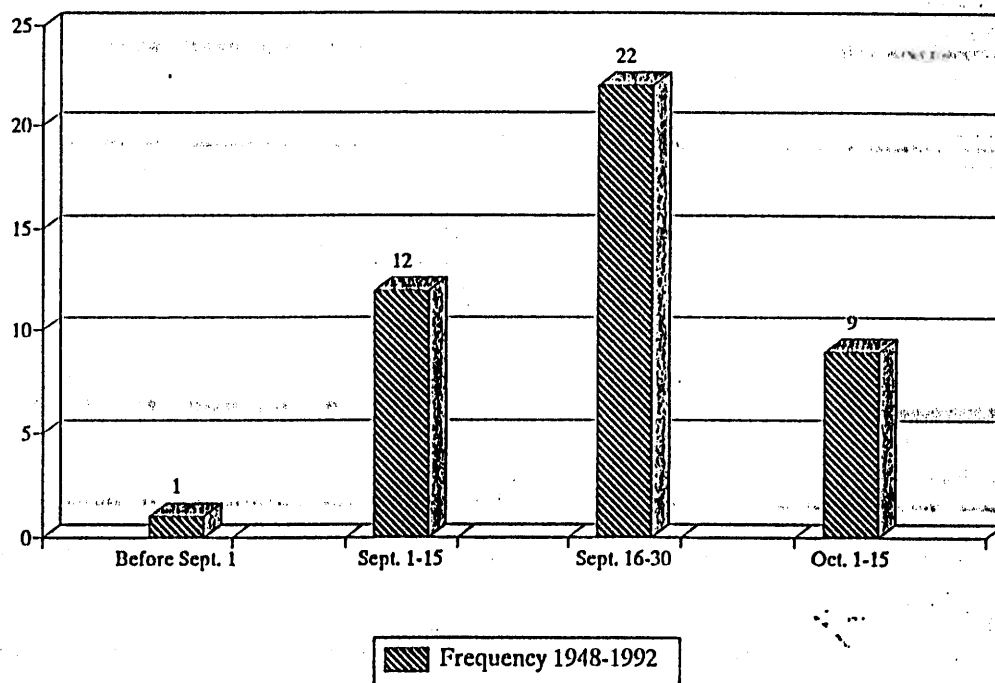


Figure 4. Histogram showing dates of first frost, Flagstaff Airport weather station.

Date of Last Frost, Flagstaff Airport Weather Station

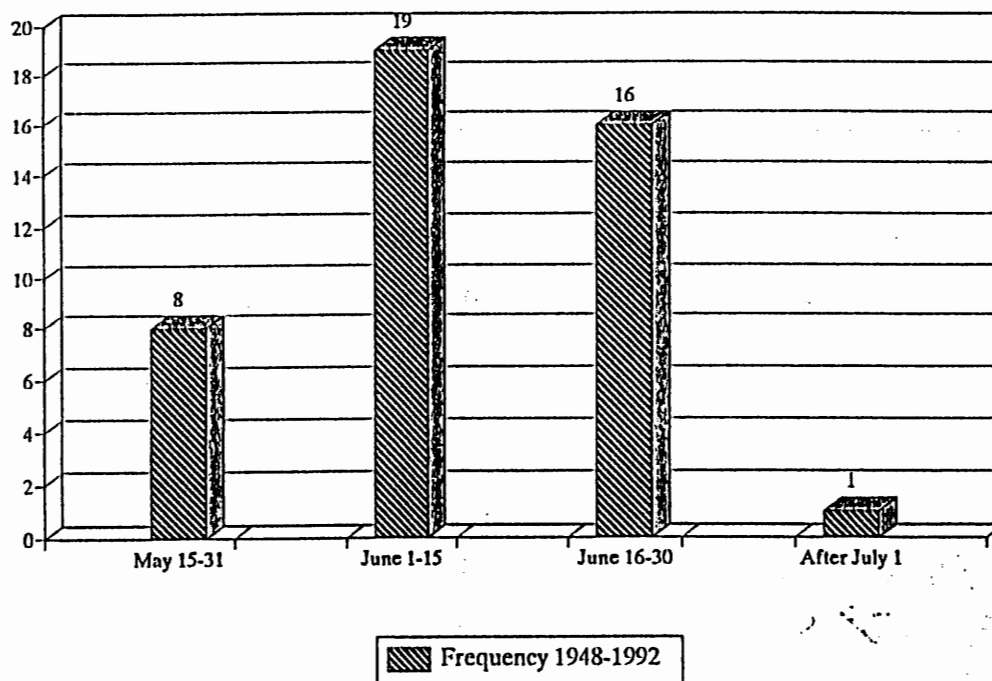


Figure 5. Histogram showing dates of last frost, Flagstaff Airport weather station.

Figures 6-7 and Table 1. The average date for the beginning of summer rains at Walnut Canyon is July 6, and the average ending date is September 7, for an average summer wet season of 64 days. During this season, an average of 5.83 in. (14.81 cm.) of rain falls, an amount representing approximately one-third (31%) of the 18.61 in. (47.27 cm.) of the annual precipitation at Walnut Canyon (Figure 8). The beginning date for the summer wet season (Figure 6) is fairly predictable, occurring nearly two-thirds of the time (63%) within a three week period between the third week of June and the second week of July. Occasionally, however, the rains come as early as June 15, and on one occasion (1993), the summer wet season did not commence until after August 1. The end of summer rains (Figure 7) shows similarly predictable timing.

Winter Wet Season

To determine the duration of the culturally relevant winter wet season, the following methods were used. First, as described above, each day of the year was assigned a numeric value. Next, we examined the weather records for Walnut Canyon to determine a reasonable definition for the first snowfall. Because snowfall is recorded in increments of 0.10 in. (0.25 cm.), it was decided to use a minimum snowfall of 0.10 in. as the threshold for a snow event. In a manner similar to that described for calculating the onset of the summer wet season, we then calculated the onset of the winter wet season. This was done by considering the first snowfall of the season as a minimum snow of 0.10 in. that occurred sometime after August 1. The last snowfall of the season was considered as the last snow of at least 0.10 in. that occurred sometime after the following January 1. Numeric values for the onset and end of the snow season were then summed and averaged for the years 1950-1992.

Results of these efforts are reported in Figures 9-10. At Walnut Canyon, the average date for the first snowfall of the season is November 13, and the average date for the last snowfall is April 12, for an overall winter wet

season of 126 days. During this time, an average of 8.30 in. (21.08 cm.) of precipitation falls, representing about 45% of the average annual precipitation total. That much of this moisture comes as frozen precipitation is reflected in the fact that Walnut Canyon receives an average annual snowfall of approximately 58 in. (147.3 cm.) (Sellers and Hill 1974:543), and has received as much as 91.3 in. (231.9 cm.) in a single month (December 1967). Thus, the winter wet season provides a very significant proportion of the precipitation at Walnut Canyon, with much of it usually stored naturally on the ground as snow.

Drought Periods

Summer and winter wet seasons are punctuated by spring and fall dry seasons. According to Sellers and Hill (1974:8-9):

Drought conditions are most common in Arizona in May and June. ...All parts of the state are affected by this late spring drought, with even the relatively moist central and plateau sections going without rain in one month or the other in about one year out of every four. Unusually dry weather also occurs in Arizona in the fall, perhaps the most pleasant season of the year. ... [T]his dry spell is most pronounced in October in the southern half of the state and in November in the northern half. The fall drought is much less severe than that of spring....

Thus, while the summer and winter wet seasons probably provided the Sinagua with ample opportunities for collecting water, the spring and fall dry seasons would have presented the most extreme challenges in terms of water procurement.

Having developed an empirical measure of the duration of wet seasons, it is now possible to examine the nature and severity of

Table 1. Data for wet and dry seasons at Walnut Canyon National Monument.

	Season				Row Totals
	SPRING DRY	SUMMER WET	FALL DRY	WINTER WET	
Average length of season, in days	95	64	80	126	365
Total average precipitation for season, in inches	1.55	5.83	2.93	8.30	18.61
Percentage of season's contribution to total days in calendar year	26.0%	17.6%	21.9%	34.5%	100.0%
Percentage of season's contribution to total average annual precipitation	8.3%	31.3%	15.8%	44.6%	100.0%
Percentage of days during season with some measurable precipitation	4.2%	22.9%	7.6%	15.3%	
Average quantity of precipitation per precipitation event, in inches	0.391	0.398	0.482	0.431	
Average precipitation per day during season, in inches	0.016	0.091	0.037	0.066	

Onset of Summer Rains, Walnut Canyon National Monument

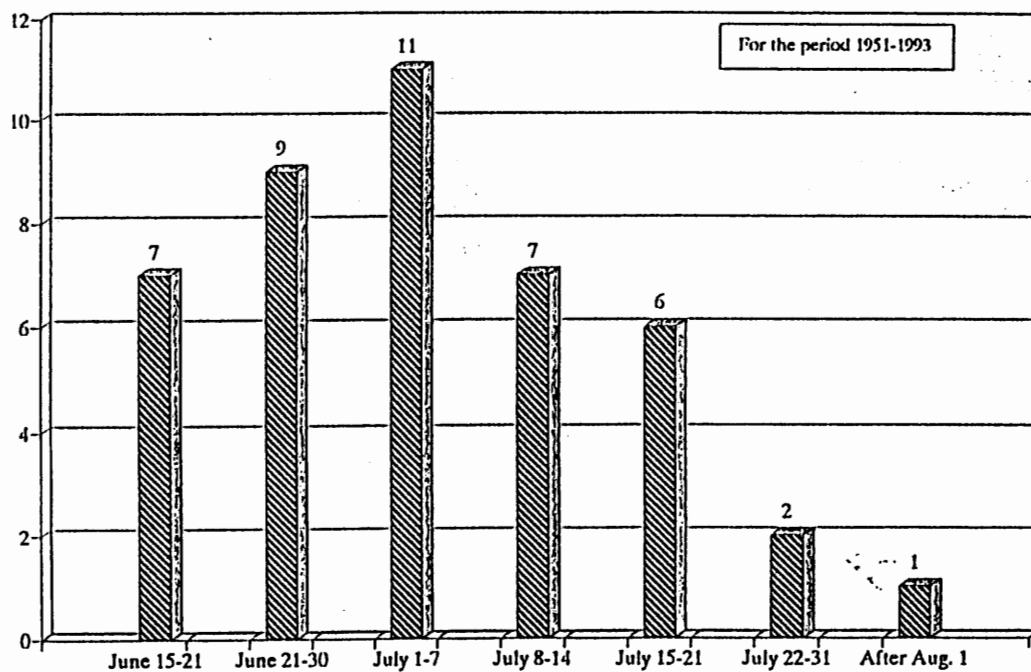


Figure 6. Histogram showing dates for onset of summer rains, Walnut Canyon National Monument.

End of Summer Rains, Walnut Canyon National Monument

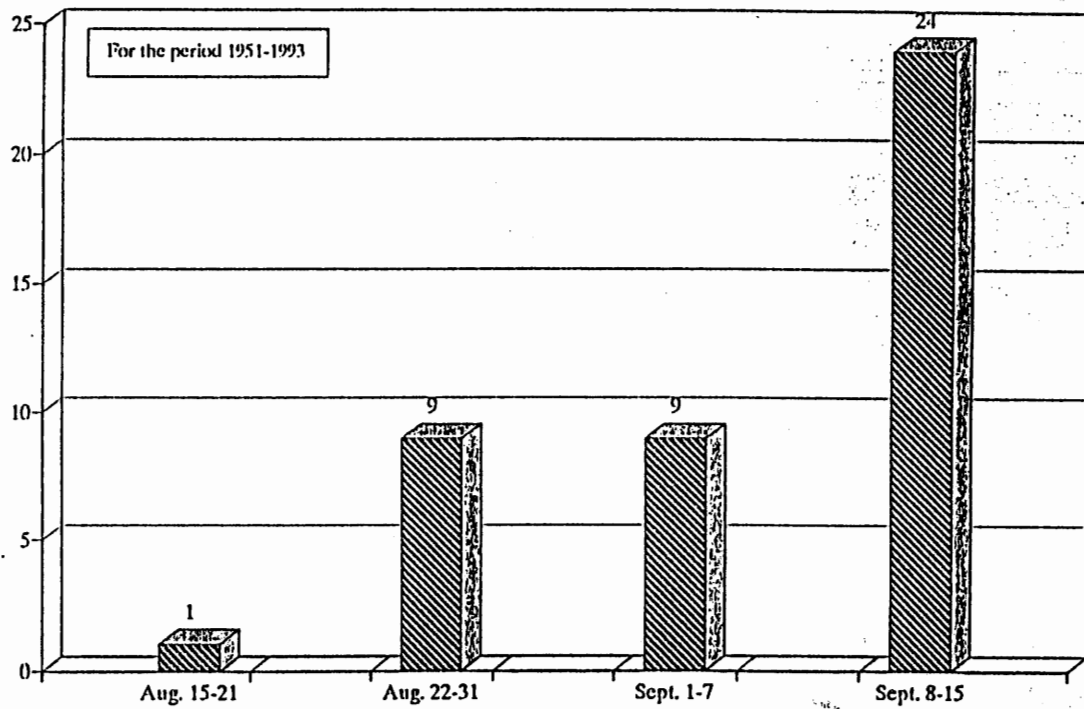


Figure 7. Histogram showing dates for end of summer rains, Walnut Canyon National Monument.

Distribution of Precipitation by Season, Walnut Canyon National Monument

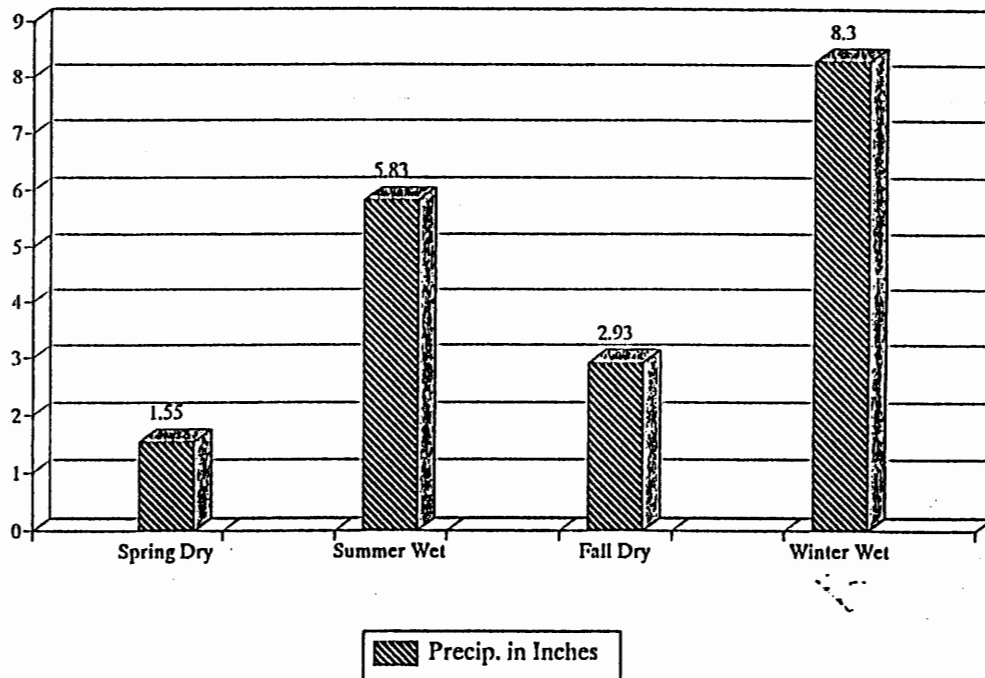


Figure 8. Average distribution of precipitation in inches at Walnut Canyon National Monument, by season.

Date of First Snow, Walnut Canyon National Monument

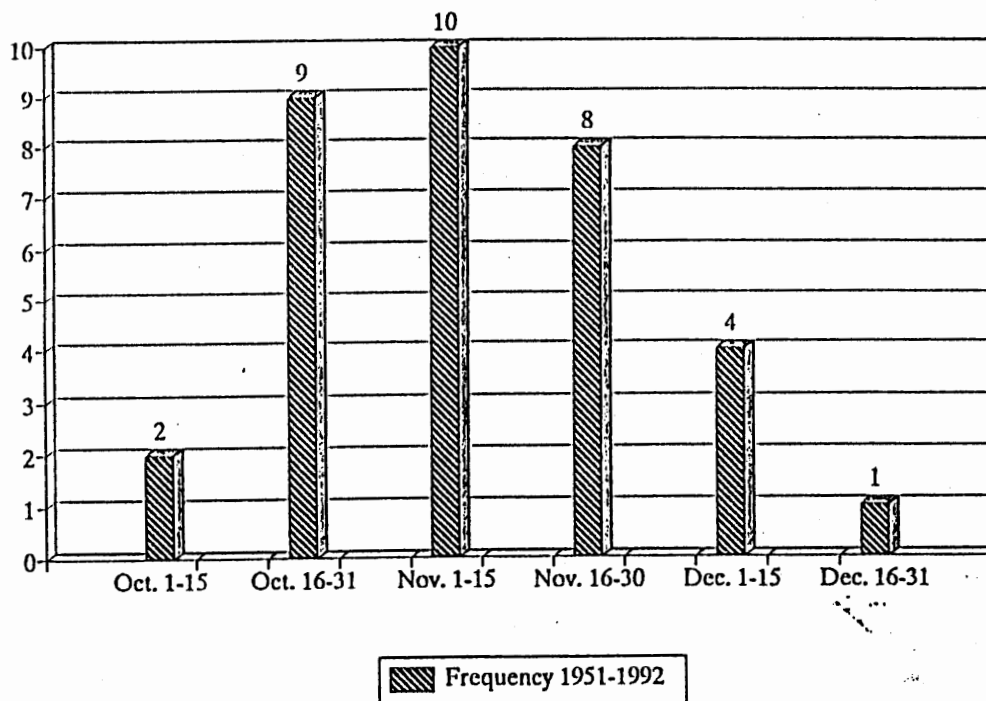


Figure 9. Histogram showing dates for beginning of snow season, Walnut Canyon National Monument.

the dry seasons at Walnut Canyon. Several different measures reflect the scarcity of precipitation during these times. One way to consider the duration of wet and dry seasons is to compare average total precipitation on a monthly basis. As shown in Figure 2, average monthly rainfall during the spring (April, May, and June) and fall (October and November) dry seasons is considerably lower than the monthly averages for the summer and winter wet seasons. Another way to consider the dry seasons is to compare their contribution to average yearly precipitation with that made by the wet seasons. Figures 11-12 and Table 1 show that by several measures, there are dramatic differences in precipitation values for wet and dry seasons. For example, although the dry seasons account for nearly half (47.9%) of the total days in the year, they account for less than one-fourth (24.1%) of the average annual precipitation. Another way to conceive of differences in precipitation is to consider the average frequency of rainfall. Frequency is considered a better measure than intensity, because as shown in Table 1 and Figure 11, the intensity of an average precipitation event does not vary dramatically between the seasons. The spring dry season has the lowest average for a precipitation event (0.391 in. [0.993 cm.]), but the differences between all four seasons are not extreme. Instead, it is the frequency of precipitation events that varies most significantly, with precipitation events coming much more often during the wet seasons. As depicted in Figure 12, precipitation falls on 22.9% of the days in summer, and during the winter wet season, on 15.3% of the days. This compares with figures of only 4.2% and 7.6%, respectively, for spring and fall dry seasons.

Daily precipitation averages during dry seasons are also markedly lower than for wet seasons. Summer and winter wet seasons have values of 0.091 in. (0.231 cm.) and 0.066 in. (0.168 cm.), respectively, while spring and fall dry seasons average only 0.016 in. (0.041 cm.) and 0.037 in. (0.094 cm.) of daily precipitation. On average, then, wet seasons experience about 2.7 times as much precipitation per day as the dry seasons (based on a pooled average of 0.0743 in. [0.189 cm.] of daily precipitation for

wet seasons, vs. 0.0272 [0.0691 cm.] for dry seasons).

However, as informative as average precipitation figures are, they mask significant information about the severity of dry spells that would have been important to prehistoric inhabitants in need of water on a daily basis. Therefore, we devised another measure that gauges the drought severity, one that counts the number of consecutive days without rainfall. Given that much of the prehistoric water collection at Walnut Canyon was probably opportunistic and took place during and soon after individual precipitation events, the number of consecutive days *without* rain is an important index for describing hardship.

Figures 13-16 depict several ways of assessing the length and frequency of rainless streaks at Walnut Canyon for the years 1951-1992. Our definition of a "rainless" day is any day with less than 0.10 in. (0.254 cm.) of precipitation. The rationale for this threshold is our field observation that precipitation events of less than 0.10 in. do not bring significant opportunities for water collection. At Walnut Canyon, a rainfall of less than this is usually absorbed rather quickly into the ground and does not result in runoff or surface accumulation. This is especially true during the spring, when the soil is extremely dry, temperatures are very high, humidities are low, and winds are often extreme (Sellers and Hill 1974:27-34). Fall brings lower temperatures and gentler winds, but soil moisture and relative humidity are still quite low, and, as in the spring, small amounts of rain are quickly absorbed into the ground. Thus, while our definition of a rainless day does not mean a complete lack of precipitation, we believe that it is a reasonable way to conceive of drought conditions in terms relevant to water collection.

To calculate the duration of rainless periods, for each dry season between 1951 and 1992 we computed the length of individual periods between rainfalls of 0.10 in. or more. As shown in Figure 13, there are significant differences between the average length of rainless periods between dry and wet seasons. The spring dry season presents the highest average period (22.9 days between rains), with

Date of Last Snow, Walnut Canyon National Monument

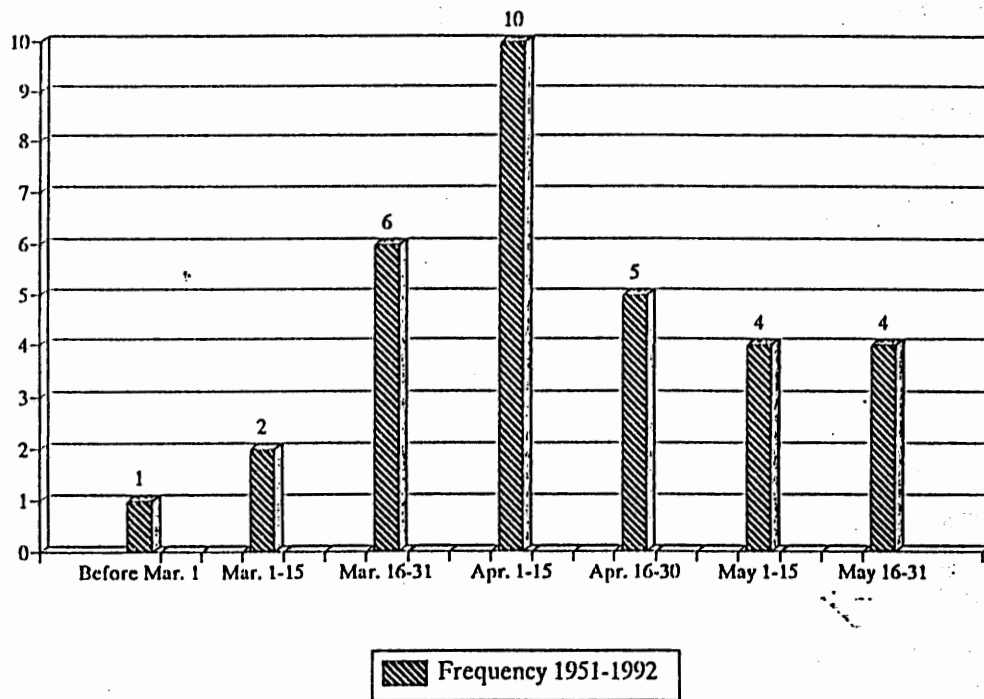


Figure 10. Histogram showing dates for end of snow season, Walnut Canyon National Monument.

Average Precipitation per day, in inches, Walnut Canyon

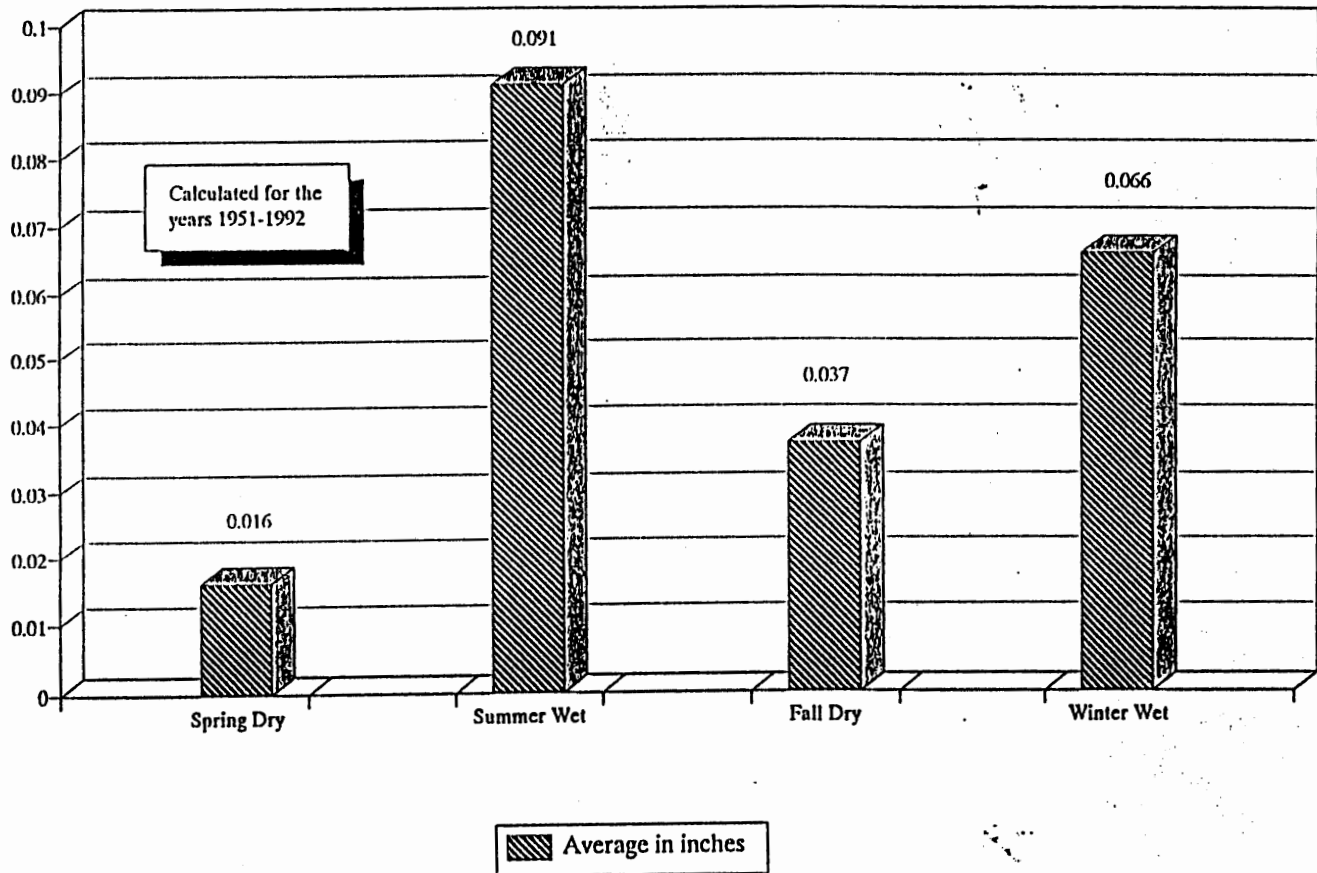


Figure 11. Average precipitation per day in inches, by season, Walnut Canyon National Monument.

Percentage of Days with Precipitation, by Season, Walnut Canyon

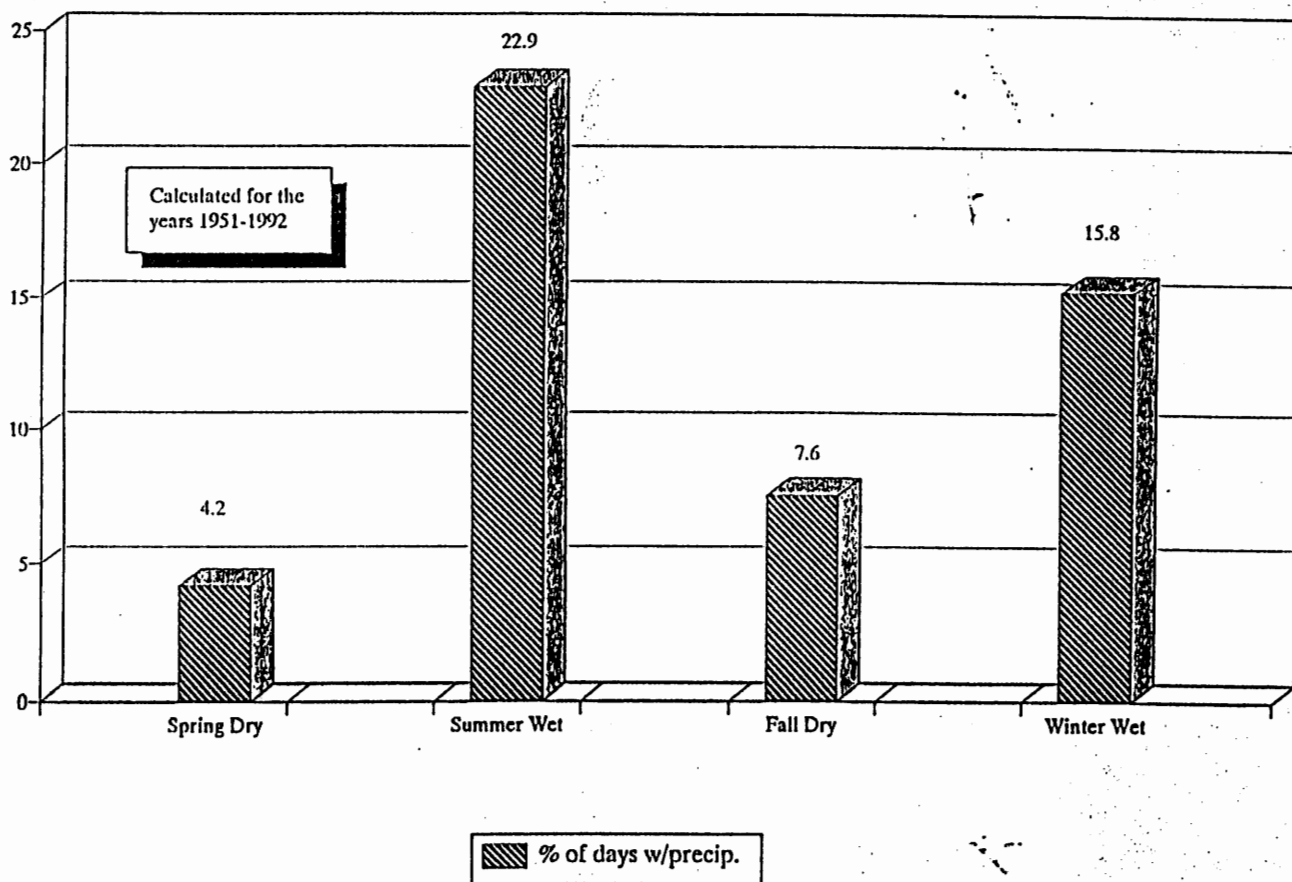


Figure 12. Percentage of days with measurable precipitation, by season, Walnut Canyon National Monument.

Average Length of Periods Without Rain, By Season, WACA

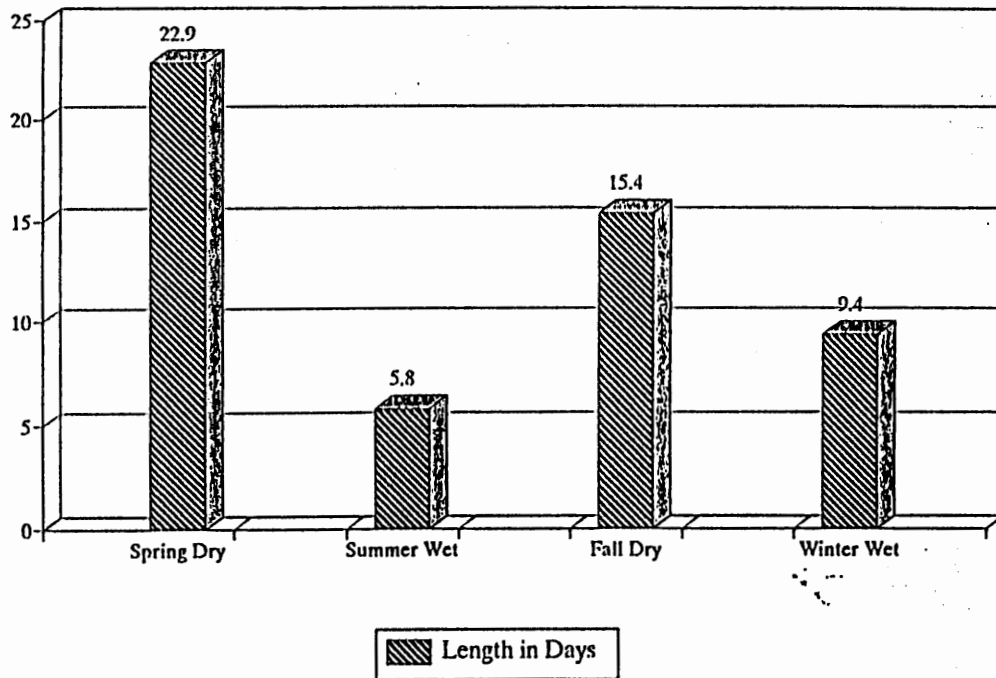


Figure 13. Average length of periods without at least 0.10 inch of rain, by season, Walnut Canyon National Monument.

Median Values for Consecutive Days Without Rain, by Season, WACA

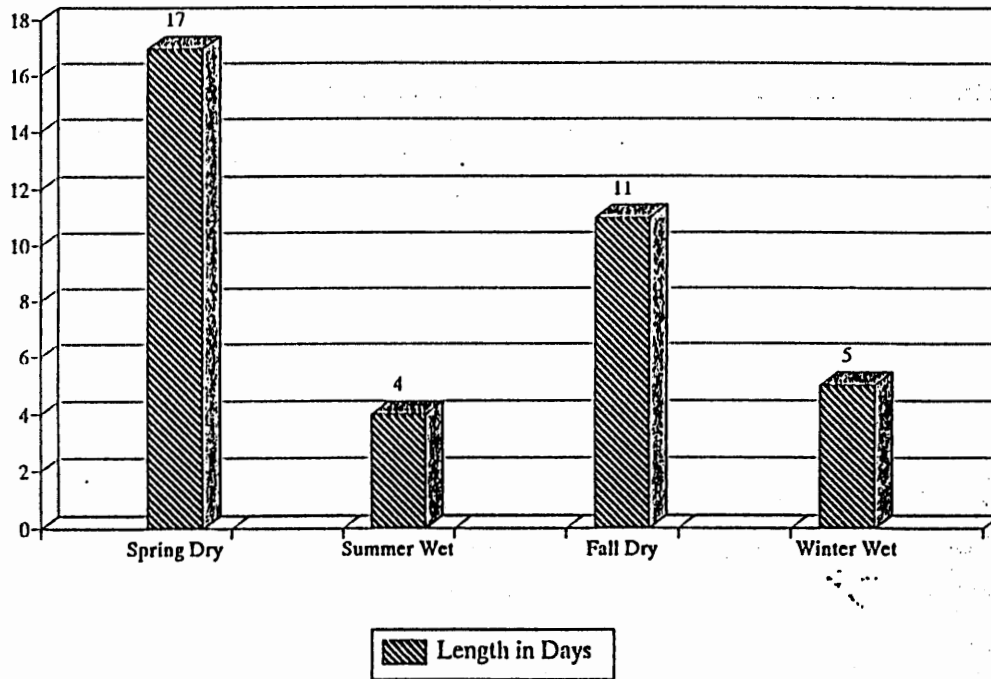


Figure 14. Median values for length of periods without at least 0.10 inch of rain, by season, Walnut Canyon National Monument.

Consecutive Days Without At Least 1/10
Inch of Rain, Spring Dry Season, WACA

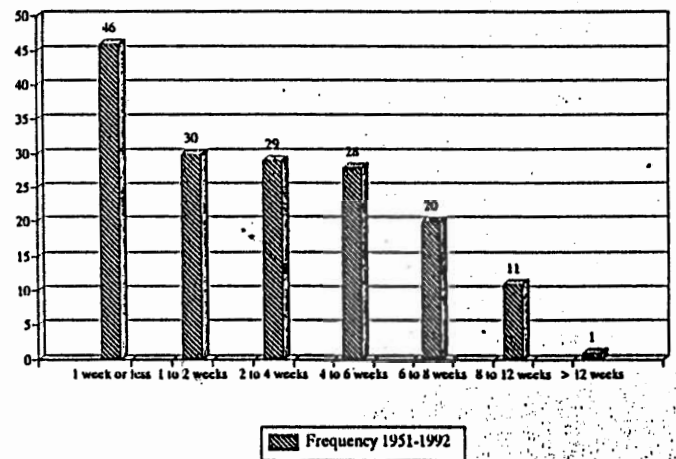


Figure 15. Histogram showing lengths of periods without at least 0.10 inch of rain during spring dry season, Walnut Canyon National Monument.

Longest Streak of Rainless Days During
Each Year's Spring Dry Season, WACA

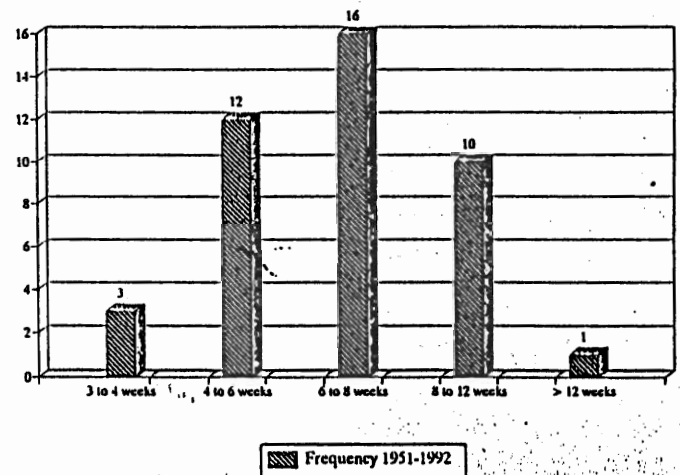


Figure 16. Histogram showing lengths of longest periods without at least 0.10 inch of rain during each year's spring dry season, Walnut Canyon National Monument.

the fall dry season somewhat lower (15.4 days). Summer and winter wet seasons are much less severe in terms of rainless streaks, showing average dry periods of 5.8 and 9.4 days, respectively. Median values (Figure 14) show comparable differences. For the spring dry season half of all rainless streaks exceed 17 days, and for the fall, 11 days. This compares to respective median values of only 4 and 5 days for summer and winter wet seasons.

Looking more specifically at the spring dry season, we can observe that it would have presented the Sinagua with particularly difficult conditions for water procurement. Not only is the overall length of the average spring dry season about two weeks longer than the fall season (95 days for spring, vs. 80 for the fall), and average weather conditions are considerably hotter and drier, the spring season also has the most prolonged dry periods. An example of just how long such periods can be is provided by a drought during the spring of 1974, when a rainless streak persisted for 94 days, from April 2 until July 5. Because weather records from Walnut Canyon span only the past few decades, it seems likely that a more extended climatic data series would show even more extreme droughts.

Figures 15-16 show the distribution of rainless streaks during the spring dry season. Although a fairly high percentage of dry periods (27.8%) are less than one week long, more than one third (36.3%) persist for more than one month, and nearly one fifth (19.4%) last for more than six weeks. This means that on any given day with rain during the dry season, the odds are about one in four that it will rain again within a week, but there is one chance in three that it will not rain again for a month or more, and one chance in five that it will not rain for at least six weeks. During such extended dry streaks, it seems likely that there would have been few opportunities for collection of runoff or other forms of surface water except perhaps for that contained in deep bedrock catchments or issuing from the canyon walls in the form of seeps. However, depending on antecedent moisture conditions, it is possible that in some years even these water sources would have failed. Therefore,

given the fairly high odds of extended drought during the dry season, and considering the absence of reliable springs and the fact that Walnut Creek flowed only seasonally, the Sinagua must have had effective contingency plans - e.g., storage of water in ceramic vessels - to deal with the relatively common phenomenon of dry spells that could last for up to three months.

In summary, the spring and fall dry seasons would have provided great challenges to prehistoric water procurement. These seasons have the fewest chances for opportunistic water collection, and during the most severe dry spells (e.g., the 94 day streak observed in 1974), it is possible that even the few seeps and deep bedrock pools that exist in Walnut Canyon would have dried up. As the Sinagua surely learned through centuries of occupation in the Flagstaff area, it was these "worst case" conditions that entailed the greatest risks to survival and continued occupation of Walnut Canyon. Therefore, it seems likely that the Sinagua would have developed strategies for coping with extended dry spells during the spring and fall. Such strategies will be discussed in a subsequent section of this report.

PALEOCLIMATIC RECONSTRUCTIONS

Because our most detailed understanding of Walnut Canyon's climate comes from weather records accumulated since 1951, a major question concerns the degree to which the climatic record in the past four decades resembles prehistoric climates. Obviously, if modern climate is significantly different, then the above reconstructions may not have much relevance to understanding prehistoric Sinagua water use. For example, if prehistoric conditions were considerably drier than the modern record, then the severity of drought has been seriously underestimated. If conditions were significantly wetter, then our projections regarding the difficulty of obtaining water have exaggerated these problems for the Sinagua. Therefore, a consideration of paleoclimates is necessary to assess the degree to which modern conditions are relevant to the

12th and 13th century Sinagua occupation.

Regarding the nature and seasonal timing of precipitation at Walnut Canyon, it seems likely that modern patterns do indeed reflect those of the 12th and 13th centuries. The general atmospheric conditions that create seasonal precipitation patterns have been persistent throughout the historic period of weather observation, and a variety of data sources (e.g., alluvial stratigraphy, pollen, faunal remains, and vegetal contents of packrat middens) show that there have been no drastic general climatic changes on the Colorado Plateau over the past 2,000 years or so, and probably much longer (Schoenwetter 1962; Rose et al. 1981). Certainly, there have been oscillations in the ratios of summer and winter precipitation, as well as temperature regimes. These oscillations, however, probably would not have resulted in radically different climatic conditions, nor would they have meant markedly different precipitation events in terms of frequency or intensity.

Likewise, average annual precipitation values have probably not changed dramatically in the past several centuries. One extremely important source of information on precipitation values that supports this conclusion is the annual rings of certain tree species in the Southwest (Rose et al. 1981:6). Several tree species in the Southwest, particularly conifers, produce annual rings that are potentially sensitive to yearly differences in precipitation. Refinements in the science of dendroclimatology have resulted in a series of paleoclimatic reconstructions based on tree-ring specimens recovered from living trees and archaeological sites (Dean and Robinson 1977, 1978). These reconstructions are specific to particular areas of the Southwest referred to as "stations." These stations encompass areas of varying size chosen "so as to contain a maximum of dendroclimatic information and to represent the tree growth of a fairly restricted, environmentally homogeneous area" (Dean and Robinson 1977:3). One such station, relevant to reconstructing climate change at Walnut Canyon, is the Flagstaff station, centered on modern Flagstaff, Arizona.

Table 2 and Figures 17 and 18 depict

dendroclimatic reconstructions from the Flagstaff station. These reconstructions are expressed in terms of tree-ring indices, which are standardized values reflecting variation in the width of annual tree rings. Using a set of complex statistical procedures, these measures are standardized and manipulated to extract the maximum amount of climate-related variability. The result is a series of yearly values that reflect the combined effects of annual precipitation and temperature for the station. Table 2 and Figure 17 express this information in terms of decade-level departures in ring-width indices from a mean based on the entire series of climatic data from A.D. 680 to 1970, while Figure 18 shows annual variability for a more restricted period spanning A.D. 1060 to 1310 (an interval encompassing most of the inferred Sinagua occupation of Walnut Canyon). In Figures 17 and 18, the solid line (the 0 axis) reflects the series mean, while in Figure 18 the dashed line represents a running average of values. Table 2, Figure 17, and Figure 18 all show variability expressed in terms of standard deviations from the mean.

A review of the paleoclimatic data from the Flagstaff station suggests two conclusions. First, it appears that prehistoric variability in precipitation, considered both on an annual and decade-level basis from dendroclimatologic reconstructions, is not outside the range of modern climatic variability. It is especially worth noting that by far the wettest decade in the dendroclimatic sequence, at 4.70 standard deviations above normal, occurred during the years 1910 to 1919, and that one of the driest decades (at -2.60 standard deviations below normal) was the period 1870 to 1879. These modern values can be contrasted with the deviations observed during the Sinagua period of occupation (ca. A.D. 1100 to 1300), which range from -2.70 to +1.40 standard deviations from the mean. Hence, it can be inferred that climatic conditions during the Sinagua period were not significantly more extreme than the modern period in terms of precipitation values, and that the Sinagua did in fact confront climatic conditions roughly similar to those of today.

Secondly, it can be observed that the so-

Table 2. Dendroclimatic data from Flagstaff
Station, by decade, A.D. 680 - 1970

(Note: Values are expressed in terms of standard deviations from average of tree-ring growth indices for the entire series of data from the Flagstaff dendroclimatic reporting station; see Dean and Robinson 1977.)

Decade Ending	Value	Decade Ending	Value	Decade Ending	Value
689	2.00	1139	-2.70	1589	-3.10
699	0.70	1149	-0.50	1599	-0.80
709	-2.00	1159	-0.30	1609	-0.70
719	-2.00	1169	1.40	1619	2.10
729	-1.00	1179	0.50	1629	1.40
739	2.50	1189	1.20	1639	-0.10
749	-0.60	1199	0.50	1649	0.90
759	-2.20	1209	0.10	1659	-1.20
769	0.90	1219	-1.90	1669	0.40
779	-0.10	1229	-0.60	1679	0.10
789	0.00	1239	0.70	1689	0.80
799	-1.20	1249	0.70	1699	2.20
809	2.50	1259	0.10	1709	0.00
819	0.30	1269	-0.60	1719	1.20
829	0.40	1279	-0.20	1729	1.70
839	0.80	1289	0.00	1739	-1.20
849	-1.30	1299	-0.40	1749	1.50
859	1.60	1309	-0.80	1759	-0.20
869	0.10	1319	-2.00	1769	0.10
879	0.90	1329	-1.20	1779	-2.00
889	-0.30	1339	1.00	1789	-0.90
899	1.60	1349	-0.50	1799	3.10
909	-2.70	1359	1.30	1809	-1.60
919	0.60	1369	0.90	1819	-1.10
929	-1.40	1379	1.60	1829	0.50
939	0.40	1389	2.90	1839	2.60
949	3.00	1399	-1.10	1849	-1.80
959	-1.30	1409	1.00	1859	-0.50
969	0.70	1419	-0.90	1869	0.00
979	-0.80	1429	-1.10	1879	-2.60
989	-0.90	1439	0.00	1889	-0.90
999	-1.60	1449	-2.60	1899	0.10
1009	0.70	1459	0.30	1909	1.00
1019	0.50	1469	-1.70	1919	4.70
1029	-0.40	1479	0.10	1929	1.90
1039	-1.00	1489	2.40	1939	-1.40
1049	-0.10	1499	0.70	1949	-0.80
1059	1.40	1509	-0.70	1959	-2.40
1069	0.80	1519	-0.70	1969	1.00
1079	0.70	1529	-2.30		
1089	3.00	1539	-1.90		
1099	-2.70	1549	-0.90		
1109	0.10	1559	1.00		
1119	1.00	1569	1.70		
1129	-1.00	1579	-2.30		

DENDROCLIMATIC DATA FROM FLAGSTAFF STATION, EXPRESSED AS DECADE-LEVEL DEPARTURES FROM NORMAL

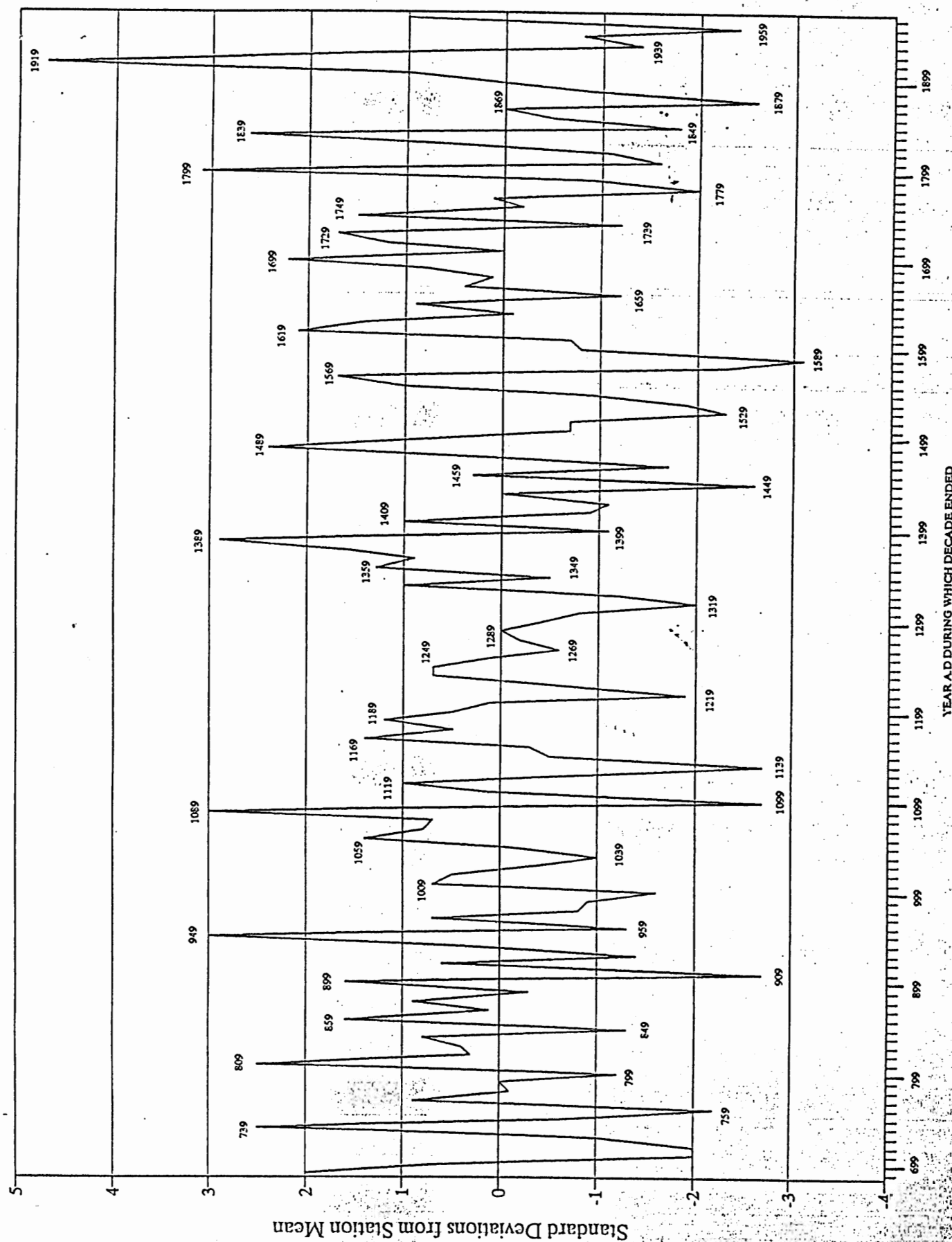


Figure 17. Precipitation values from dendroclimatic reconstructions from the Flagstaff, Arizona station, showing decade-level values expressed in standard deviations from the mean, A.D. 680-1970. The solid line represents the mean.

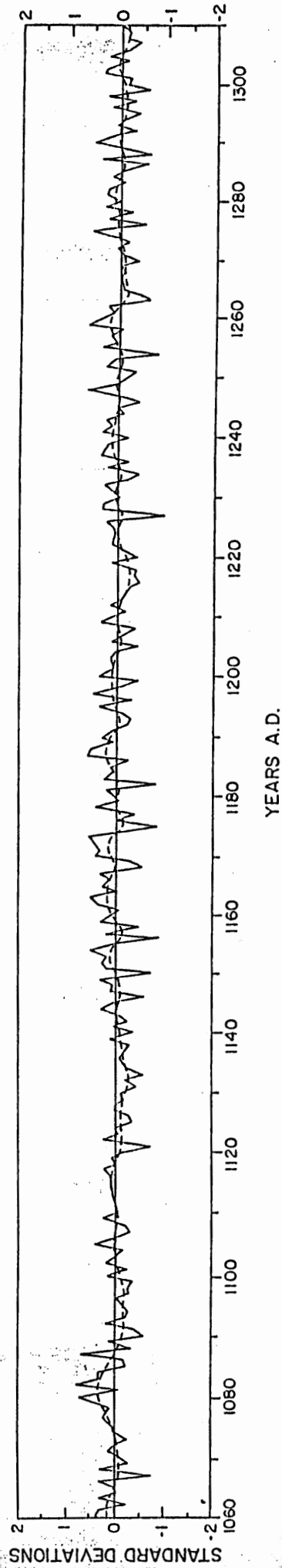


Figure 18. Precipitation values from dendroclimatic reconstructions from the Flagstaff, Arizona station, showing yearly values expressed in standard deviations from the mean, A.D. 1060-1310. Solid line shows yearly departures from normal, dashed line represents average values.

called "Great Drought," a period of sub-normal precipitation that afflicted some parts of the northern Southwest during the years A.D. 1276 to 1299, did not significantly affect the Flagstaff area. Decade-level precipitation values during this period for Flagstaff range from 0.0 (the mean) to only 0.40 standard deviations below the mean. These values do not signal a particularly severe drought, and in fact are exceeded in severity by several consecutive decade-level values during earlier periods of Sinagua occupation (e.g., from A.D. 1130 to 1159, and A.D. 1200 to 1229). It would therefore appear that the Great Drought cannot be implicated directly as a causal factor in the Sinagua abandonment of Walnut Canyon, especially if such a model attempts to relate the climatic conditions of the late 1200s to agricultural failure or a lack of drinking water. The Sinagua had experienced even more severe precipitation deficits in the preceding 150 years or so, and thus evidently had developed effective means for coping with drought.

PREHISTORIC CAPTURE, STORAGE, AND USE OF WATER IN THE SOUTHWEST

In recent years there has been an increased interest in the topic of how prehistoric peoples of the Southwest were able to capture, store, and use water (Ritterbush 1984; Crown 1987; Scarborough 1988; Bayman and Fish 1992). Although water storage features can be documented as far back as the early Archaic (ca. 6,500 years ago; see Evans 1951; Agenbroad and Huckell n.d.), most of those discovered in the Southwest date to the late prehistoric period and are associated with an agricultural adaptation. Systematic study and comparison of prehistoric water-management technologies is still relatively undeveloped, so many of the efforts thus far have concentrated on description and classification (e.g., Crown 1987). However, as noted by Scarborough (1988) and Bayman and Fish (1992), the capture and storage of water was a vitally important aspect of prehistoric peoples' adaptation to arid environments. In fact, the development of effective technologies

to cope with the problem of procuring domestic water was probably a crucial factor in the occupation of many areas of the Southwest, and the failure of these technologies in the face of prolonged drought may have been an important factor in seasonal or episodic abandonments. Bayman and Fish (1992:301-303) further propose that the development and elaboration of water storage technology may have had even broader theoretical importance. In their view, the effective use of prehistoric reservoirs greatly expanded the scale of Hohokam occupation in the Sonoran Desert, hence enlarging the scope of regional exchange networks. Whatever the merits of these particular arguments, it is clear that the study of prehistoric water management in the Southwest is a growing topic of interest, and one that may have considerable potential for understanding the foundation, interaction, and abandonment of individual settlements and perhaps even settlement systems as a whole.

Crown (1987) provides probably the most useful summary and classification of prehistoric features that were designed to collect and store water. She points out that there has been inconsistent application of terminology used to describe the water storage features of the prehistoric Southwest, and proposes a more comprehensive classification that concentrates on the means by which water was introduced into a feature. In her typology, a major distinction is made between Diversion Features, which shunt water from a natural source (e.g., canals and ditches that divert water from a stream), and Conservation Features, which conserve water at its source. The latter category (Conservation Features) is further subdivided based on whether or not the source of water is "internal" (coming from subsurface water tables or surface springs), or "external" (coming from surface runoff).

Crown's (1987:213) typology consists of five major types of features. The first, termed *reservoirs*, are defined as "basins filled by artificially diverted water." Thus, the term reservoir is applied only to features that hold water carried to them by ditches or canals originating from a stream. For those features that conserve water from an internal source,

Figure 19. Artist's conception of capturing water from canyon rim runoff (in preparation).

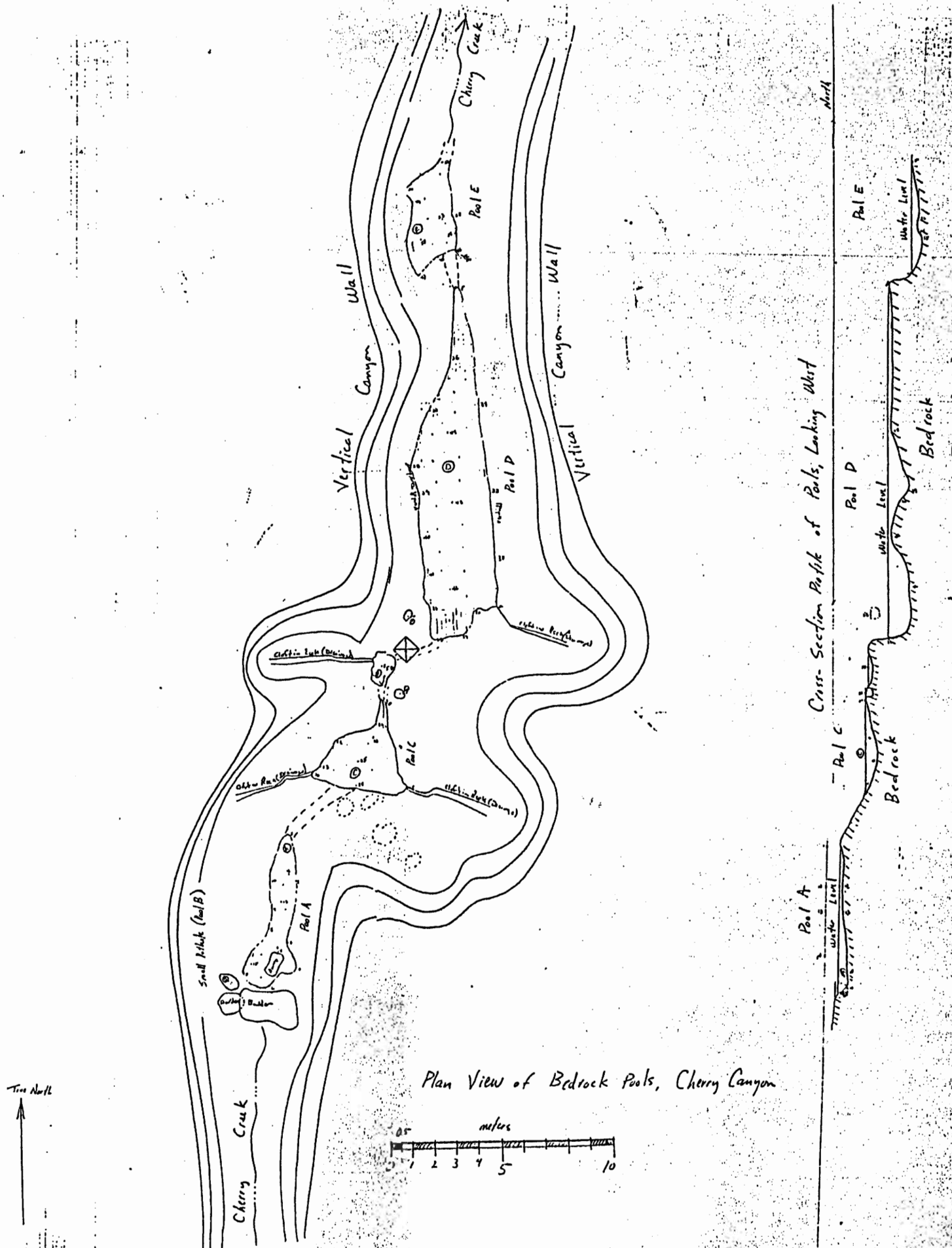


Figure 20. Plan and profile map of Cherry Canyon bedrock pools (to be drafted).

two categories are proposed: *wells*, for "features tapping subsurface waterflow," and *walled springs*, used to describe improvements designed to capture surface spring water. Features that hold surface runoff are designated as follows: *catchment basins*, described as impoundments "situated in incised stream channels," and *retention basins*, distinguished by their location "in level or sloping terrain, but not in incised stream channels."

The features described by Crown were used in all parts of the Southwest. At the time her summary was written (in 1987), 150 water storage features had been described in the literature with sufficient precision to warrant classification (Crown 1987:214). Since that time, many additional water storage features have been reported (e.g., Scarborough 1988; Bayman 1992). Though the sample is not yet sufficiently large to justify strong conclusions, Crown has noted that retention basins and catchment basins are a relatively late prehistoric phenomenon, and that the development of such features may have been an important prerequisite to pueblo aggregations. In the following section, we will explore how the Sinagua residents of Walnut Canyon may have used a variety of features, including catchment and retention basins, to supply their domestic water needs.

WALNUT CANYON AND WATER

As noted in the climatic summary presented above, precipitation at Walnut Canyon comes mostly during two distinct wet seasons: (1) a summer season, featuring brief, intense thunderstorms, and (2) a winter season, when much of the moisture falls during more prolonged precipitation events, often in the form of snow. Also as noted, these two seasons are separated by prolonged periods with little or no precipitation, referred to as the spring and fall dry seasons. Because these four seasons bring quite different opportunities for the collection of water, a consideration of Sinagua water procurement practices requires that we review how the Sinagua might have collected water when it was available at the surface, and how they might have coped in

times when it was not. In the following sections, we will discuss Sinagua water collection and storage methods during the summer and winter wet seasons, and how the Sinagua could have dealt with the problem of water procurement during the spring and fall dry seasons.

Probable Sources of Surface and Near-Surface Water

Prior to the construction of the dams on Upper and Lower Lake Mary, Walnut Creek had a somewhat predictable seasonal flow. In years when there was sufficient snowfall in the preceding winter season, the creek would begin to flow when daytime temperatures rose high enough to melt the snowpack on the surrounding terrain and send the resulting meltwater into tributary drainages. The amount of flow depended upon a number of factors, including the quantity of snow, the amount of residual soil moisture, and temperatures. An additional factor in the timing and amount of flow is rainfall. If weather conditions are right, heavy rains can come at any time during the winter and spring seasons. When such rains fall on top of a heavy snowpack, the snow melts quickly and is rapidly converted into runoff, resulting in flood conditions. Just such an event happened in mid-February, 1993, causing such a heavy volume of runoff that Upper and Lower Lake Mary were filled to overflowing. Water cascaded over the dams and into Walnut Creek, causing an extremely heavy flow that persisted for several days.

It is impossible to specify for the prehistoric past how frequently Walnut Creek would have flowed, when the flow would have begun, and when it would have ended. However, modern observations suggest that the creek would have flowed during the late spring of most years, and that the flow would have lasted from several days to several weeks depending on the conditions cited above. The implications of this flow for the prehistoric Sinagua are that in most years, sometime from late March to early May, there were opportunities to collect water from the creek

bed. Thus, as the snow in and around Walnut Canyon began to disappear, snowmelt in the canyon bottom became available as surface flow.

Observations at Walnut Canyon in the spring of 1993 suggest that even in years when the flow is particularly heavy, surface water in the canyon bottom begins to disappear by mid- to late April. This means that the flow of water in the canyon ceases, and water is available only from the deeper pools in the channel of the creek. As noted above, there is some evidence to suggest that since the construction of Upper and Lower Lake Mary dams, the canyon bottom has become choked with silt and vegetation, and many of the bedrock catchments that once existed in the channel have been filled. However, we can assume with relative certainty that during the Sinagua period of occupation there were a number of bedrock catchments in the canyon bottom. Furthermore, assuming that the creek began to flow with snowmelt sometime in the month of March, and continued to flow until mid- to late April, we can infer that in most years these catchments would have formed pools that persisted throughout this interval.

How long such pools would have continued to hold water is very difficult to assess. Because they are now filled with sediment, their volume can no longer be measured directly. However, in the summer of 1993 we were able to map and measure the volume of a similar bedrock catchment feature in the bottom of Cherry Canyon, a tributary stream that enters Walnut Canyon from the south. At this site (Figure 3), there were four major catchments, each of which was 0.5 to 1.0 meters deep (Figure 20). Based on a consideration of their surface area and depth, we have calculated their aggregate volume of these pools at approximately 6,900 U.S. gallons. As we will argue below, based on a consumption rate of about 0.875 gallons of water per person, per day, and given a peak population of 185 persons at Walnut Canyon, this set of pools could have supplied all Sinagua residents of Walnut Canyon with drinking water for about 42 days (assuming it was collected immediately, with no loss due to

seepage or evaporation).

Therefore, a major source of water during the latter part of the spring, and continuing for an unknown time into the spring dry season, could have been the bedrock pools at the bottom of Walnut Canyon. We envision that the Sinagua probably collected water from these pools into large ceramic vessels. At times when the pools were too shallow to immerse the vessel, water could have been collected using ceramic scoops or ladles. Both of these artifact categories – scoops or ladles, and large jars – have been observed and collected from Walnut Canyon.

Precisely where the pools were located, and how the Sinagua would have gained access from the cliff dwellings above, remains speculation pending archaeological surveys designed to locate trails. However, several likely buried pools, marked by seeps, accumulated fine sediments, and hydrophilous vegetation types, have been located (Figure 3), and it seems possible that a careful survey of the canyon walls could locate the most probable access routes. Trails might be discerned by first identifying the most likely topographic routes, then performing a careful survey to see if the routes were marked by a greater density of artifacts than exist in adjacent areas. Prehistoric trails have successfully been identified using archaeological remains in other parts of the Southwest, and the routes used by Walnut Canyon residents to access their water sources are good candidates for successful study.

A final bit of evidence concerning the use of bedrock pools at Walnut Canyon concerns petroglyphs. One of the most celebrated petroglyphs at Walnut Canyon, reproduced by the National Park Service on trail signs, trail guides, and other media, is a set of twin figures, facing one another, each holding a long, thin object that intersects with the face in about the position of the mouth. These twin figures have been interpreted in the past as Kokopelli images, and the long thin objects have been interpreted as flutes. However, another possible interpretation is that the figures are not playing flutes, but rather are drawing water from a pool through a long straw formed by a reed or horsetail (*Equisetum*

sp.) plant. In this interpretation, the "twin" representation might be an attempt to show the reflection of the figure in a pool of water.

Whatever the interpretation of this particular glyph, it is important to note that the "Kokopelli" petroglyph is accompanied by others, and that they exist in the canyon bottom not far from a number of seeps and probable locations of bedrock pools. It is recommended that if possible and if appropriate tribal permission is granted, an ethnographic consultation be done with members of the Hopi tribe to assess the possibility that the petroglyphs here are related to water symbolism.

In most years at or about the time the snowmelt has ceased to flow in Walnut Creek, there begins a prolonged period of extremely dry conditions that we have characterized above as the spring dry season. In our definition, this season persists from about mid-April to mid-June. During this time, temperatures rise, there is a great deal of wind (usually from the west or southwest), and precipitation is very scarce. Because these conditions can persist for weeks on end, drying up any residual surface moisture left from the winter wet season, this season would have presented the Sinagua with their most severe challenges to water procurement.

To deal with the late spring drought, it seems likely that the Sinagua developed the means to store sufficient quantities of drinking water. As we noted above, the most likely technology for storing water involved the use of very large ceramic vessels. Assuming that the Sinagua were aware that the spring drought occurs with regularity, but that it is also eventually broken by the onset of the summer rainy season, it can be inferred that they probably collected and stored sufficient water to last throughout their perception of what would have constituted a "worst case" scenario for spring drought. As discussed in a previous section of this report, weather data from Walnut Canyon indicate that during the past 40 years, the most severe rainless streak of the spring dry season was 94 days. Although it is impossible to know with certainty how this streak corresponded with the availability of

surface water in the bed of Walnut Creek, it seems probable that the stream remained dry during most of this interval. If so, and if the historic stretch of 94 days is representative of comparable prehistoric late spring drought periods, the Sinagua would have been wise to have kept on hand enough water to last during such a period. As we will discuss in more detail below, it would have easily been possible for the Sinagua to store a 100-day water supply without much difficulty, particularly if this water were contained in large pottery vessels (approximately 20 gallons each) placed in the abundant storage rooms that exist in and around the canyon.

The spring dry season ends with the onset of the summer rains, which begin with considerable predictability sometime in the latter part of June or early July. When the summer rains commence, there come a number of opportunities for obtaining water, either by capturing it directly as it falls or cascades off the canyon walls, or by gathering it from pools that form after a heavy rain. Based on personal observation at the Cherry Canyon catchment basins described above, heavy summer thunderstorms often induce local runoff sufficient to cause Walnut Creek to flow for short periods and thus fill the bedrock catchments that once existed in the bottom of Walnut Canyon. In addition, the runoff often soaks into the bedrock walls of the canyon, and later issues forth as surface flow in the form of seeps near the canyon bottom.

The summer rainy season therefore would have ended the Sinagua reliance on stored water reserves. During the summer, we can infer that the Sinagua would use a variety of water collection techniques. Perhaps the easiest of these would have involved placing a ceramic vessel in a strategic location underneath a rock overhang, and capturing the water flowing off the overhang in a ceramic vessel (Figure 19). During the course of this study, the authors have had several opportunities to observe the runoff from thunderstorms cascading off the canyon walls, and it would be easily possible to collect hundreds of gallons of water in a very short time simply by moving a pot into the right position below the canyon

rim. Just such an opportunistic method of water collection seems to have been preserved at Wupatki Pueblo, where Albert Schroeder (1944) discovered the remains of a large Moenkopi Corrugated jar placed beneath a bedrock outcrop in such a position that it would have captured the water flowing from a bedrock outcrop above. In addition, it would have been a simple matter to employ a ceramic ladle to scoop water from the many shallow "potholes" and depressions that exist on the horizontal rock outcrops of Walnut Canyon.

The opportunistic methods of water collection described above most likely would have been supplemented abundantly by the water contained in bedrock catchments in the canyon bottom. Because of the volume of water accumulated in these catchments, we infer that in the summer, the Sinagua collected water from them in the manner described above for collecting the snowmelt runoff of the spring. Such pools may have been an especially important water source later in the summer, when the heavy rains taper off and the opportunities diminish for collecting runoff directly in jars. In addition, the bedrock pools were probably the source of much of the water that was collected for storage throughout the fall dry season, in the time between the end of the summer wet season (about mid-September) and the beginning of the winter wet season (about mid-November).

Conversion of Snowpack into Water

Although summer and winter wet seasons exhibit a number of similarities in the regularity and intensity of precipitation events (Sellers and Hill 1974:9), they differ in one very important respect, and that is the wintertime presence of snow and other forms of frozen precipitation. For the Flagstaff Airport weather station, approximately 75 percent of all winter precipitation comes in the form of snow (Sellers and Hill 1974:208). In terms of prehistoric water procurement and use, snow has one very special quality: until it melts, it forms a vast blanket of frozen water that does not immediately infiltrate into the ground and can be easily obtained and used for drinking

water.

Unfortunately, no reliable data exist to document the intervals during which snow remains on the ground during the winter wet season. The weather data from Walnut Canyon do record observations of existing snow depth, but these do not appear to have been made consistently, and in any case they refer only to the area immediately surrounding the weather instruments and do not encompass shaded areas and canyon slopes. However, because of the cold temperatures that prevail at Walnut Canyon during the winter, the shade provided by vegetation, and the shade that exists on the north-facing canyon slopes, snow often persists in at least a few locations from late fall through the middle of spring. Personal observation of the snow cover at Walnut Canyon suggests that in most years, some amount of snowpack would have been available to Sinagua residents from late fall to early spring, i.e., from about mid-November until mid-April.

An additional factor in the use of snow involves temperature differentials between day and night, wherein daily cycles of thawing and freezing prolong the moisture available from snow by locking it up in the form of ice. During the day, when winter temperatures often rise above freezing at Walnut Canyon, water from melting snow flows down the canyon walls. At night, when temperatures drop well below freezing, the water solidifies as ice. Some locations in the canyon, particularly on the north-facing slopes and in areas beneath bedrock outcrops, accumulate significant quantities of such ice, which is much more resistant to subsequent melting than the snow cover. Thus, ice that forms from snowmelt would also have provided Sinagua residents with a readily available source of water during the colder months.

Cultural practices might also have played an important role in the use of snowpack by the Walnut Canyon Sinagua. It has been reported that the Zuni would conserve snow and delay its melting by rolling it into large snowballs, which in turn would be rolled into water-retention basins excavated into the ground and walled with earth and stone.

embankments. According to Mindeleff (1891:91):

The Zuni claim to have practiced a curious method of water storage. They say that whenever there was snow on the ground the villagers would turn out in force and roll up huge snowballs, which were finally collected into these [water retention] basins, the gradually melting snow furnishing a considerable quantity of water. The desert environment has taught these people to avail themselves of every expedient that could increase their supply of water.

At Walnut Canyon, no built retention basins have yet been identified that might have been used for such a purpose. However, along the canyon rim and sides, snowballs could have been rolled onto bedrock potholes capable of holding the water from melted snow. The rolling of snowfall into large snowballs in itself might also be considered an effective water storage technique, since the collection and compression of the snow delays its melting. It was recently reported to the senior author by a Hopi resident of Shungopavi that several decades ago, as a boy, he used such a method to conserve snowfall. At his mother's instruction, snowballs were made and rolled into reservoirs and potholes where the meltwater could be conserved. Whenever a quantity of water was immediately needed, his mother would remove snow from the large snowball, collect it into a pot, and melt it indoors. He commented that such water was especially good for drinking because of its purity.

In summary, snowpack at Walnut Canyon was probably an important source of drinking water from about mid-November until perhaps as late as mid-April. Of course, there is considerable yearly variation in the overall amount of precipitation and in the amount of this precipitation that falls as snow. Nonetheless, because Walnut Canyon receives

an average of nearly five feet of snow per year, snow was probably an extremely important factor in the Sinagua occupation of Walnut Canyon.

Quantification of Water Use at Walnut Canyon

One way to consider the seasonal and annual water requirements of Sinagua residents at Walnut Canyon is to model their peak population levels and per-capita water consumption and use. Fortunately, recent full-scale archaeological survey of Walnut Canyon National Monument provides a basis for estimating population levels, and a few studies (e.g., Adolph 1947) have explored the issue of daily water requirements in arid environments. In addition, there have been a number of recent attempts to model the agricultural production of prehistoric pueblo populations. Combined with reliable population estimates, these efforts give a basis for modeling the annual crop requirements of the Sinagua, and allow us to estimate overall annual water use.

Estimating Sinagua Population at Walnut Canyon

Past archaeological investigations at Walnut Canyon, particularly those completed within the last decade (Baldwin and Bremer 1986; Bremer 1988; Harper 1993), have produced a wealth of information regarding the Sinagua occupation. The most important effort has been an intensive archaeological inventory survey conducted by the U.S. National Park Service in 1985 and 1987. This work resulted in the documentation of 249 archaeological sites within an area of approximately 1,600 acres (648 hectares). Three more sites were discovered during a 1991 site recording project undertaken by Christopher Harper of Northern Arizona University, boosting the total number of recorded sites to 252.

Split-twig figurines and lithic artifacts (Olson 1966; Baldwin and Bremer 1986:128) indicate that prehistoric occupation at Walnut Canyon extends back to at least the middle Archaic period (ca. 3,000 to 4,000 B.P.), but the

vast majority of archaeological evidence dates to the Sinagua period of occupation. Based on the temporal range of the tree-ring dated ceramic types recovered from Sinagua sites, it appears that the occupation probably began within the first few decades after the eruption of Sunset Crater (i.e., by about A.D. 1100) and ended no later than about A.D. 1300. In fact, the most intensive period of occupation at Walnut Canyon probably took place during the Elden and Turkey Hill phases of the Sinagua culture, ca. A.D. 1150 to 1275, and it appears that the population peak probably came some time around A.D. 1250.

The most impressive archaeological remains in the canyon are a series of masonry rooms built by the Sinagua within natural alcoves and shelters formed by erosion of the canyon's limestone strata. Although many of these structures were heavily damaged and their artifacts and other contents were removed by vandals prior to the creation of Walnut Canyon National Monument, most retain their original outlines and give reliable information on form. Many of the rooms have standing walls and show important construction details such as doorways, threshold steps, and ventilator holes. Several rooms retain wall and floor plaster, which is often blackened from smoke. Dry conditions within the rooms have preserved a number of normally perishable artifacts and materials, including cordage, corn cobs, sandal fragments, twigs, and matting. Many of the rooms also contain potsherds, chipped stone debitage, broken ground stone, and other artifacts. Trash deposits exist downslope from the rooms, some of which were deposited during the prehistoric occupation, and some of which have been thrown from abandoned rooms by vandals during their excavations.

Several prehistoric sites also exist above the canyon rim. The majority of these are classified as single structure, single room, "field houses," presumed to have been occupied or used by the Sinagua on a temporary basis in conjunction with agricultural pursuits (Bremer 1988:129; Harper 1993:108). Rock alignments, terraces, and check dams are often located within a short distance of these sites, marking

the locations of probable agricultural plots (Cramer 1965; Baldwin and Bremer 1986:89; Harper 1993:30). Many of the check dams and terraces lie in the beds of small tributary streams leading into the canyon, and quite clearly were intended to trap runoff and sediment carried by the streams. In addition to these sites, there are also a few multi-room masonry pueblos that most likely served as permanent habitations, and a more limited number of large masonry structures that have been classified as "forts" or ceremonial rooms (Baldwin and Bremer 1986:108-127).

Because recent archaeological surveys have produced detailed maps and descriptions of architectural features, the well-preserved and relatively well-dated pueblo architecture at Walnut Canyon is useful for reconstructing prehistoric population levels. In a detailed study of Walnut Canyon's pueblo ruins, Harper (1993) developed a functional typology of sites and individual rooms. The typology relied primarily on the overall size of each room, which was carefully measured in terms of interior dimensions.

Based on discontinuities in the distribution of size data from both canyon and mesa-top rooms, Harper identified three major size classes, which he believed could be interpreted as functional categories. For canyon rooms, the smallest size class, consisting of rooms less than 11.0 square meters, were identified as probable storage rooms (Harper 1993:112-125; see also Dean 1969; Hill 1970; Nordby 1981; Adams 1983:59; and Burchett 1990). Intermediate size rooms, ranging from about 11.0 to 18.50 square meters, were interpreted as probable habitation rooms. The largest size class, greater than 18.50 square meters, were thought to have been devoted to specialized uses, probably ceremonial. Mesa top rooms showed similar breaks in size categories, with rooms up to 9.99 square meters designated as storage rooms, those from 10 to 16.99 square meters as habitation, and those at or above 17.0 square meters as ceremonial rooms.

Applying this typology to the Walnut Canyon rooms, Harper identified a total of 109 habitation rooms, 365 storage rooms, and 20

Table 3. Data for population estimates, peak of Sinagua occupation at Walnut Canyon National Monument.

Basis for Population Estimate

Assumed Percentage of Rooms in Use	Number of Rooms	Naroll 1962*	Casselberry 1974**	Clark 1974***
50%	55	74	123	246
75%	82	110	185	368
100%	109	147	246	491
	Average Number of People per Room	1.36	2.27	4.53

* Based on one person per 10 square meters of floor space.

** Based on one person per 6 square meters of floor space.

*** Based on one person per 3 square meters of floor space.

ceremonial rooms. This ratio of number of habitation rooms to number of storage rooms (approximately 1 to 3.35) compares favorably with habitation/storage room ratios from a variety of 12th and 13th century sites in the northern Southwest (Harper 1993:123). In addition, the ratio of floor areas for habitation and storage rooms (approximately 1 to 1.65) also is comparable to floor area ratios reported from other areas. Thus, comparative evidence provides some confidence that the typology is correct.

To estimate overall population levels at Walnut Canyon, we considered only those rooms that were classified as habitation rooms and were considered to have been occupied year-round. A total of 109 rooms (80 within the canyon and 29 above the canyon rim) fit these criteria. In order to convert the information on floor area into population figures, we employed three different methods of population estimation, that of Naroll (1962), Clark (1974), and Casselberry (1974). Each of these methods uses overall floor area of habitation spaces as a means for estimating population, but each employs a different formula. Naroll's (1962) formula, based on a study of ethnographic data from 18 societies, postulates that each person requires approximately 10 square meters of roofed space for habitation. Thus, a ratio of one person for each 10 square meters is indicated. Clark (1974) proposes a much lower figure of one person for every three square meters, and Casselberry (1974) proposes an intermediate figure of 1:6. Because we wished to explore various means for estimating population, all three figures were used in our calculations. Naroll's formula therefore provides the most conservative population estimate and Clark's the most liberal, with Casselberry's between the two extremes.

A crucial issue in estimating population levels from archaeological evidence involves the issue of absolute contemporaneity of features. To estimate *maximum* population figures, it is necessary to know how many rooms were occupied at the same time during the height of population levels. Because of the likelihood that at least some of the rooms at Walnut

Canyon would have been abandoned or not yet built at particular moments during the Sinagua occupation, and because of uncertainties regarding the absolute contemporaneity of rooms at Walnut Canyon, we estimated population according to three different occupancy assumptions. The most conservative estimate was that only 50% of the habitation rooms at Walnut Canyon would have been in use at the peak of Sinagua occupation, sometime in the mid-13th century. The other two estimates were based on occupancy figures of 75% and 100%. The intermediate figure of 75% is probably the most realistic (see also Wetterstrom 1986:44).

Results of our attempt to estimate Walnut Canyon's peak population are given in Table 3 and Figure 21. Given that there were three separate formulae for estimating population from floor area, as well as three different assumptions regarding occupancy rates, the estimates vary considerably. Using the most conservative method i.e., that each person required approximately 10 square meters of floor space and that only 50% of Walnut Canyon's rooms were occupied, we derived a figure of about 74 people; a 75% occupancy assumption boosts the estimate to 110, and a 100% assumption raises it to 147. At the other extreme, using Clark's figure of three meters of roofed space per person, the population estimate jumps to 246, 368, and 491 persons, respectively, for occupation rates of 50%, 75%, and 100% of the Walnut Canyon rooms. Casselberry's more moderate formula indicates peak population levels of 123, 185, and 246 people for the same percentages of occupancy. Thus, the overall range for the various methods is from 74 to 491.

It seems likely that the true peak population figure for Walnut Canyon lies somewhere between these extremes. Thus, our preferred estimate is that derived by using Casselberry's formula of 6 square meters of floor space per person, and an occupancy rate of 75%. This method yields a population estimate of 185 people for the sites within Walnut Canyon National Monument. Therefore, our preferred estimate for the Sinagua occupation at Walnut Canyon, and the

Population Estimates for 13th-Century Sinagua Occupation at Walnut Canyon

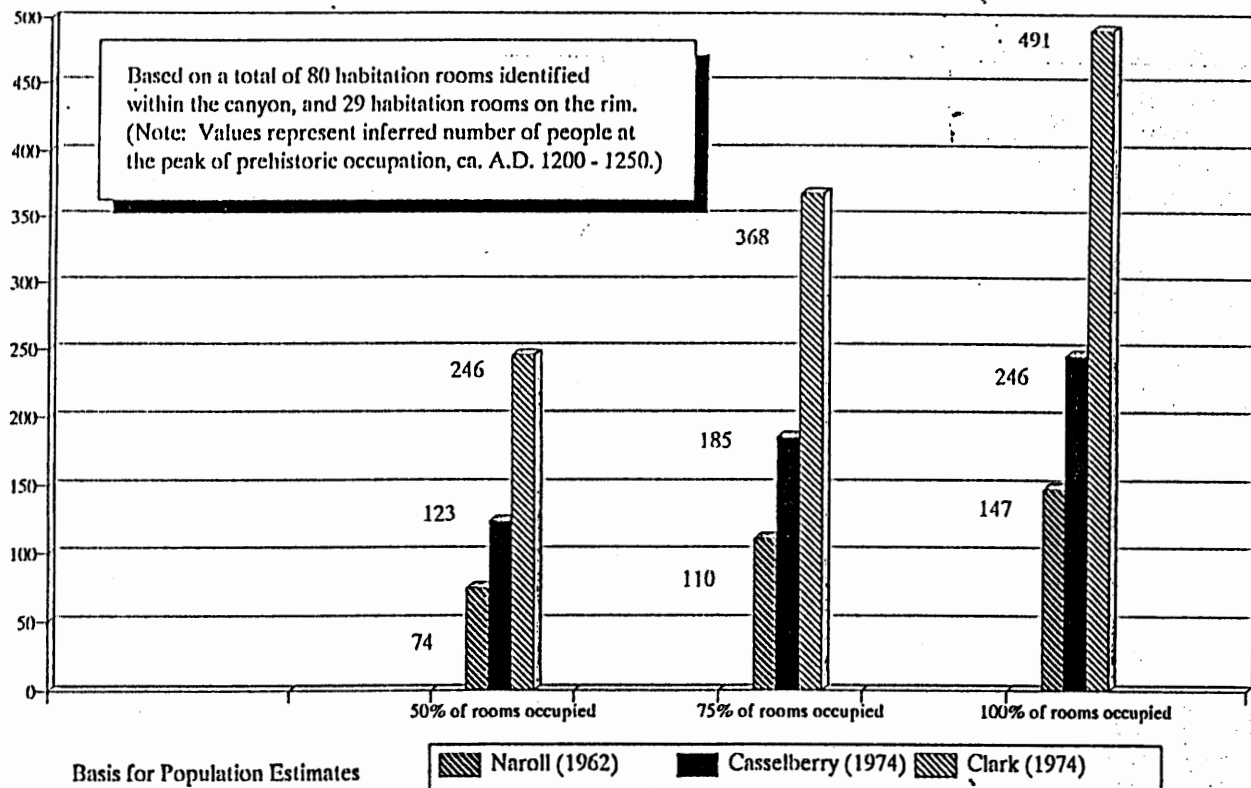


Figure 21. Estimates for peak population at Walnut Canyon, ca. A.D. 1250, using three methods of estimation and three assumptions regarding percentage of habitation rooms in use.

one that will be used in subsequent calculations of water use and storage, is 185 people.

Sinagua Water Consumption

Using the figures on population levels derived from the methods described above, it is a fairly straightforward matter to estimate the annual domestic water requirements of Walnut Canyon residents. According to Adolph (1947:113) and Fish and Nabhan (1991:31), each active person in an arid environment requires approximately six to seven quarts of water per day during the summertime. It seems likely that during the Sinagua period residents of Walnut Canyon probably got by with less water for short periods of time, for example, in the winter when outdoor activities were restricted. Also, the cooler climate of Walnut Canyon might somewhat reduce average daily water needs, especially in the summer. However, because this figure applies strictly to drinking water, and does not include domestic use of water for other purposes (e.g., processing food, cooking, weaving baskets, constructing and maintaining dwellings, making pottery, preparing medicines, etc.), we retain it as a rough index of per-capita domestic water needs. Our formula for calculating these needs therefore can be expressed as follows: Number of people at peak population of Walnut Canyon * Daily water need of 0.875 gallon * 365 days = Total domestic water requirement per year, in gallons.

Table 4 and Figure 22 present information on the estimated annual per-capita domestic water requirements at Walnut Canyon. These figures vary considerably depending on the method used to estimate population. Again, Naroll's population estimation formula, and an assumption of only 50% occupancy forms the lower limit for the estimate, while Casselberry's formula and an occupancy of 100% is the upper limit. Considering these two extremes, the estimated annual domestic water consumption at Walnut Canyon ranges from a low of 26,634 gallons to 156,813 gallons. Using the preferred population figure of 185 persons, cited above, we arrive at a more moderate figure of 59,084

gallons of water per year.

Sinagua Use of Water for Agricultural Production

The estimates for Walnut Canyon's peak population levels also make it possible to consider yearly agricultural requirements and water use. Estimation of agricultural effort and consumption of agricultural products is a complicated procedure involving a number of assumptions. The estimate is not entirely guesswork, however, and is based on a large amount of relevant ethnographic data from several aboriginal southwestern societies. In this effort, we rely primarily on the data, assumptions, and methods employed by Burns (1983) and Van West and Lipe (1991) for the Mesa Verde Anasazi. This seems to be an appropriate comparison, because although they differ in many important respects, Walnut Canyon and Mesa Verde are also similar in important ways. Both lie at a similar elevation, both have comparable environmental settings and geology, both were occupied during roughly the same time period, and the prehistoric residents in both places engaged in similar agricultural practices using similar crops.

Estimating prehistoric agricultural production and consumption of crops requires information on at least these factors: (1) average daily caloric requirements of an individual; (2) percentage of total daily caloric requirements provided by particular crops; (3) caloric yield of these crops, expressed in terms of calories/kilogram; (4) yields for particular crops, expressed in terms of kilograms/hectare; (5) percentage of crops lost each year; (6) percentage of crops reserved for seed; and (7) anticipated storage or surplus needs. These factors are discussed below.

Average daily caloric requirements.

According to Van West and Lipe (1991:112), "minimum daily caloric requirements vary from person to person and depend on factors such as age, gender, metabolism, and level of activity." Generally, estimates range from about 2,000 to 2,500 calories per day (Hassan 1981; Schlanger 1985; Kohler et al. 1986).

Percentage of daily caloric requirements provided by crops. Estimating this factor

Table 4. Estimated per-capita annual domestic water requirements for Sinagua occupants of Walnut Canyon, ca. A.D. 1250. (Calculated as Number of Persons * 0.875 gallons per day consumed * 365 days per year.)

Basis for Population Estimate Used in Calculation

Assumed Percentage of Rooms in Use	Number of Rooms	Naroll 1962*	Casselberry 1974**	Clark 1974***
50%	55	23,634 gal.	39,283 gal.	78,566 gal.
75%	82	35,131 gal.	59,084 gal.	117,530 gal.
100%	109	46,948 gal.	78,566 gal.	156,813 gal.

* Based on one person per 10 square meters of floor space.

** Based on one person per 6 square meters of floor space.

*** Based on one person per 3 square meters of floor space.

Estimated Annual Water Consumption For Sinagua Residents of Walnut Canyon

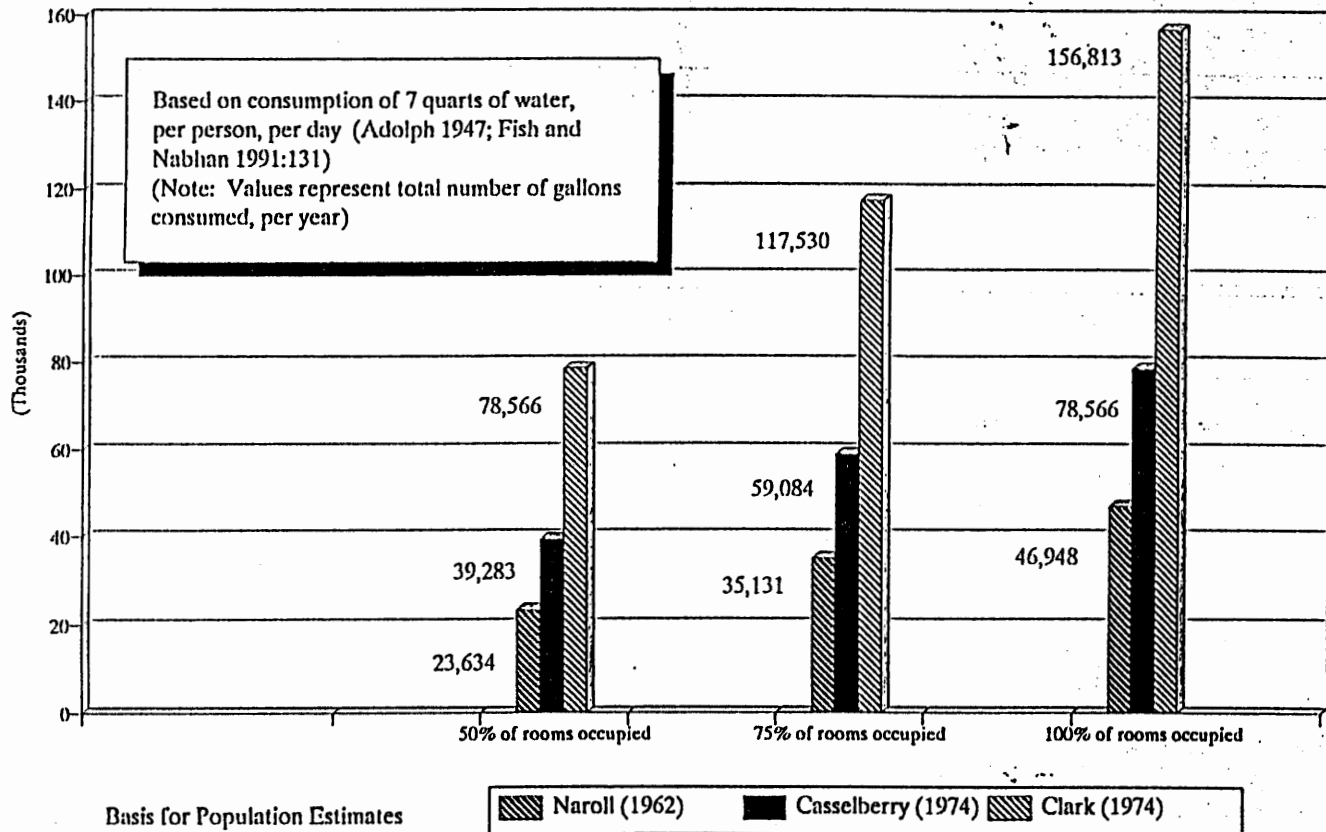


Figure 22. Estimated annual domestic water consumption by Sinagua residents of Walnut Canyon at peak of prehistoric occupation.

Table 5. Estimated per-capita maize production for Sinagua occupants of Walnut Canyon, ca. A.D. 1250. (Calculated as Number of Persons * 600 kg of corn; assumes a per-capita consumption of 160 kg of corn per year, with 10% loss of corn and 10% set-aside of corn seed for planting; see Van West and Lipe, 1991.)

Basis for Population Estimate Used in Calculation

Assumed Percentage of Rooms in Use	Number of Rooms	Naroll 1962*	Casselberry 1974**	Clark 1974***
50%	55	44,400 kg	73,800 kg	147,600 kg
75%	82	66,000 kg	111,000 kg	220,800 kg
100%	109	88,200 kg	147,600 kg	294,600 kg

* Based on one person per 10 square meters of floor space.

** Based on one person per 6 square meters of floor space.

*** Based on one person per 3 square meters of floor space.

depends not only on knowing daily caloric requirements, but also the proportion of calories provided on a daily basis by crops. Following Van West and Lipe (1991:112), we assume that the Sinagua of Walnut Canyon were similar to other Pueblo Anasazi groups in their consumption of maize. Recent studies addressing the issue of maize consumption for prehistoric Anasazi groups (Kohler et al. 1986; Decker and Tieszen 1989; Minnis 1989) have postulated that maize was a significant source of calories, contributing from 61% to 77% of the diet. Given this range of values and the estimated average daily caloric requirement of 2,000 to 2,500 calories per day, we follow Van West and Lipe's conclusion that each individual consumed about 1,534 calories per day in maize.

Caloric yield of crops. Because maize appears to have been a principal source of cultivated foods, with beans and other crops contributing much less (Wetterstrom 1986:54-55), here we consider only the caloric yield of maize. Following Van West and Lipe, we accept Cook and Borah's (1979:164) estimate that maize yields about 3,500 calories per kilogram. Given the figure cited above, i.e., that each person would have consumed approximately 1,534 calories from maize each day, this translates to an annual per capita maize consumption of about 160 kg.

Crop yields. Several estimates are available for maize yields, depending on assumptions about the variety of corn grown, including the spacing of plants, soil types, amount of water delivered to the crops, the amount of fertilizer added, and the length of growing season. In this study, we adopt Bradfield's (1971) estimate for Hopi of 12 bushels per acre. At approximately 56 pounds per bushel, this translates to a figure of about 753 kg. of maize per hectare (Van West and Lipe 1991:110).

Crop loss. According to Van West and Lipe (1991:111), approximately 10% of each year's maize harvest "would have been lost in transport, or to pests and spoilage" (see also Hassan [1981] and Williams [1989]).

Seed. Each year's maize crop depends on setting aside some portion of the previous

year's harvest for seed. Van West and Lipe (1991:111) suggest that approximately 10% of the harvest would have been reserved for this purpose.

Anticipated surplus and storage. Some portion of the decision about how much land to cultivate in a given year is based on desired surplus. Because of high interannual variability in rainfall and temperature, and occasional hailstorms, floods, and pest infestations, crop failure can be expected on a relatively frequent but unpredictable basis. To cope with these uncertainties, surplus crops were undoubtedly desired by the Sinagua. The major unknown is how much additional land would have been planted, cultivated, and harvested each year to produce a surplus. Several ethnographic sources point to a two-year surplus as the standard for contemporary Pueblo people (Hough 1915; Forde 1931; Parsons 1936; Whiting 1939; Titiev 1944; Ford 1968; Bradfield 1971; all cited by Van West and Lipe 1991:112). Given that Walnut Canyon was probably near the upper elevational limit of corn agriculture in the Flagstaff area, and given the high interannual variability in rainfall here, we propose that crops would indeed have been planted with the desired goal of producing a two-year surplus in addition to the coming year's food and seed needs.

With the preceding figures as a guide, we can attempt to model the annual agricultural practices of Walnut Canyon's Sinagua inhabitants. A formula for computing the annual harvest of corn can be stated as follows: Annual per capita maize requirements, expressed in kilograms * Number of people at the peak of Sinagua occupation of Walnut Canyon = Estimated annual maize production, in kilograms. This equation relies on the factors discussed above, wherein each person consumes approximately 160 kg. of maize per year; approximately 20% must be added to the annual consumption to account for crop loss and setting aside of seed; and each year's crop is planted with the hope of achieving a 2-year surplus in addition to the coming year's maize consumption needs.

Results of the attempt to model annual maize production at Walnut Canyon are given

in Table 5 and Figure 23. As in the previous discussion of per capita water consumption, it can readily be seen that there is considerable amount of variability in these figures, depending on the method used to estimate population. Thus, estimated annual production of maize ranges from a low of 44,400 kg. per year to a high of 294,600 kg. Adopting the intermediate, preferred population figure of 185 people for the peak of Walnut Canyon's Sinagua occupation (see discussion of population estimates, above), the annual maize production at Walnut Canyon is estimated at 111,000 kg.

While at first glance this quantity of maize may seem impossibly high, it is in fact within the range of maize production observed ethnographically for Pueblo farmers, and modeled archaeologically in several areas (e.g., Wetterstrom 1986:46-51). If put into terms of ~~per capita~~ storage requirements, the figure of 111,000 kg. of maize translates to approximately 154 cubic meters of storage. This volume would accommodate not only the coming year's food requirements, but also the postulated two years' maize surplus. To put this figure into perspective, it should be realized that the storage rooms identified at Walnut Canyon enclose at least 2,430 square meters of space (Harper 1993:124). As will be discussed in more detail below, even if storage technology was extremely wasteful of this overall floor area, as might be expected if shelled corn were stored in rotund pottery vessels that could not be effectively stacked on top of one another, the 2,430 square meters of floor area would have provided many times the needed storage space for food.

Having modeled the annual crop production at Walnut Canyon in kilograms of maize, it is possible to estimate the amount of land that would have been cultivated each year. This estimate in turn allows us to consider the annual water requirements of such cultivation. First, if we accept the various figures given for maize production, we can translate these into number of hectares cultivated. This is accomplished by converting the total estimated crop production figures (in kilograms) into the area required to produce that yield, then

calculating how much water would have been used to water this area during the growing season. Conversion of corn production into area cultivated relies on the Hopi production figure cited above, i.e., that approximately 12 bushels of corn per acre (753 kg. per hectare) could have been produced at Walnut Canyon. Employing an estimated peak population of 185 people and projecting a desired crop yield of 600 kg. per person, we derive an estimate of 147.4 hectares (364.3 acres) under cultivation.

It is difficult to estimate how much water would have been used to cultivate corn within this area. The Sinagua residents of Walnut Canyon undoubtedly used a number of methods for cultivation, including dry farming of land on the mesa top above the canyon, cultivation of floodwater plots contained behind check dams and terraces, and perhaps cultivation of plots within the canyon bottom and on the erosional benches leading down into the canyon. These techniques involve a range of strategies for delivering water to crops, ranging from simply utilizing the available precipitation that falls on a given plot to diverting runoff with the use of small ditches, brush weirs, and other devices. Therefore, the most conservative method for estimating agricultural water use is to consider only the moisture available from precipitation. As outlined previously in this report, an average of 5.83 inches of water falls during the summer growing season. If we assume that this represents the average *minimum* amount of water needed to germinate and mature a corn crop, and if we figure that all rain falling on a given plot was necessary for agricultural success, the water employed for agricultural purposes can be calculated. Employing these assumptions, we can determine that agricultural pursuits would have used about 177 acre-feet of water (57.67 million U.S. gallons).

Archaeological Implications

Using the figures above as a guide, we may now review the archaeological implications in terms of the Walnut Canyon Sinagua's storage requirements for water and food. Regarding water, if we accept the per-capita

Table 5. Estimated per-capita maize production for Sinagua occupants of Walnut Canyon, ca. A.D. 1250. (Calculated as Number of Persons * 600 kg of corn; assumes a per-capita consumption of 160 kg of corn per year, with 10% loss of corn and 10% set-aside of corn seed for planting; see Van West and Lipe, 1991.)

Basis for Population Estimate Used in Calculation

Assumed Percentage of Rooms in Use	Number of Rooms	Naroll 1962*	Casselberry 1974**	Clark 1974***
50%	55	44,400 kg	73,800 kg	147,600 kg
75%	82	66,000 kg	111,000 kg	220,800 kg
100%	109	88,200 kg	147,600 kg	294,600 kg

* Based on one person per 10 square meters of floor space.

** Based on one person per 6 square meters of floor space.

*** Based on one person per 3 square meters of floor space.

Estimated Annual Production of Corn at Walnut Canyon, in Kilograms

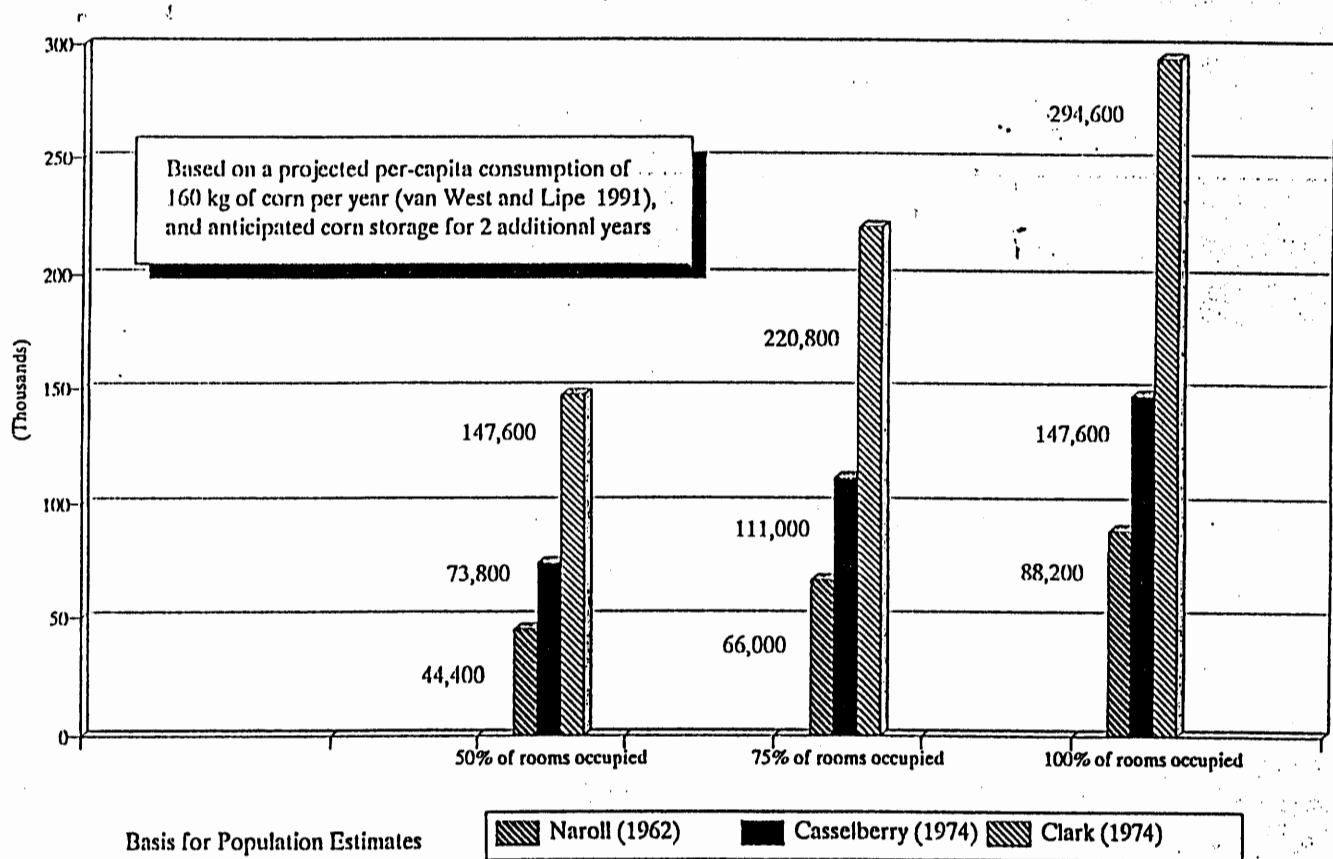


Figure 23. Estimated annual maize production by Sinagua residents of Walnut Canyon during peak of prehistoric occupation.

consumption figures referred to above, and consider a late spring "worst case" drought of 100 days, we can conclude that it is entirely possible to store enough water to last through dry seasons. Using a figure of 100 days worth of anticipated water storage, and employing our preferred peak population figure of 185 people, having a minimum daily requirement of 0.875 gallons of water per day, yields a water storage requirement of 16,188 gallons. Some Sinagua pots (e.g., Sunset Red, an abundant Walnut Canyon pottery type often made in the form of large jars) have a storage capacity of more than 35 gallons, and many of them are above 20 gallons. If we postulate that storage jars held an average of 20 gallons each, it would take a total of 809 such pots (an average of 4.4 pots per person) to account for all of the water storage needs of all Walnut Canyon residents for 100 days. Considering that each 20 gallon pot has an average diameter of about 2 feet (61 cm), each pot would have taken up approximately 0.4 square meters of floor space. The total storage volume for all water storage pots, therefore, would have been about 324 square meters. According to Harper (1993), the total measured floor space of storage rooms at Walnut Canyon is about 2,430 square meters; assuming a 75% occupancy rate for Walnut Canyon rooms (as we did for deriving the population figure of 185 persons), there would have been about 1,823 square meters of storage space available at the peak of Walnut Canyon's occupation. Thus, the storage of water would have taken up only about 18% of *all* the available floor space in Walnut Canyon's storage rooms (Figure 24).

Subtracting the amount of storage space devoted to a 100 day water supply leaves about 1,499 square meters of storage space for food and other essentials. As we have discussed above, a three year supply of corn for all of Walnut Canyon's 185 Sinagua residents would only have occupied about 154 cubic meters. This translates into about 220 "gallons" of corn, per person, a quantity that could have been held in only 11 large storage jars holding 20 gallons each. This could have been accommodated by a total (Walnut Canyon as a whole) storage space of about 814 square meters

of floor area (i.e., the total required for 2,035 pots of 20 gallons each). Thus, both the food and water storage requirements *together* at Walnut Canyon would have consumed only about 62% of the total available storage space (Figure 24).

CONCLUSION

In this report, we have attempted to understand the use of water by the Sinagua residents of Walnut Canyon during a period from about A.D. 1100 to 1300. In doing so, we have turned to several sources of information, including the modern climatic record, the record of past climates recorded in climatically-sensitive trees, a field survey of potential water sources, and archaeological evidence pertaining to the Sinagua occupation. We have concluded that although the procurement of water was often difficult, and varied according to the seasons, the Sinagua employed a diverse set of behavioral strategies and technologies to gather and store their water. Summer and winter seasons brought different opportunities for water collection, but in both seasons the Sinagua were able to accumulate enough water for use on a daily basis, and for long-term storage in pots for anticipated use during the prolonged dry seasons that separate winter and summer.

From the abundant archaeological remains within Walnut Canyon, it might seem obvious that the Sinagua were able to survive at Walnut Canyon for nearly two centuries, and that they obviously were successful at procuring the daily, biological necessities of water and food. However, to date there has been little specific information or inference regarding how in behavioral and technological terms they were able to accomplish this. In this study, we have used the existing architectural remains at Walnut Canyon to infer a peak population level of about 185 persons, sometime around A.D. 1250, and we have proposed some specific reconstructions regarding how the Sinagua were able to gather and store water for use in both the wet and dry seasons. We have also attempted to model the

Postulated Use of Storage Space in Prehistoric Pueblo Rooms, Walnut Canyon

(Based on the assumption that 75% of Walnut Canyon's pueblo rooms were occupied during the peak of Sinagua occupation, ca. A.D. 1250, and that a corresponding 75% proportion of the 2,430 square meters of identified storage space would have been in use.)

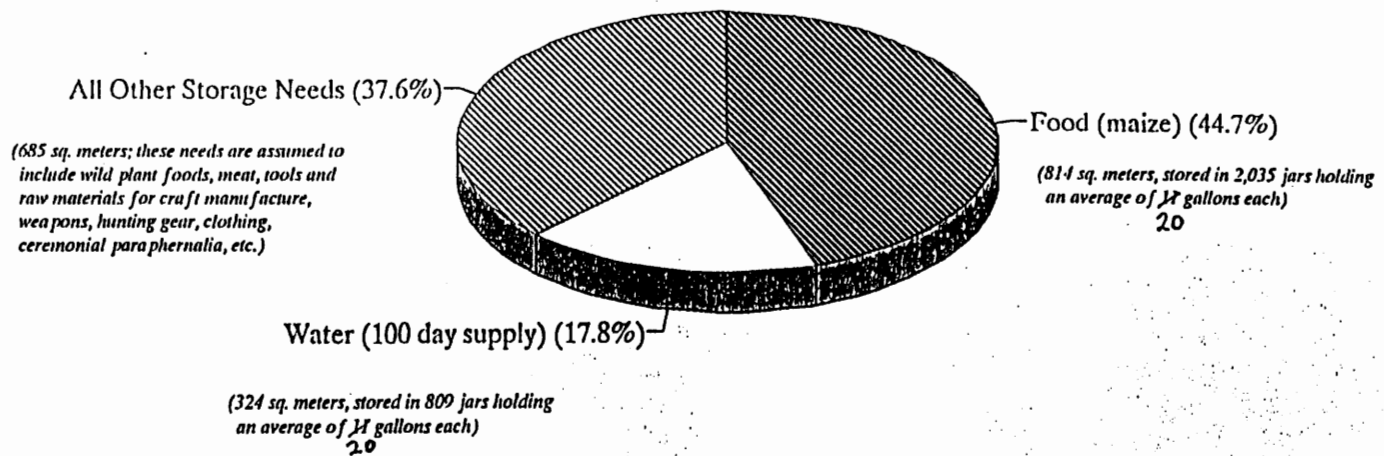


Figure 24. Postulated use of storage space in prehistoric pueblo rooms at Walnut Canyon during peak of Sinagua occupation.

subsistence activities of the Sinagua, in terms of cultivated area, water requirements, and long-term food storage needs. It is apparent that there remains much to be learned about the Sinagua of Walnut Canyon, but we hope this report has illuminated some of the specific ways in which the Sinagua were able to survive in this sometimes generous but often harsh environment.

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