Prehistoric Irrigation Systems in the Salt River Valley, Arizona

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Summary. This article discusses prehistoric irrigation canals recently excavated near Phoenix, Arizona. The canals were constructed by the Hohokam Indians between A.D. 850 and 1450. Several aerial photographs taken at various times in the past five decades clearly show the paths of hundreds of the canals, including some of those recently excavated. These data provide new insights on Hohokam irrigation technology and society. Despite the destructive inroads of modern development, much significant archeological information can still be retrieved both by conventional excavation methods and by the archival study of aerial photographs.

For more than a century the broad valleys of southern Arizona's Sonoran Desert (Fig. 1) have been noted for their fertility and suitability for irrigation agriculture (*1*). Less well known is the fact that beneath the modern farms and cities of this region are the vestiges of an equally impressive array of prehistoric canals and villages, the product of the Hohokam Indians who occupied this region from approximately 300 B.C. to A.D. 1450.

These remains received the attention of archeologists in 1887 during the Hemenway Expedition, the first major archeological program carried out in the Southwest (*2–4*). However, since that time modern farming and construction have largely obliterated the traces of Hohokam agricultural activities. As early as 1903 it was noted that most of the prehistoric canal systems had already been destroyed (*5*). Figure 2 illustrates the location of the major canals reliably recorded in the lower Salt River Valley by the early investigators, along with many of the prehistoric villages. Of the more than 500 kilometers of major canals (*6*) and 1600 kilometers of smaller canals (*7*) recorded, less than 10 kilometers remain intact (*6, 8*).

Few studies of southern Arizona's prehistoric canals have been performed. Haury's detailed examination in 1964–1965 of six canals at the Gila Valley Hohokam village site of Snaketown (*9*, pp. 120–151) and Woodbury's 1959–1960 excavation (*10–13*) of a few canals at the sites of Snaketown, Gatlin (near Gila Bend), and Pueblo Grande (in Phoenix) are the two most comprehensive studies published to date.

This article is based on the results of projects undertaken in the Phoenix area by the Arizona State Museum between 1973 and 1978 (*14–16*). A total of 34 different canals were excavated, revealing important information on the age and morphology of individual canals. The article is also based on a set of aerial photographs, taken by the Arizona Department of Transportation in the early 1960's, which clearly depict aspects of the organizational structure of Hohokam canal systems. Together these data provide an improved understanding of Hohokam irrigation technology.

The Canals of Pueblo Grande

The remains of two parallel-trending canals, the largest canals known from pre-Columbian North America, are preserved in the Park of Four Waters, a small city park adjacent to the prehistoric Hohokam village of Pueblo Grande. In 1959 Woodbury (*10, 13*) dug a 60-meter-long trench through the park, providing a cross section of the two canals. He observed that the canals, which date from early in the Hohokam Classic Period (A.D. 1150 to 1450), differ considerably from one another in construction morphology. The north canal is approximately 11 m wide at the former ground level and 3 m deep, and the distance between the bank crests is 26 m. The overall shape of this canal is that of a broad U. In the fill of the canal Woodbury found a layer of chocolate-brown clay, 5 to 9 centimeters thick, which he hypothesized was a hand-applied lining to retard water loss. The south canal, on the other hand, is V-shaped, with the width at the former ground level being only 6 m, the depth 4 m, and the distance between the bank crests 18 m. The banks of both canals were still standing at a height 2 to 3 m above the former ground level. On the basis of early maps it appears that the north and south canals were originally more than 14 and 11 km in length, respectively. Woodbury hypothesized that the north canal supplied water to various field locations while the south canal drained excess water from the same fields (*13*).

The proposed construction of a new bridge across the Salt River immediately west of the Park of Four Waters gave me the opportunity in 1976 to restudy the north and south canals (*15*) and to evaluate some of Woodbury's observations. In an area of modern plowed fields approximately 150 m wide (east to west) and 800 m long (north to south) I placed more than 3 km of backhoe trenches. This effort was rewarded by the discovery of 17 distinct prehistoric canals (*17*) in addition to the north and south canals (Fig. 3). Another canal was discovered north of this area by the Arizona State Museum in 1978 (*16*). Table 1 summarizes the salient characteristics of these canals.

There are two notable discrepancies between my data and those of Woodbury. One was my failure to find evidence that the north canal had ever been intentionally lined. Two cross sections approximately 350 and 450 m west of Woodbury's trench did reveal discontinuous thin bands of brown clay. However, not just one but three distinct thin clay lenses, identical to one another in composition, are present. In terms of shape and uniformity of thickness, these lenses differ little from a variety of natural clay and silt deposits in at least six other excavated canals.

I also did not find evidence that the south canal functioned as a drain. There is considerable similarity between the fills of the north and south canals, which would not be expected if the canals had

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different functions. An even stronger argument against a drainage function for the south canal is the presence of an apparent branch extending to the northwest. The branch is situated in such a way that it could have served only to carry water away from the south canal.

Shape does not seem to reflect functional or temporal differences among the Pueblo Grande canals. The canals can be classified into two basic shapes, trapezoidal (flat-bottomed) and parabolic. There is a tendency for trapezoidal cross sections to be found in the smaller canals, but otherwise no consistent differences are noted between the canals exhibiting these two shapes.

Despite their differences cross-sectionally, the north and south canals probably carried similar volumes of water—a point that will be elaborated on later. The V-shape and greater depth of the south canal is most likely related to the physical characteristics of the Salt River at the time of canal construction. Euler *et al.* (*18*) demonstrated from several paleoenvironmental parameters that portions of the northern Southwest experienced a severe drought around A.D. 1150, a time probably coincident with the construction of the south canal. A drop in the volume and water level of the Salt River (or, alternatively, entrenchment of the river) could have created a need for a canal whose bottom was at or near the same level as the bottom of the river channel.

The Hagenstad canal (*19*) (Fig. 3) is a large canal with a complex depositional history. It is by far the largest known Hohokam canal dating from before the Classic Period, and compares favorably in size to the north canal. Evidently this canal was constructed, remodeled twice, and abandoned within the Hohokam Sedentary Period (A.D. 900 to 1150), most likely between A.D. 1000 and 1150 (*20*). Three distinct channels (or two remodelings) can be seen in cross section (Fig. 4). The destructive effect of severe flooding in the Phoenix area has been amply demonstrated for historic canal systems (*1*), a point most recently emphasized by the monumental floods in April 1980. Based on the distribution and dating of floodwater deposits at Pueblo Grande, it is likely that many, if not most, of the canals assignable to the Sedentary Period at Pueblo Grande saw sequential rather than contemporaneous use due to the periodic destruction of canal segments by flooding. Severe flooding would have necessitated the remodeling of canals as well as the construction of completely new canal seg-

Table 1. Morphological characteristics of the Pueblo Grande canals.

Canal	Channel	Suggested period of last usage*	Maximum width (m)	Minimum depth (m)	Cross-sectional shape	Angle of side walls†
1	Upper	Sedentary	2.3	1.1	Parabolic	55
1	Lower	Sedentary	3.6	1.1	Parabolic	30
2	Upper	Classic	1.5	0.5	Parabolic	50
2	Lower	Sedentary	2.4	1.2	Parabolic	60
South	Main	Classic	3.4	3.2	Parabolic	75
South(3a)	Branch	Classic	1.6	0.6	Trapezoidal	55
4	Upper	Classic	1.2	0.5	Parabolic	45
4	Lower	Sedentary	1.8	1.2	Trapezoidal	60 to 85
5	Highest	Protohistoric	1.5	0.6	Trapezoidal	65
5	Middle	Sedentary	3.0	1.5	Parabolic	50
5	Lowest	Sedentary	?	?	?	?
6		Protohistoric	0.8	0.6	Trapezoidal	70
Hagenstad	Highest	Sedentary	4.0	2.5	Parabolic	60
Hagenstad	Middle	Sedentary	7.0	2.4	Trapezoidal	60
Hagenstad	Lowest	Sedentary	10.0+	3.5	Parabolic	40
8	Highest	Sedentary	2.5	0.8	Parabolic	25
8	Middle	Sedentary	1.3	0.8	Parabolic	35 to 45
8	Lowest	Sedentary	2.0	1.4	Trapezoidal	55
9		Colonial(?)	1.5	1.0	Trapezoidal	50
10		Sedentary	2.5	2.5	Parabolic	55
North	Upper	Classic	7.0	2.1	Parabolic	40
North	Lower	Classic	9.0	2.1	Parabolic	25 to 35
12		?	1.1	0.4	Parabolic	?
13		Classic	2.7	0.7	Parabolic	20
14		Classic	2.8	1.8	Parabolic	55
15		?	0.6	0.5	Parabolic	?
16		Sedentary	1.8	0.4	Trapezoidal	50
17		Sedentary	2.0	0.4	Trapezoidal	40
18		Sedentary-Classic	2.6	0.9	Parabolic	40
19		Classic	5.1	1.5	Parabolic	40

*The dates assigned to these periods are as follows: Colonial, A.D. 550 to 900; Sedentary, A.D. 900 to 1150; Classic, A.D. 1150 to 1450; Protohistoric, A.D. 1450 to 1850. †Measured from the horizontal to the nearest 5°.

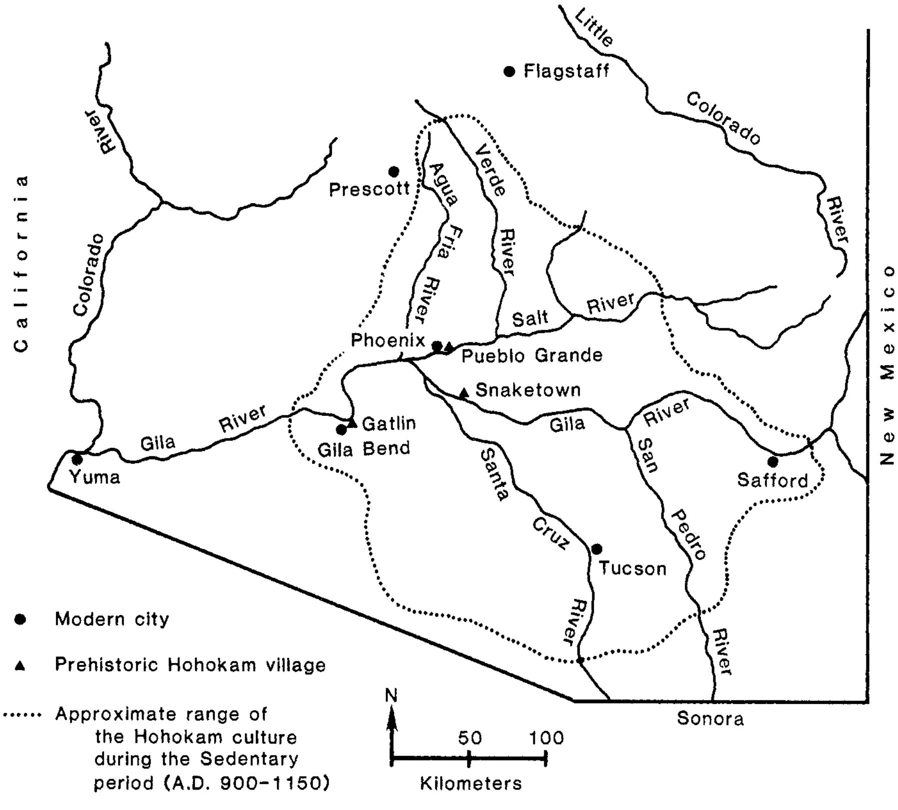

Fig. 1. Map of southern and central Arizona.

ments. The initial construction, the remodelings, and the abandonment of the Hagenstad canal are all presumed to represent, at least in part, responses to Sedentary Period flooding.

Canal 6 (Fig. 3), the smallest canal found, is also the highest stratigraphically. The bottom is less than 1.5 m below the present ground surface. By tracing out this feature it was discovered that canal 6 is actually a branch of the highest channel of canal 5. The latter is identical in morphology and bottom depth to canal 6, and both display similar pollen profiles. These two canals appear to represent a small-scale irrigation system constructed no earlier than the Classic Period. The presence of a few temporally undiagnosable ceramics and the total lack of historic refuse seem to preclude historic usage of these canals. Haury (*9*, pp. 149–150) termed a similar manifestation found at Snaketown an echo canal; that is, the canal was an attempt, following the Classic Period, to revive earlier Hohokam canal systems. While Haury was hesitant to ascribe cultural or temporal affinities to these echo canals, I tentatively suggest that they are the handiwork of protohistoric (A.D. 1450 to 1850) Piman Indians.

A program of pollen analysis, mechanical and chemical soil analyses, and comparisons between the prehistoric canals and abandoned historic canals of documented usage was undertaken to quantify the often radical differences in color and texture between various canal deposits. Mechanical analysis was performed on discrete depositional layers in most of the canals, including the abandoned Hayden (San Francisco) canal, constructed in 1875 on the south side of the Salt River (*1*, p. 53). This was coupled with tests for organic carbon content, x-ray diffraction of darkly stained basal deposits for identification of mineralogical constituents, and in-field keying of soil color with a Munsell soil color chart. These analyses (*21*) indicate that the lighter deposits tend to consist of sands and sandy silts with little organic carbon, while the darker deposits contain clays and clayey silts with a somewhat higher proportion of organic carbon. In modern earth canals, clayey deposits are often the product of water whose movement is slowed by excessive growth of aquatic plants (*22*, pp. 91–92). Coarse sand is more likely to be deposited by faster flowing water, unsuitable as a habitat for most aquatic plants. Another possible source for the organic carbon in the darker deposits is periodic burnings, a common method for clearing fields and canal banks of weeds and brush. Flecks of charcoal are ubiquitous in some of the alluvial deposits adjacent to the canals and may represent countless burnings. The color of the canal deposits also appears to be affected by different concentrations of minerals such as magnetite (dark) and quartz and feldspars (light).

Four of the canals exhibit black or yellowish-black stains in and below the sediments forming the bottom of the canal. These proved to be variable concentrations of manganese oxide, limonite, and magnetite. While the factors responsible for the formation of these deposits are unclear, the deposits made the task of tracing the course of these canals easier since the stains were more

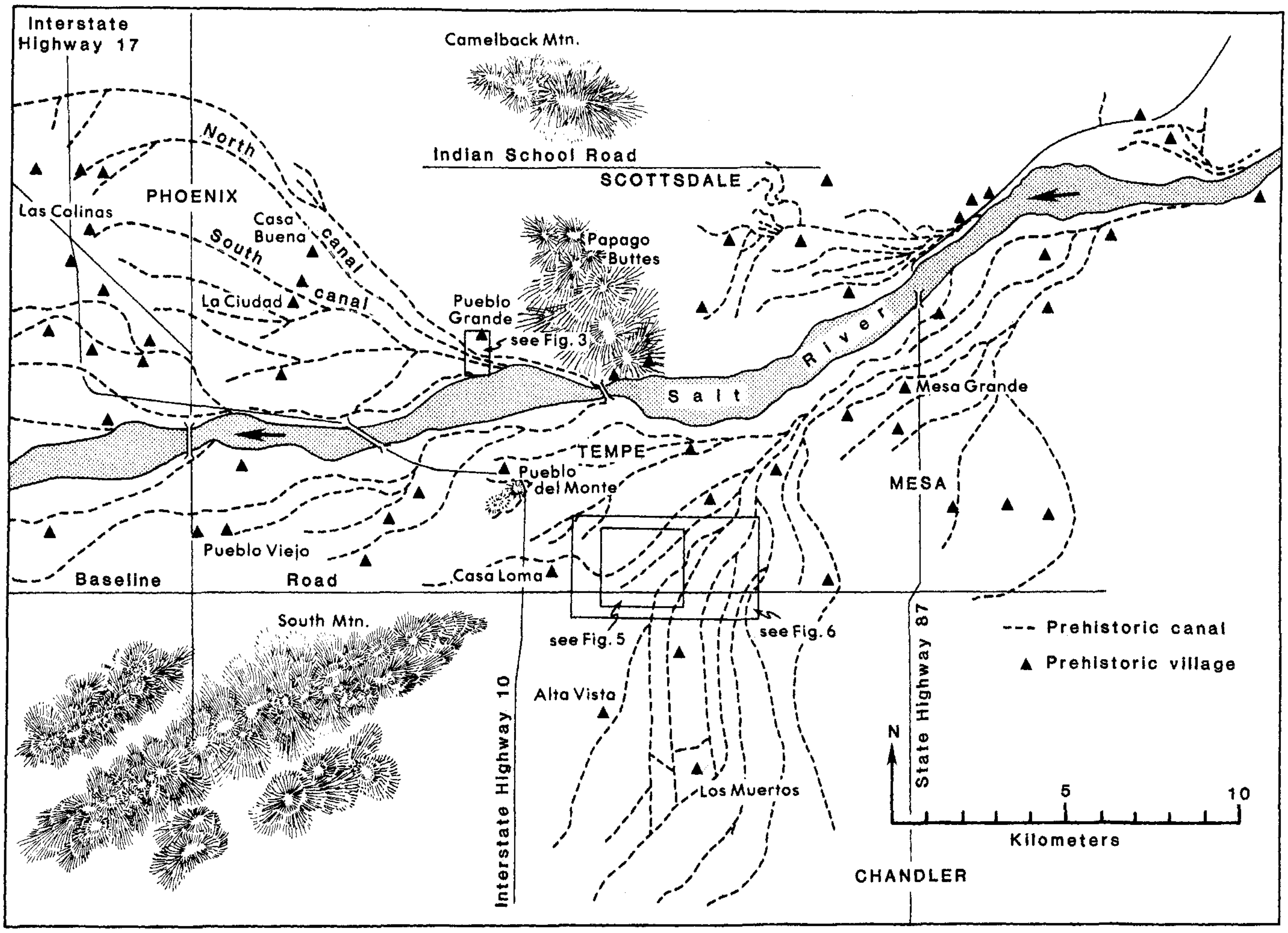

Fig. 2. Map of the major prehistoric Hohokam canals recorded by early investigators in a portion of the lower Salt River Valley. [Adapted, in part, from Turney (*40*) and Midvale (*6*)]

or less continuous. Most other deposits in the canals, however, were discontinuous; just a few meters of horizontal distance in the same canal often produced strikingly different depositional profiles.

The palynological work on the Pueblo Grande canals (*23*) was only partly successful because of the unpredictable nature of pollen grains in moving water. Seasonal information can be obscured by depositional factors such as water velocity and the weight and size of the particle itself. In addition, pollen from any environmental setting along the river/canal system can be introduced into the channel; and the erosive action of moving water in an earth canal is bound to mix at least some of the pollen deposited at an earlier period with the ongoing rain of pollen.

Despite these interpretive difficulties, some information was obtained on the prehistoric local conditions around the canals. It appears likely that the canals were surrounded by "cheno-am" species (Chenopodiaceae and *Amaranthus*) —plants such as amaranth (*Amaranthus palmeri*), goosefoot (*Chenopodium* spp.), and saltbush (*Atriplex* spp.), which are active colonizers of floodplains, abandoned fields, and other disturbed soil with a fairly high water table. The presence of cattail (*Typha*) pollen in most of the canal deposits is suggestive of slow water flow, even in the largest canals. In terms of evidence of prehistoric domesticated crops, only three grains of corn (*Zea*) were recovered. Such a situation appears to be typical for Hohokam sites and does not necessarily reflect agricultural productivity. It is noted, however, that the Pueblo Grande area is ideally situated for the heading of canals (*24*); the canals may primarily have been utilized to convey water to fields in other locations, reducing the chances of domestic pollen being introduced into the canals at the Pueblo Grande area itself.

Low cheno-am and high pine (*Pinus*) and juniper (*Juniperus*) pollen counts in the Hayden canal are probably the result of introduced ornamentals (*23*, p. 68). This suggests that palynology can be used as a tool for distinguishing between the early canals and those constructed after about 1870.

Hohokam Irrigation Systems

Few studies have attempted to treat prehistoric canals, or groups of canals, as part of much larger community or regional water supply systems. One such study was undertaken in 1973 and 1974 by Herskovitz (*14*). While conducting excavations along the route of a proposed freeway corridor in Tempe, Herskovitz obtained aerial photographs taken at different times by the Arizona Department of Transportation. These photographs show the traces of scores of canals through the disturbed soils of fallow fields (Fig. 5) (*25*). Herskovitz excavated five Classic Period canals and tested eight other prehistoric canals, with five of the 13 being first observed in the aerial photographs.

A question raised by Fig. 5 is how the canals are visible at all. Several factors have created a situation in which the deposits of the prehistoric canals became darker than the surrounding dry alluvium. The upper deposits of these canals have been truncated and exposed by plowing. These clayey canal deposits retain moisture much longer than the surrounding sandy alluvium, facilitating plant growth on the deposits. Also, the months previous to the aerial photography were marked by unusually low precipitation in Tempe.

Another question concerns the organizational structure of the canal systems (*26*). A Hohokam irrigation system consists of (i) a single main canal, whose head is on a permanent or semipermanent flowing source of water (such as the Gila River and its major tributaries), (ii) all subsequent branches of that canal,

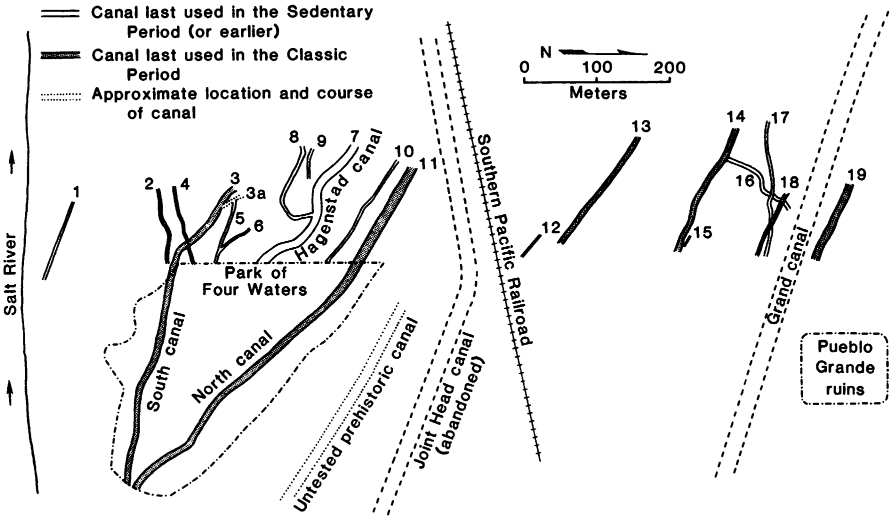

Fig. 3. Map of the excavated canals at Pueblo Grande. See Fig. 2 for approximate location.

Fig. 4. Cross section of the Hagenstad canal. Scale is 3 m in length. [Arizona State Museum—H. Teiwes, photographer]

and (iii) all villages directly serviced by any portion of the system. Figure 2 shows a number of main canals heading off the Salt River.

To present a clearer picture of the smaller components of an irrigation system, all the prehistoric canals visible in the aerial photographs used in this study (including Fig. 5) are shown schematically in Fig. 6 (*27*). The main canal is divided into a myriad of branches (distribution canals), each serving various field locations. Lateral canals, the smallest visible component of the irrigation system, are usually sandwiched between, and run perpendicular to, the distribution canals. The laterals are spaced somewhat regularly from one another, usually by about 45 to 60 m. The distribution canals are parallel to and the laterals usually perpendicular to the direction of the slope. This system appears amenable to the type of irrigation termed wild flooding (*22*, pp. 297–299; *28*), a method that is efficient and economical if handled properly. Individual plots were covered with a thin sheet of water tapped from the upslope laterals. Excess water was continuously shifted to the next lower plot by means of the lower laterals and the field distribution canals. Eventually the excess water was lost in the terminal portions of the irrigation system. This method not only provided water for irrigation, but also allowed for some drainage.

At least ten main canals and their associated irrigation systems are present within the area shown in Fig. 2. Most of these canals date to the Classic Period and probably were used contemporaneously (*29*). If Fig. 2 reflects the actual number and distribution of main canals that simultaneously tapped this portion of the Salt River, then it can be estimated that individual irrigation systems ranged in areal extent from 1,000 to 10,000 hectares (10 to 100 km^2). The largest single system appears to be that which serviced the important Classic Period villages of Los Muertos, Alta Vista, Casa Loma,

Fig. 5. Aerial photograph showing the remnants of prehistoric irrigation canals (faint dark lines) in fallow fields at Tempe, Arizona. See Fig. 2 for approximate location. [Arizona Department of Transportation]

Pueblo del Monte, and at least five other unnamed villages. This is the system sampled by Herskovitz (*14*) and depicted in Figs. 5 and 6. Of course, a significant portion of the area circumscribed by each irrigation system was probably not used for farming, since local soil and topographic conditions may have favored some locations over others and since the villages themselves covered a sizable percentage of the potentially usable farmland.

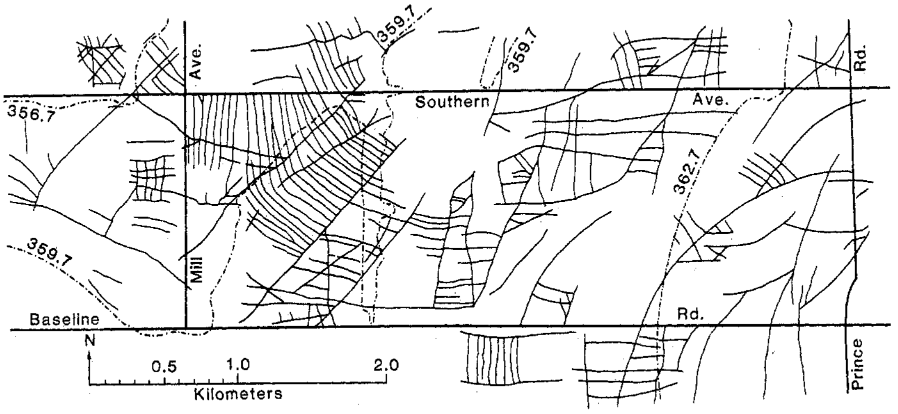

Fig. 6. Composite map constructed from aerial photographs of the prehistoric irrigation systems at Tempe, Arizona. Dashed lines are approximate contour intervals (3 m) adapted from U.S. Geological Survey maps of the area. See Fig. 2 for approximate location.

To better understand the duty and regimen of water in Hohokam irrigation systems, the carrying capacity of a number of the Pueblo Grande canals was estimated by the Manning equation, a method commonly used by hydraulic engineers to design open channels for the uniform conveyance of water (*30, 31*). The Manning equation states that $V = (1/n)R^{2/3}S^{1/3}$, where V is the mean velocity in meters per second; n is the roughness coefficient, an empirical measurement of the resistance to flow in a given channel; R is the hydraulic radius in meters, computed as the flow cross section divided by the wetted canal perimeter; and S is the slope of the canal bottom in meters per kilometer. The volume of water moving through a canal is then obtained by multiplying the velocity derived from the Manning equation by the flow cross section in square meters.

The figures listed in Table 2 are conservative (*32*), and thus are realistic estimates of the volume of water actually used by the Hohokam. Some of the estimates may even be quite low. Haury (*9*, p. 144) tentatively calculated that the main canal at Snaketown may have serviced 194 to 340 ha of tillable land. This calculation was based on modern standards of irrigation, whereby a volume of 0.028 m^3/sec can provide water for 16 to 28 ha. If we were to apply the lower figure (16 ha) to the Pueblo Grande canals, the north and south canals would each have carried enough water to irrigate more than 1600 ha, while the Hagenstad canal could have provided water for nearly 3900 ha.

The last column in Table 2 gives the percentage of the total volume of water in the Salt River tapped by each canal during the months of March and July 1889. These two months were selected because if, as suggested by Bohrer (*33*), the Hohokam planted and harvested irrigated crops twice a year (a pattern utilized by the historic Pima), then large amounts of irrigation water would have been needed in March and July. The volume figures for these 2 months, 247.6 and 14.0 m^3/sec, respectively, are suggested as being typical for the Salt River during historic times, with the March figure perhaps being somewhat too high. The yearly averages for 1889 and 1890 were 73.0 and 106.8 m^3/sec; the latter figure includes an unusually large flood in early 1890. I am assuming, correctly I believe, that the prehistoric volume of the Salt River was comparable to that recorded in the late 19th century.

Table 2. Volume (flow) estimates for the Pueblo Grande canals.

Canal	Channel	Cross-sectional area (m^2)	Wetted perimeter (m)	Slope (m/km)	Volume (m^3/sec)	Percentage of Salt River volume*	
						March 1889	July 1889
1	Lower	2.0	3.5	4.40	1.83	0.7	13.1
2	Lower	1.5	2.5	4.57	1.44	0.6	10.3
South	Main	3.8	5.6	2.26	2.79	1.1	19.9
4	Lower	1.3	3.3	8.48	1.29	0.5	9.2
5	Middle	1.2	3.1	0.74	0.35	0.1	2.5
6		0.4	1.6	4.33	0.21	0.1	1.5
Hagenstad	Lowest	11.5	9.1	0.62	6.69	2.7	47.7
8	Lowest	2.6	4.3	7.80	3.28	1.3	23.4
9		0.8	2.1	18.57	1.06	0.4	7.6
10		3.1	4.3	1.27	1.78	0.7	12.7
North	Upper	5.5	6.3	0.79	2.82	1.1	20.1
13		0.9	3.1	−0.13	?	?	?
14		1.9	3.7	−0.18	?	?	?
16		0.5	2.2	5.40	0.27	0.1	1.9
17		0.5	2.2	0.94	0.11	0.0	0.8
18		0.8	2.4	1.00	0.24	0.1	1.7
19		2.8	5.5	5.44	2.63	1.1	18.8

*These percentages are based on the volume of each canal divided by the average daily flow of the Salt River during March (247.6 m^3/sec) and July (14.0 m^3/sec) 1889. The volume of the Salt River was measured at a point approximately 1.6 km below its juncture with the Verde River.

Hohokam Irrigation and Society

The Pueblo Grande canals apparently tapped a significant portion of the water in the Salt River, especially during the summer months. But these canals were only a few of the systems tapping this river. There would have been many times during the year, especially during the summer months, when full or even partial use of just a few of the irrigation systems could totally drain the river. This suggests that two periods of irrigated crop plantings may have been a difficult achievement. It is likely that the normally diminished summer water supply, coupled with a substantial Hohokam population (*34*), greatly reduced the chances of successfully planting and harvesting an irrigated crop in late summer, at least on a large scale. I believe that a population increase beginning early in the Sedentary Period was accompanied by an intensification of agriculture, but not by means of two irrigated plantings a year. The Hohokam concentrated their spring efforts on their sophisticated irrigation systems, while the summers were spent gathering wild plants (*35*) and developing thousands of acres of dry farming fields known to have been used throughout much of southern Arizona during the Sedentary and Classic periods (*26*).

Regardless of whether two irrigated crops were planted by the Hohokam each year, the nature of the management of the irrigation systems remains a critical question. This concern is augmented by the fact that the canals supplied water not only for irrigation but also for domestic purposes. Both Haury (*9*, pp. 148–149) and Woodbury (*11*, pp. 556–557; *13*, pp. 49–50) indicated the need for cooperation among villages attached to a single irrigation system, although neither scholar saw the need for centralized control among the various systems or even within a single system (*36*). More recently, Doyel (*37*; *38*, pp. 163–165) advocated that each irrigation system ("irrigation community") was organized by social ranking principles, with one village exercising economic and social controls over the others. However, the archeological correlates of the ranked villages have not yet been satisfactorily delineated and tested, especially for the Sedentary Period settlement system (*39*).

On the basis of the Pueblo Grande data, I suggest that some form of coordination or control was necessary not only within single irrigation systems but among all the systems in the Salt River Valley. Unless the Hohokam were adept at manipulating the often savage and unpredictable floods of the Salt River, there would have been a need to schedule and allocate normal river flow for periodic irrigations and domestic purposes.

One of the purposes for the Hohokam colonization of the upstream tributaries to the Salt and Gila rivers during the Sedentary Period may have been to maintain regional control over their water supply. The breakup and reorganization of the Hohokam polity around A.D. 1150 may have been partially in response to climatic perturbations disrupting the fabric of the regional water control system. The dissolution of a regional system of water management and the resultant abuses of the water supply upstream could have been responsible for the abandonment of the Gila Bend area.

Water management permitted the Hohokam to flourish in the Arizona desert for more than a millennium. Multidisciplinary study of Hohokam irrigation systems is important not only for the understanding of Hohokam settlement patterns and social organization, but also for a more general comparative understanding of the role of water management in cultural evolution. Scrutiny of as yet unstudied aerial photographs and the excavation of additional canal systems should continue to be fruitful avenues of research.

References and Notes

1. Modern irrigation farming in this region had its modest beginnings in 1867, when a rancher diverted water from the Salt River into his 5-km-long earthen canal just east of the as yet unfounded settlement of Phoenix [A. P. Davis, *U.S. Geol. Surv. Water-Supply Pap. 2* (1897), p. 51].
2. F. H. Cushing, *Congrès International des Américanistes: Compte-Rendu de la Septième Session* (Berlin, 1890), pp. 151–194.
3. F. W. Hodge, *Am. Anthropol.* **6**, 323 (1893).
4. E. W. Haury, *Pap. Peabody Mus. Archaeol. Ethnol. Harv. Univ.* **24** (No. 1) (1945).
5. H. R. Patrick, *Phoenix Free Mus. Bull. 1* (1903).
6. F. Midvale, *Kiva* **32**, 28 (1967).
7. O. S. Halseth, *Masterkey* **5**, 164 (1932).
8. Prehistoric canal segments that have survived to the present include those at the Park of the Canals in Mesa, the Park of Four Waters in Phoenix, and along Arizona State Highway 87 (Beeline Highway) northeast of Mesa.
9. E. W. Haury, *The Hohokam: Desert Farmers and Craftsmen* (Univ. of Arizona Press, Tucson, 1976).
10. R. B. Woodbury, *Am. Antiq.* **26**, 267 (1960).
11. ———, *Am. Anthropol.* **63**, 550 (1961).
12. ———, in (*9*), pp. 141–142.
13. ——— and J. Q. Ressler, *Anthropol. Pap. Univ. Utah* **62**, 41 (1962).
14. R. M. Herskovitz, unpublished manuscript.
15. W. B. Masse, *Ariz. State Mus. Contrib. Highw. Salvage Archaeol. Ariz. 43* (1976).
16. B. Bradley, unpublished manuscript.
17. Not discussed in this article is a small canal found on the south side of the Salt River that almost certainly dates to the early portion of the Gila Butte Phase of the Hohokam Colonial Period (A.D. 550 to 700). This canal averaged only 50 cm in width and 20 cm in depth and had a gradient of 2.35 m/km.
18. R. C. Euler, G. J. Gumerman, T. N. V. Karlstrom, J. S. Dean, R. H. Hevly, *Science* **205**, 1089 (1979).
19. This canal was named in memory of Brett Hagenstad, a crew member of the 1976 project, who died shortly after completion of the fieldwork.
20. Prehistoric canals are extremely difficult to date, especially on the basis of artifacts recovered from short excavated stretches. The construction of canals through earlier trash deposits, the stabilizing of canal banks with earlier trash, the burrowing of animals, and the mixing of later shards into canal fills by flooding are all ways in which the temporal interpretations of short canal sections can be distorted. Stratigraphic data and superposition relationships have helped in the relative dating of the Pueblo Grande canals, but absolute chronological placement is somewhat problematic for several of the canals. Temporal assignments presented in Table 1 should be viewed as tentative. Dating of the Hagenstad canal is based on the recovery of diagnostic ceramics within and beneath the earliest channel and by the obliteration of traces of the canal banks by the spoil from the north and south canals in the Park of Four Waters.
21. W. B. Masse, unpublished manuscript.
22. O. W. Israelsen and V. E. Hansen, *Irrigation Principles and Practices* (Wiley, New York, ed. 3, 1962).
23. D. P. McLaughlin, in (*15*), pp. 64–69.
24. The heads of canals are best placed slightly upstream from the outside of a river bend [J. D. Zimmerman, *Irrigation* (Wiley, New York, 1966), p. 60].
25. R. M. Herskovitz was not the first to recognize spiderweb-like Hohokam canal systems in aerial photographs. This was accomplished earlier by N. M. Judd [*Explor. Field Work Smithson. Inst. 1930* (1931), p. 166] and O. S. Halseth (*7*, pp. 172–173); but Herskovitz is credited with being the first to complete a paper on the topic (*14*).
26. Not considered here are techniques used by the Hohokam which did not involve irrigation, such as floodwater farming [W. B. Masse, *West. Archeol. Cent. Publ. Anthropol.* **12** (1980)] and dry farming [———, *Kiva* **45**, 141 (1979)].
27. Figure 6 is adapted and enlarged from R. M. Herskovitz (*14*, figure 12). Aerial photographs used to produce the present map include five exposures from the Arizona Department of Public Transportation, taken between 1961 and 1965, and one exposure from the files of the Salt River Project (Phoenix office), taken in 1934. These were provided through the courtesy of the Arizona State Museum. Aerial photographs taken by the Arizona Department of Public Transportation in 1972 indicate that fully 90 percent of the canals depicted in Fig. 6 have been obliterated by residential housing projects.
28. F. H. Newell, *Irrigation in the United States* (Crowell, New York, 1902), pp. 199–202.
29. Most of the canals noted by Patrick (*5*) and other early workers date from the Classic Period, presumably because the older canals were destroyed by flooding during the Sedentary Period and because those not destroyed were reused during the Classic Period. It is surprising that more historic canals were not encountered in the recent work at Pueblo Grande and Tempe. However, this recent work strongly suggests that nearly all of the untested canals depicted in Fig. 6 are prehistoric. Moreover, it is possible that most of the canals were in use simultaneously, since there appears to be relatively little superpositioning of canals. The distribution of Classic Period villages in the Salt River Valley [S. Upham and G. Rice, *Ariz. State Univ. Anthropol. Res. Pap. 23* (1980)] seems to coincide well with the canal locations depicted in Fig. 2.
30. V. T. Chow, *Open-Channel Hydraulics* (McGraw-Hill, New York, 1959), pp. 98–123.
31. C. D. Busch, L. M. Raab, R. C. Busch, *Am. Antiq.* **41**, 531 (1976).
32. It was impossible to detect the actual level of normal water flow in the excavated canals, so the estimates of cross-sectional area and wetted perimeter are based on an arbitrary freeboard consisting of approximately one-third the total depth of the canal. Such a space would have guarded against overtopping by waves and unexpected fluctuations in water level caused by floods. This freeboard figure is especially conservative since all the Pueblo Grande canals have been truncated by modern agriculture to a depth 0.4 to 1.0 m beneath the present ground surface. The normal prehistoric cross-sectional areas and wetted perimeters were probably somewhat greater than indicated in Table 2. A roughness coefficient of .05 was used to establish the water velocity. Busch *et al.* (*31*, p. 532) implied that a value for *n* of .0027 might be justifiable for Hohokam canals. However, such a value would apply to straight channels whose flow is uniform and whose banks are generally free from vegetation. I favor the more conservative, lower velocities created by a value for *n* of .05 because of the sinuous nature of some of the Pueblo Grande canals, the presence of large cobbles at the channel bottoms and in their banks, and the possibility that brush and weeds were not regularly cleaned from the canal banks. The major uncertainties for the volume estimates in Table 2 concern the canal slope figures and the possibility that erosion subsequent to the last use of any canal may have enlarged the original dimensions of that canal. Canal slopes could only be measured for short distances because testing had to be confined to the highway right-of-way. Canals 2, 4, 6, 9, 14, 16, and 18 were measured for 20 to 45 m; the remainder, for 53 to 130 m. The steep slopes observed in canals 4 and 9 probably are the product of the shortness of the measurement. Erosion can be a problem for earthen canals [G. W. Pickels, *Drainage and Flood-Control Engineering* (McGraw-Hill, New York, ed. 2, 1941), pp. 202–205]. However, the gentle slopes of most of the Pueblo Grande canals, the depositional evidence for slow water flow, and the probability of moderate to heavy vegetation on the canal banks suggest that the measurements listed in Table 2 are realistic approximations.
33. V. L. Bohrer, *Am. Antiq.* **35**, 428 (1970).
34. E. W. Haury (*9*, p. 356) tentatively estimated that the Classic Period Hohokam of the Gila and Salt river valleys numbered between 50,000 and 60,000, a figure eight to ten times the size of the historic Piman population.
35. A. C. Goodyear, *Ariz. State Univ. Anthropol. Res. Pap. 9* (1975); W. H. Doelle, *Ariz. State Mus. Archeol. Ser. 103* (1976); W. B. Masse, *West. Archeol. Cent. Publ. Anthropol.* **12**, 313 (1980).
36. E. W. Haury and R. B. Woodbury base their models on direct analogy with historic Piman irrigation practices. The general layout of Piman irrigation systems is similar to that of the Hohokam systems. For example, the modern Piman system mapped by Haury near Snaketown (*9*, figure 8.4) strikingly resembles the prehistoric system (Fig. 6) discussed in this study. Howev-

er, there are several critical differences that make direct analogy difficult, if not inappropriate. Most of the land irrigated by the Pimans was in the floodplain and lowest terrace of the Gila River and its tributaries [R. A. Hackenberg, *Aboriginal Land Use and Occupancy of the Pima-Maricopa Indians* (Garland, New York, 1974), vol. 1, pp. 148–149]; the Hohokam utilized thousands of hectares of higher terrace farmland as well. Whereas the historic Pimans farmed a maximum of only about 6000 ha [*ibid.*, vol. 2, pp. 67–69], the Hohokam had many times that amount under cultivation throughout the Sedentary and Classic periods. Another important difference between Piman and Hohokam irrigation systems concerns the number of villages in direct association. According to Hackenberg (*ibid.*, vol. 1, p. 139), "both Pima and Maricopa villages were made up of groups of families who farm adjoining acreages. In addition to kinship bonds, these families were held together by common interest in the particular acreage which they cultivated. . . . [A]boriginally, a village consisted of all those families receiving their water for irrigation from a common ditch." E. F. Castetter and W. H. Bell [*Pima and Papago Indian Agriculture* (Univ. of New Mexico Press, Albuquerque, 1942), p. 126] noted that even when large tracts of land were being newly developed, only one to three Piman villages were involved in the undertaking. The Hohokam, on the other hand, had perhaps as many as nine or more villages linked to single irrigation systems. The organizational aspects of water management would of necessity have been more rigidly controlled by the Hohokam because of the larger number of variables (such as village, group, and individual needs) that had to be accounted for. Population size and density may have been the most critical factors in the differences between Piman and Hohokam water management. This hypothesis is supported by ethnographic data on the relationship between population and the development of social complexity [W. C. Kappel, *Pap. Univ. Ariz.* **25**, 159 (1974)].

37. D. E. Doyel, *Am. Sci.* **67**, 544 (1979).
38. ______, *Classic Period Hohokam in the Escalante Ruin Group* (University Microfilms, Ann Arbor, Mich., 1977).
39. Models of settlement hierarchy were recently developed for the Classic Period Hohokam, with the suggestion that Gila River Valley villages such as Casa Grande [D. R. Wilcox and L. O. Shenk, *Ariz. State Mus. Archeol. Ser. 115* (1977)] and Escalante (*38*) were the highest ranked villages within their individual settlement (irrigation) systems. These promising models have yet to be critically evaluated.
40. O. A. Turney, *The Land of the Stone Hoe* (Arizona Republican Print Shop, Phoenix, 1924).
41. I thank David R. Wilcox, Carroll L. Riley, George J. Gumerman, Robert L. Rands, Jeffrey S. Dean, and Scott C. Russell for comments on an earlier draft of this article. Financial assistance for the drafting of Figs. 1, 2, 3, and 6 was generously provided by the Center for Archaeological Investigations and the Department of Anthropology, Southern Illinois University, Carbondale. These figures were drafted by Karen Schmitt. I also thank Laurens C. Hammack, Alan Ferg, David A. Gregory, Alan P. Sullivan, and Ellen Horn of the Arizona State Museum and Mason Toles, James Dorre, and William Hayden of the Arizona Department of Transportation for assistance in various aspects of the study.

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