STREAMFLOW AND POPULATION CHANGE IN THE LOWER SALT RIVER VALLEY OF CENTRAL ARIZONA, ca. A.D. 775 to 1450

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Floods and droughts and their effects on Hohokam canal systems and irrigation agriculture play a prominent role in many cultural-historical interpretations of the Hohokam trajectory in the lower Salt River valley (modern-day Phoenix, Arizona metropolitan area). Catastrophic floods and associated geomorphic stream channel changes may have contributed to settlement and population changes and the substantial depopulation of the lower Salt River valley ca. A.D. 1450 or later. In this study, archaeological data on Hohokam domestic architecture is used to infer changes in prehistoric population growth rates from ca. A.D. 775 through 1450 in the most thoroughly documented canal system in the Salt River valley. Changes in growth rates are compared to the retriductions of annual streamflow discharge volumes derived from tree-ring records. Contrary to expectations, population growth rates increased as the frequency, magnitude, and duration of inferred flooding, drought, and variability increased. These results challenge existing assumptions regarding the relationship among floods and droughts, conditions for irrigation agriculture, and population change in the lower Salt River valley.

Las inundaciones y las sequías, así como sus efectos en los sistemas de canales Hohokam y en la agricultura de riego figuran de manera importante en muchas de las interpretaciones culturales históricas sobre la trayectoria de la cultura Hohokam, en la cuenca inferior del Río Salado (Phoenix, Arizona, EE.UU.). Las inundaciones catastróficas y los cambios geomorfológicos asociados con los cauces del río pueden haber contribuido a los cambios en el patrón de asentamientos a través del tiempo y a la despoblación significativa de la cuenca mencionada (ca. 1450 d.C. o después). En este estudio, se deducen cambios en las tasas de crecimiento de la población prehistórica por medio de datos arqueológicos sobre la arquitectura habitacional Hohokam, desde 775 d.C. hasta 1450 d.C., asociados con el sistema de canales de riego más minuciosamente documentado en la cuenca del Río Salado. Se comparan los cambios demográficos con las estimaciones retrospectivas de los volúmenes anuales del caudal derivados del registro de anillos de crecimiento de los árboles. Contrariamente a lo que se esperaba, la tasa de crecimiento demográfico aumentó al igual que la frecuencia, la magnitud, la duración y la variabilidad de las inundaciones y las sequías deducidas. Estos resultados cuestionan las suposiciones actuales acerca de la relación entre las inundaciones y las sequías, las condiciones para agricultura de riego y los cambios demográficos en la cuenca inferior del Río Salado.

The purpose of this study is to examine the relationship between variation in Salt River streamflow discharge volume and Hohokam population growth and decline in Canal System 2 between A.D. 775 and 1450. As a result of more than twenty-five years of development-related archaeology, Canal System 2 is the most thoroughly documented settlement area and canal system in the lower Salt River valley (metropolitan Phoenix, Arizona). I infer population growth and decline in Canal System 2 based on excavated domestic architecture. Since Graybill (1989) retracted prehistoric annual streamflow discharge volumes of the lower Salt River from tree-ring records, streamflow events have played a prominent role in many cultural-historical interpretations of the Hohokam trajectory in the lower Salt River valley and beyond. Graybill et al. (2006) and Nials et al. (1989) argue that high magnitude annual discharges (inferred floods) and pronounced variability may have resulted in changes in river channel position and/or morphology that created unfavorable conditions for Hohokam irrigation agriculture. They further hypothesized that catastrophic floods and associated geomorphic channel changes contributed to settlement and population changes and the substantial depopulation of the lower Salt River valley after A.D. 1400.

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Based on the inferred relationship between streamflow events and Hohokam irrigation systems developed by Graybill et al. (2006) and Nials et al. (1989), I expected that as the frequency, magnitude, and duration of high magnitude discharges and variability increased, population growth rates would decrease. Likewise, based on common assumptions regarding the negative effects of drought on irrigation agriculture, I expected that as the frequency, magnitude, and duration of low-flow years increased, population growth rates would decrease. As a result of the evidence considered in this study, and contrary to these widely accepted expectations, I find just the opposite seems to occur. Population growth rates generally increased as the frequency, magnitude, and duration of inferred flooding, drought, and variability increased. These results pose a variety of new questions regarding the role of streamflow discharge volume and variability in the prehistoric population dynamics of the lower Salt River valley Hohokam.

**Research Setting and Background**

The agriculturalists of the lower Salt River valley of central Arizona developed large, integrated irrigation systems with multiple canals, some in excess of 24 km in length, from about A.D. 600 to 1450 (Howard 1993). This study considers the influence of streamflow on population in the northwest portion of the lower Salt River valley. The primary canal system in this portion of the Salt River system is referred to as Canal System 2 (Turney 1929). This canal system includes an integrated set of canals and villages sharing a common headgate location west of the Papago Buttes near the site of Pueblo Grande (Figure 1). These canals and sites represent a dynamic, changing system through time (Howard 1993). The lower Salt River/middle Gila River basin was one of the persistent core areas of Hohokam society. In addition to irrigation agriculture, characteristic Hohokam cultural manifestations include monumental architecture (ball courts, platform mounds, and big houses), marine shell ornament production and circulation, cremation and inhumation mortuary practices, sedentary village-based communities, and red-on-buff ceramics.1

A number of inferences, based primarily on historic analogs, connect streamflow events and patterns to Hohokam population change. In this section, I present a model of the relationship between streamflow events, changes in stream channel location and morphology, canal functioning, conditions for irrigation agriculture, and population change. This model was developed as a part of the analysis of the

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1982–1984 excavations at a site called Las Colinas in Canal System 2. From tree-ring records, Graybill (1989) retrodicted annual streamflow discharge volumes of the Salt River during the Hohokam period. These retrodictions are used to infer the effects of streamflow discharge variation on Hohokam irrigation systems. The data, interpretations, and model are developed in five chapters in the Las Colinas report (Graybill and Gregory 1989; Graybill and Nials 1989; Graybill 1989; Nials and Gregory 1989, Nials et al. 1989). The model is primarily applied in Nials et al. (1989). Recently, Graybill et al. (2006) updated and extended their original analysis by expanding the number of retrodicted streamflow discharge years and including the nearby Gila River in their analysis. I employ and examine their inferences in this study because their model has been widely adopted and constitutes the prevailing view among many Hohokam researchers of the relationship between streamflow, irrigation agriculture, and settlement and population change. At the conclusion of this section, I evaluate their model based on recent data on alluvial stratigraphic sequences of the nearby Gila River (Waters and Ravesloot 2000, 2001) and note some alternative interpretations of the impact of streamflow variation on conditions for irrigation agriculture and Hohokam population change.

**Linking Streamflow and Population Growth Rates**

**Streamflow, Channel Location and Morphology, and Canal Functioning.** Using tree-ring records, variation in annual discharge of the lower Salt River has been retrodicted by Graybill (1989) and extended by Graybill et al. (2006) for the interval between A.D. 572 and 1988. Streamflow is retrodicted in million acre-feet per year and is reported for water years, October to September. One acre-foot of water is approximately 326,000 gallons, enough water to cover a football field one-foot deep in water. Lower Salt River streamflow is comprised of discharge from the Salt River, Verde River, and Tonto Creek tributaries. Precipitation patterns are bimodal with peak moisture occurring during the winter and summer. Prior to dam construction in the early twentieth century, the Salt River flowed perennially.

Graybill et al. (2006) and Nials et al. (1989) argue that specific streamflow events and patterns may induce major changes in stream channel position and/or morphology. They also argue that changes in channel position and/or morphology negatively impact gravity-fed irrigation systems by changing the location and/or height of the water within the channel relative to intakes and diversion structures, headgates, and canals. Graybill et al. (2006:82) define four types of annual discharge events and patterns that are potentially significant for inducing major changes in channel position and/or morphology. These include (1) extremely high annual flows that may have included “catastrophic” flood events, (2) closely spaced clusters of high-magnitude annual flows, (3) larger annual flows or clusters of them preceded by prolonged periods of drought in headwater areas, and (4) prolonged periods of pronounced variability [Graybill et al. 2006:82].

Graybill et al. (2006) and Nials et al. (1989) further argue that flooding likely damaged and/or destroyed canal infrastructure and agricultural land due to erosion or the deposition of impermeable silts. Low magnitude annual discharges (inferred drought if prolonged) reduced water availability to irrigated fields and may have increased the potential for stream channel change during subsequent high magnitude events. Periods of high variability are associated with greater variability in channel morphology. These inferences are based on “the known physical characteristics of Hohokam canals, on analogies with early historic canal systems, and on geologic principles” (Nials et al. 1989:59) as well as on studies of floods and the channel dynamics of arid-land rivers (Graybill et al. 2006; Graybill and Nials 1989).

**Canal Functioning and Conditions for Irrigation Agriculture.** The effect of floods, drought, and stream channel migration on early Anglo and Pima (Akimel O’odham) irrigation form the basis for inferences on the effects of streamflow on Hohokam irrigation systems (Nials and Gregory 1989; Nials et al. 1989). Salt River streamflow variation had an enormous impact on late 1800s to early 1900s Anglo and Piman irrigation prior to the construction of a number of dams on the major central Arizona rivers (Ackerly 1989:46–61). Multiple historic documents indicate that historic flooding damaged canals and irrigated fields and caused
canal abandonment (Ackerly 1989, Ackerly 1991; Nials and Gregory 1989; Zarbin 1980). The Akimel O’dham, along the nearby Gila River during the late nineteenth century, experienced malnutrition as a consequence of repeated crop failures caused by flood-induced channel widening and the resulting reduced flow and difficulty of getting water into the canals (Waters and Ravesloot 2001:292). Historic Anglo farmers also experienced water shortages and these shortages led to disputes over water rights and usage as well as talk about unifying existing irrigation systems for efficiency and conservation (Zarbin 1997). Masse (1981:413) concluded that full as well as partial use of a few of the prehistoric irrigation systems along the lower Salt River, especially during the summer, could have totally drained the river. With respect to changes in channel morphology, Graf (1983:125) finds “Over the record period of more than a century, the channel appears not to have been in equilibrium considering geometry, discharge, and sediment.” Graf (1983) documented up to 1.6 km of lateral migration of the main channel of the Salt River due to flooding.

**Streamflow Events and Population Change.** Population change has been linked to streamflow conditions in the lower Salt River valley. Nials et al. (1989:66) hypothesize that population declines during the Colonial period (ca. A.D. 775–975) were the result of poor conditions for irrigation agriculture caused by destructive streamflow events and patterns during the A.D. 798–899 interval. Gregory (1991:187) also considers the possibility that floods during the Colonial period may explain Hohokam settlement in previously unoccupied areas, some expansion into marginal areas, and the presence of Hohokam populations outside of the Hohokam area and, in some cases, within non-Hohokam settlements. Masse (1991:217) argues that as a result of the presumed disastrous flooding of A.D. 899, although Graybill et al. (2006) and Nials et al. (1989) do not specify why lower Salt River valley irrigators would leave their lands when floods damaged the canal system, presumably they would be seeking access to wild resources and/or undamaged irrigable fields to start canal irrigation again. They might have also sought to draw on social relationships and indebted individuals in other locations as a buffering strategy. Perhaps most significantly, streamflow events and associated geomorphic changes in the stream channel, because they may have rendered the canal systems inoperable and unrecoverable, have been argued to be the primary causal factor in the depopulation of the lower Salt River valley ca. A.D. 1400 (Graybill et al. 2006; Nials et al. 1989).

**Agricultural Conditions and Population Change.** Streamflow events and patterns are linked to population change by assuming that success in food provisioning affects human behavior (immigration and emigration), fertility, and mortality. High growth rates may indicate immigration, increasing fertility, and/or declining mortality. Conversely, low or negative growth rates may indicate emigration, decreasing fertility, and/or increasing mortality. Hohokam population and associated growth rates in the lower Salt River valley are notoriously difficult to determine due to the long occupational histories of many villages, historic disturbances of archaeological remains, idiosyncratic selections of sites excavated in the developed urban area of metropolitan Phoenix, and poor dating due to a lack of refinement of ceramic types and sequence and the lack of tree species in the desert amenable to dendrochronological dating.

The relationship between fertility and mortality is affected by complex interactions of a variety of factors and population growth cannot be taken for granted. Cowgill, in an examination of population changes using worldwide regional level population data, writes:

> decisions and behavior affecting growth rates and other demographic variables always occur in the context of multiple economic, technological, social and ideological factors. Wishes for large or small families, large or small communities, and high or low regional population densities are only a part of the complex of considerations that enter into behavior affecting demography. Subtle and fairly minor shifts in
these complexly inter-related factors can lead to relatively minor changes in fertility or mortality which in turn have large effects on pre-industrial growth rates [Cowgill 1975:513].

Cowgill further concludes that “sedentary food-producing populations themselves experience many very significant changes in their growth rates, and that periods of extremely slow or negligible growth, or even population decline, are interspersed with surges of relatively rapid growth” (1975:511).

Alternative Interpretations of the Influence of Streamflow Variation

Not all researchers agree on the impact or importance of streamflow variation on conditions for irrigation agriculture and the cultural-historical trajectory of the Hohokam. Alternatives to the model developed by Graybill et al. (2006) and Nials et al. (1989) are presented below.

The stratigraphic evidence documented by Waters and Ravesloot (2000; 2001) provides landscape-level context for the retrodictions of annual streamflow discharge volume developed by Graybill (1989) and Graybill et al. (2006). Waters and Ravesloot (2000, 2001) document a major period of channel cutting and widening along the nearby Gila River and regionally sometime between A.D. 1020 and 1160 based on alluvial stratigraphic evidence. Recent investigations of the soil-stratigraphic record near the confluence of the Gila, Salt, and Agua Fria Rivers suggests that the lower Salt and middle Gila Rivers have very similar, if not identical, alluvial histories and landscape evolution sequences (Onken et al. 2004). The Salt River is a major tributary of the Gila and the base level of the Salt River would control the base-level of the Salt River. Waters and Ravesloot (2001) argue that this period of channel cutting would have been devastating to Hohokam irrigation systems and food production capabilities because of the difficulty of diverting water from a wide, porous channel. Historic channel cutting resulted in a wide channel and a braided streambed with the main flow channel shifting over the streambed with each large flow (Waters and Ravesloot 2001). Unlike periodic flooding, channel downcutting and widening along the Gila River was a catastrophic event, unprecedented in the geologic record going back 15,000 years (Waters and Ravesloot 2003). Waters and Ravesloot (2001:296) argue that this landscape-level episode of channel erosion “appears to have contributed to social, political, economic, and demographic changes seen in the Hohokam culture area between ca. A.D. 1050 to 1150 by accelerating cultural changes that were already underway.”

Waters and Ravesloot (2000, 2001) document only two periods of channel cutting and widening along the Gila River: one between A.D. 1020 and 1160 and another in the late nineteenth century. This presents the possibility that the disruptive influence of streamflow events and patterns on stream channel position and/or morphology and Hohokam irrigation systems may be less frequent than hypothesized by Graybill et al. (2006) and Nials et al. (1989). Furthermore, historic analogs of the effects of floods and drought on Anglo and Piman farmers during the early historic period may only provide evidence of the influence of these events during a degrading stream channel regime (Waters and Ravesloot 2001). Lacking historic analogs for irrigation agriculture along the Salt River during an aggrading stream channel regime may limit our understanding of the effects of floods and drought on Hohokam irrigation systems.

Streamflow variability, channel change, and associated impacts on irrigation agriculture may have simply been part of the “normal” variability Hohokam agriculturalists adapted to and worked with from year to year and generation to generation. Dean (1988) has proposed a model of high and low frequency environmental processes and their effects on human behavior. He defines high-frequency processes (such as annual streamflow variation) as those with periodicities less than a single human generation (ca. 25 years). Human populations, Dean (1988) argues, adapt to high-frequency process fluctuations and these processes are of little long-range adaptive significance. Similarly, Fish (1989:44) states that “maintenance of a comparatively stable trajectory for at least 1,000 years argues for a system which anticipated and could absorb large amounts of climatic variability through customary and effective patterns of response.” Ackerly (1989), using the Graybill (1989) streamflow retrodictions combined with monthly historic flow records and accounts from early Anglo farmers, estimates that canal headgates could have been damaged as often as every 1.6 years. Russell (1975:66–67) reports that about
every fifth year the nearby Gila River failed in mid-winter, and floods sometimes destroyed canals and washed away crops. Despite these difficulties, there are no reports of famine among the Pima by any of the early historic accounts (Ezell 1961:33). Furthermore, the use-life of Hohokam main canals has been estimated to be between 50 and 100 years (Howard 1990). These frequencies do not seem to indicate that canal repair was a rare or particularly disruptive event.

Declines in agricultural productivity resulting from streamflow events may have been temporarily disruptive but mitigated by alternative food sources and trade. Irrigation agriculture, practiced by the Pima (Akimel O’odham) along the nearby Gila River, was documented in the late 1600s by the Spanish missionary, Father Kino (Russell 1975). Castetter and Bell (1942:56–57) state that before “white contact radically disturbed the economic pattern, the Pima cultivated crop in average years comprised about 50–60 percent of the total food supply, wild plants and animals constituting the remainder.” Native wild plants, such as agave, were also cultivated in the Canal System 2 vicinity (Gasser and Kwiatkowski 1991) and may have served to offset losses in productivity from the impairment of canal irrigation. Farmers near the Salt River also practiced non-canal irrigation strategies by diverting rain water run-off from higher to lower areas (Gasser and Kwiatkowski 1991). Multiple strategies and opportunities for trade would have served to buffer losses from irrigation agriculture.

The streamflow retrodictions are also inherently limited in their ability to capture all meaningful discharge variation. The retrodictions are statistical predictions subject to the limitations of the data set from which they were derived and the occurrence of both floods and droughts are inferences and hypotheses to be tested (Graybill 1989; Graybill et al. 2006). High annual stream discharge is used as a proxy for the potential occurrence of floods as tree-ring records do not capture the occurrence or timing of individual flood events. The seasonal timing of flooding within any year would have been a significant determinant of the impact on agricultural production (Ackerly 1989). Direct physical evidence of flooding through the geoarchaeological study of canal stratigraphy is superior to the proxy data provided by tree-rings (Huckleberry 1999). High magnitude instantaneous peak flows (floods) tend to occur, however, during years of high annual discharges (Smith 1981 as cited in Smith and Stockton 1981). Flood magnitude is also not linearly related to annual discharge magnitude (Graybill et al. 2006). Ackerly (1989:61–83), however, did find significant relationships between the magnitude of peak discharge events and total annual discharge estimates using historic gauged streamflow records. Yet, these relationships existed only with above-average discharge years. During below-average discharge years, Ackerly (1989:61–83) found evidence suggesting that the magnitude of peak flood events cannot be predicted. This presents the possibility that during below-average discharge years, prehistoric farmers were challenged not only by drought but also by canal damaging floods that are not detected by the retrodictions.

As identified in this section, there are several interpretations of the impact and importance of streamflow variation, especially flooding, on conditions for irrigation agriculture and the cultural-historical trajectory of the Hohokam. The inherent limitations of tree-ring based streamflow retrodictions and the associated hypothesized effects of discharge volumes on stream channel morphology also introduce uncertainty. Most researchers would agree that, to some extent, streamflow discharge volumes, including floods and droughts, affected Hohokam irrigation agriculturalists. In what ways, to what extent, and where streamflow variation affected Hohokam farmers in the lower Salt River valley remains a subject of continuing discussion. Despite alternative interpretations and uncertainties, the Graybill et al. (1989; 2006) and Nials et al. (1989) data and model have had a significant influence on many interpretations of settlement and sociocultural change in the lower Salt River valley. Although Graybill et al. (1989, 2006) and Nials et al. (1989) have been cautious in presenting their interpretations as hypotheses for future testing, these hypotheses have significantly formed the prevailing view of many. For this reason, their extraordinary contribution to Hohokam prehistory should remain a focus for continued research and consideration for some time in the future.

Methods

The purpose of this analysis is to systematically examine the relationship between annual stream-
flow discharge variation and population growth rates. Retrodicted annual streamflow discharge volumes\(^3\) and archaeological data on domestic architecture spanning almost 700 years allows a systematic evaluation of the relationship between streamflow events and population change.

**Cultural/Temporal Phases**

This study considers population growth and decline during five cultural/temporal phases spanning from A.D. 775 to 1450. There are multiple interpretations of the Hohokam cultural chronology. Variation in the dates for phases/periods used in the excavation project reports exacerbate the challenge of creating a phase-based reconstruction. Statistical errors associated with the chronometric techniques used in Hohokam research do not permit the temporal resolution possible in other parts of the Southwest. Researchers do, however, accept the ordering of the temporal phases and generally agree on the trait lists that define phases (e.g., architectural and ceramic styles). I use the chronology proposed by Dean (1991:90) as it is derived from a comprehensive consideration of all independent chronometric dates available (as of early 1988). I modified the chronology to eliminate the ambiguity of overlapping dates between phases so that I could assign a house or a streamflow discharge year to one phase or another (Table 1). For example, Dean (1991) determined the probable range of the beginning of the Sacaton phase as A.D. 950–1000; I selected the date in the middle of this range (A.D. 975) for the start of the Sacaton phase. I use this procedure whenever Dean proposes a range of starting or ending dates. I do not use the Polvorón phase designation because it was not consistently used by researchers in the various excavation reports. Chronological refinements have continued since Dean (1991) with a recent addition provided by Henderson and Clark (2004:171). The chronology presented by Henderson and Clark (2004:171) is substantially similar to the one used in this analysis with starting and ending dates of each phase varying by no more than 25 years. These differences should have no significant analytical impact on the trends identified in the streamflow data examined in this analysis. I expect no analytical impact because there is no systematic patterning of high and low flows associated with temporal/cultural phase boundaries. I have also used many different kinds of measures of streamflow discharge volume (see below) to capture the trends in the data so that the results of this analysis do not rely on only a few streamflow pattern characterizations.

**Lower Salt River Streamflow**

The streamflow measures used in this analysis were developed to characterize annual streamflow variation in ways that indicate conditions likely to result in changes in immigration/emigration, fertility, and mortality. In other words, the streamflow measures are designed to capture variation in streamflow events and patterns that likely affected human behavior. Based on the model developed by Graybill et al. (2006) and Nials et al. (1989), I assume, for the purposes of this analysis, that high annual flows (inferred flooding) and pronounced variability created unfavorable conditions for irrigation agriculture. Low annual flows (inferred drought if prolonged) are also assumed in this research to have resulted in unfavorable conditions for irrigation agriculture. Low flows likely resulted in decreased flows throughout canal systems. Water
shortages among historic irrigators in the lower Salt River valley make this a reasonable assumption. Unfavorable agricultural conditions, created by high, low, or variable streamflow discharge volumes, likely led to food stress that motivated people to leave a place for another (emigrate) or led to reductions in fertility and/or increases in mortality. By extension of these expectations, flows that were neither high, low, nor variable should not have stressed agricultural production and resulted in significant population change.

Three methods drive this analysis of streamflow variation. First, annual streamflow discharge events and patterns are characterized by Hohokam temporal/cultural phase. Characterizing streamflow within each phase fits the streamflow data to the 100 to 200 year phase-level resolution of the architectural house data. All streamflow measures are affected by the number of years in each phase. To make these measures of streamflow comparable by phase, I use either the percent of years within each phase that meet the various criteria or standardize the measure value by dividing the measure result by the number of years within each temporal phase.

Second, high- and low-flow years are defined. As a baseline from which to infer high and low flows, I use deviation from the mean streamflow discharge volume calculated from the years A.D. 572–1450. The mean annual discharge volume for these 879 years is 1.15 million acre-feet (MAF). The amount of discharge above and below the mean that would have affected agricultural productivity and/or stream channel morphology is unknown. To address this uncertainty, I define high flows variously as above the mean, above one standard deviation (1.79 MAF), and above two SD (2.43 MAF). I define low flows as below the mean, below one half SD (.83 MAF), and below one SD (.51 MAF). There are no flows two standard deviations below the mean. By defining high and low flows with multiple thresholds, I expect to identify the trends in the data.

Third, multiple measures are used to characterize streamflow within each phase. No single measure or index effectively characterizes multiple types of streamflow events and patterns within any temporal period. Rather, multiple measures must be employed to capture a range of characteristics that likely impacted irrigation agriculture and affected human demographic behavior. For example, 10 low-flow years (inferred drought), evenly spaced over 100 years, may have had little behavioral impact as stored food reserves and alternative subsistence strategies likely buffered declines in agricultural productivity caused by insufficient water for cultivated crops in any given year. Conversely, 10 consecutive low-flow years may have seriously stressed agricultural production, storage, and alternative resources. This relationship should hold as well for high-flow years. If high flows damaged canals, fields, or otherwise impaired canal irrigation, consecutive occurrences may have prevented canal repair or relocation and the resumption of flows to crops. In this example, I argue it is the cumulative effect of consecutive low- or high-flow years that is most likely to have affected human behavior rather than the frequency of these events. In addition to considering the duration and frequency of high- and low-flow events, the magnitude of specific events must also be considered. Not all high flows are the same; that is, the effects of flooding on canal systems, irrigation agriculture, and on stream channel morphology likely increased with the magnitude of the event.

To consider multiple streamflow characteristics in this analysis, I examine the frequency, magnitude, duration, and variability of high and low flows during the five Hohokam temporal/cultural phases from A.D. 775 to 1450. The frequency, magnitude, and duration of specified discharge volumes are often used in hydrologic analyses to describe various aspects of streamflow regimes (Poff and Ward 1989; Richter et al. 1996; Walker et al. 1995. For a review of streamflow indices see Olden and Poff [2003] and Smakhtin [2001]). I adopt and modify these traditional hydrologic measures to characterize streamflow during the 100 to 200 year-long temporal/cultural phases used in this analysis. The frequency, magnitude, duration, and variability of streamflow discharge volumes are also related to conditions for irrigation agriculture and, in some cases, channel change. I also consider the frequency, magnitude, and duration of discharge years identified by Graybill et al. (2006) as potentially significant for inducing major changes in channel position and/or morphology. Specific definitions and methods used to calculate each measure used in this analysis are as follows.

High- and low-flow frequency. High- and low-flow frequency is the percent of high- and low-flow
discharge years by temporal phase. The percent of high-flow years is calculated by taking the total number of years in the phase above the mean, above one standard deviation (SD), and above two SD and dividing these numbers by the number of years in the phase. The mean and standard deviation units above or below the mean are calculated from all discharge years from A.D. 572 to 1450. For example, there were 200 years in the Sacaton phase (A.D. 975 to 1174), and 17 of these years were one standard deviation or more above the mean annual streamflow discharge from A.D. 572 to 1450. Seventeen years is nine percent (rounded from 8.5 percent) of the Sacaton phase. For low-flow years, the total number of years below the mean, below one-half SD, and below one SD is calculated.

High- and low-flow magnitude indices. Magnitude, in this study, is the extent of deviation from the mean annual streamflow discharge volume. By phase, I calculated magnitude with two methods. The first method simply involves summing the discharge volumes of all high- and low-flow years during each phase. The second method involves summing only the discharge volumes of the consecutive high- and low-flow years during each phase. Consecutive years are defined as two or more successive years that meet the various thresholds as high or low flows. The cumulative impacts of consecutive high- and low-flow years may be greater than single occurrences. I calculate magnitudes using the Z scores for each discharge year. Z scores represent the deviation from the mean in standard deviation units. Z scores are easier to interpret because low flows are expressed as negative numbers. Also, the lower the flow the higher the negative Z score. By example, the magnitude of the 17 years of the Sacaton phase equal to or below one SD results in a total Z score of -28.98. The Z score magnitude is divided by the 200 years in the Sacaton phase to make results comparable across phases. The result is -1.145. I use the same procedure to calculate magnitudes for low-flow years and the magnitudes of only the consecutive high and low-flow years.

High- and low-flow duration indices. The duration indices are the percent of consecutive high- and low-flow years in each phase. Consecutive years are defined as two or more consecutive years that meet the various thresholds as high or low flows.

Variability. Variability is the dispersion of discharge volumes around the mean. Variability is measured by the coefficient of variation of all annual discharges within each phase. This statistic characterizes the dispersion of all discharge years around the mean and compensates for the size of the mean.

Channel change indices. The channel change indices capture the frequency, magnitude, and duration of geomorphically significant streamflow events and patterns specified by Graybill et al. (2006). Graybill et al. (2006:82) define four types of annual discharge events and patterns that are potentially significant for inducing major changes in channel position and/or morphology. These events are the most likely to have resulted in channel changes that negatively affected conditions for irrigation agriculture, based on their model. Each criterion is specified in Graybill et al. (2006:82). These events and patterns and my methods for identifying years that meet the criteria are as follows:

Criterion 1: "extremely high annual flows that may have included 'catastrophic' flood events." Graybill et al. (2006:88–91) identify 12 high-magnitude annual flows in their Figures 5.6, 5.7, and 5.8. These flows are at least 2.65 SD (2.98 MAF) above a long-term mean of 1.16 MAF calculated from A.D. 572 to 1988.

Criterion 2: "closely spaced clusters of high-magnitude annual flows." Some years meeting this criterion are identified in several locations in their text and are all generally over two MAF a year. To identify years meeting this criterion I select all consecutive years (two or more years) with discharge volumes over two MAF a year as meeting this criterion.

Criterion 3: "larger annual flows or clusters of them preceded by prolonged periods of drought in headwater areas." Only three years are identified as meeting this criterion in their text, 1357 to 1359.

Criterion 4: "prolonged periods of pronounced variability." This criterion required interpretation and analysis as Graybill et al. (2006) use different analytic intervals (approximately 400 years in duration) that are not coeval with the Hohokam phases used in my analysis. Although they do use the coefficient of variation to calculate variability, variability is only one of multiple criteria used to define their analytical intervals. To define prolonged periods of pronounced variability for my analysis, I computed the coefficient of variation of annual dis-
charge volume for each ten-year interval from A.D. 775 to 1450 (e.g., 775 to 784, 776 to 785, etc.). I identified the ten-year intervals with the highest coefficients of variation and arbitrarily use the top five percent of these ten-year intervals to represent “prolonged periods of pronounced variability.” Through this method, I identified four prolonged periods of pronounced variability from 775 to 1450. The periods ranged in duration from 10 to 21 years.

The frequency, magnitude, and duration of years that meet Criterion 1 through 4 are defined as follows: The frequencies are simply the percent of years in each temporal phase identified as geomorphically significant based on the four described criterion. The magnitudes are the sum of discharge volumes (using Z scores) that meet criteria 1, 2, and 3. The Z score magnitudes are standardized by dividing the calculated magnitudes of each phase by the number of years in each phase. All years identified as geomorphically significant are consecutive years so the frequency (percent) of geomorphically significant discharge years is the same as a duration measure; therefore, a duration measure is omitted.

Methodological Limitations. There are some disadvantages of characterizing streamflow by cultural/temporal phases. Phase-level streamflow descriptions are an artificial analytical unit employed to allow comparisons with temporal trends in the number of houses (generally only measurable at the phase level). One analytical effect of grouped streamflow characterizations is that streamflow patterns may be truncated and statistically minimized by phase boundaries. For example, ten high-discharge years truncated in the middle by a phase boundary will result in five years in one phase and five years in another. To specifically examine whether or not this occurs, I examined the consecutive high and low flows (variously defined) used for the duration indices at all phase boundaries. I find that truncation of consecutive high- and low-flow discharge patterns occurs in only three instances. Each instance occurs during the calculation of high- and low-flow durations when high and low flows are defined as above and below the mean. There are no occurrences of truncation of consecutive discharge years for high-flow years over one and two standard deviations and low-flow years one-half and one standard deviation below the mean. The three instances of truncation are addressed by including the truncated years in the phase containing a majority of the consecutive years that met the criterion.

Grouped characterizations may also minimize the effect of singular, rare discharge years (e.g., A.D. 899), thereby obscuring the impact these discharge years may have on irrigation agriculture over several years. These grouped characterizations, however, may compensate for some inevitable inaccuracies of the statistical retrodictions of discharge volume for any given year by quantifying trends/patterns within each phase. This prevents focusing on a few retrodicted extraordinary discharge years and allows a consideration of the patterns that may have been the most meaningful to irrigation agriculture and demographic behavior in the long run. The channel change indices (described above), however, capture the extremely high-magnitude discharge years that were mostly likely to have induced channel change. The magnitude measures of each phase also allow comparisons of magnitudes by phase. Through these measures, the effects of rare and extreme events are considered.

Houses of Canal System 2

A total of 753 houses reported by cultural resource management or historical excavation projects are used in this analysis (Table 2). These projects include the vast majority of houses excavated within the geographic area defined as Canal System 2. A “house” is defined as a structure likely used for year-round occupation. Houses varied in style through time and included pit houses (houses in shallow pits), aboveground freestanding adobe rooms/houses, and aboveground contiguous adobe rooms/houses. Walls were of brush, adobe, caliche, masonry, or some combination of these materials (Haury 1976:45–77).

The house counts are made comparable across phases using the following methodological decisions:

First, I use the temporal phase assignment determined by the researchers who examined the available evidence. Researchers used multiple lines of evidence to assign a house occupation to a temporal phase of 75 to 200 years in duration. Evidence includes associated ceramic types/styles/composition, architectural style, stratigraphic placement, and archaeomagnetic and radiocarbon dating.
Second, both complete and partially excavated houses including those with and without hearths are used, if dated. Structures without hearths are counted for several reasons: First, a visual examination of multiple plan-view drawings of excavated houses contained in the excavation reports revealed that a significant number of hearths had been removed by backhoe trenched used for excavation. Second, I examined floor sizes of houses with and without hearths and virtually no size differences existed based on hearth presence/absence. This result provides no support for inferring habitation vs. nonhabitation (storage) functions for houses with or without hearths. Third, there is no common understanding or agreement on the archaeological signature of a Hohokam storage structure. Finally, the decision to use both houses with and without hearths has no analytical impact on this study. Growth rates (discussed below) calculated from houses with or without hearths are very similar.

Third, houses not assigned a date or temporal phase and houses assigned to three or more temporal phases (usually a result of insufficient evidence to make a chronological assignment) are eliminated.

Fourth, houses identified by researchers as “field houses” are eliminated. “Field houses are individual structures and associated facilities established solely for the purpose of tending agricultural fields; they are inferred to have been occupied during periods of planting, growing, and/or harvesting of crops” (Gregory 1991:163).

Fifth, houses assigned to two phases are divided between the two assigned phases (one half a house is counted in each phase). About eighteen percent of the houses used in this analysis were assigned to two adjacent phases by researchers. I tested the impact of counting houses assigned to two phases as one house for each assigned phase, rather than one-half a house. Growth rates (discussed below) for all phases were virtually the same.

Sixth, I do not count houses/structures located on top of platform mounds or within the walled mound complexes. A residential function for these houses/structures remains a matter of continuing debate (see Downum and Bostwick 2003; Doyel
Seventh, for each phase, house counts are standardized by dividing the number of houses in a phase by the number of years in the phase. This provides a proxy value comparable from phase to phase. To enhance the interpretability of this standardized number, I multiply it by an assumed 25-year house use-life to provide a rough and relative estimate of the number of contemporaneous houses within a phase (cf. Kintigh et al. 2004). The use-life and length of occupation of Hohokam houses is unknown but estimates typically range from 10–40 years (Abbott and Foster 2003; Layhe 1988; Haury 1976; Henderson 1987; Craig 2000).7

**Methodological Limitations.** The 753 houses used in this study are a sample used to represent population change in Canal System 2. The house data and interpretations contained in the excavation reports used for this analysis are limited by the spatial extent of the excavated portion of each site. Early twentieth-century surveys and excavations by professional and amateur archaeologists have provided evidence for longer occupational sequences of some sites than indicated in the data provided by the more recent excavated sample (for a summary of site histories in Canal System 2 see Rice 2000). Based on these early observations and the existing excavated sample, house samples at some sites are clearly underrepresenting the size of the village. Complete excavation of a settlement in the lower Salt River valley is uncommon. Only La Lomita Pequeña (Mitchell 1988) was likely completely excavated. Three other projects have resulted in samples that may represent individual site/settlement trajectories at certain time periods: El Caserío during the Gila Butte and Santa Cruz phases, La Ciudad from the Gila Butte through Sacaton phases, and Pueblo Grande from the Sacaton through Civano phases. The proportion of each settlement excavated is generally unknown due to spatial limits on development-related excavation, the dispersed nature of Hohokam settlements, and long-term settlement occupations. This is not an individual settlement-based analysis, however, so the extent of excavation at each location is less important than the representativeness of phase-level data represented by the entire sample of houses from the thirteen projects considered throughout Canal System 2.

Several factors may have affected the number of houses recorded by phase. The number of houses are likely undercounted during the early phases (Red Mountain through Snaketown phase, ca. A.D. 0–774) for several reasons: long occupation of many sites and the possibility of prehistoric disturbance, a dispersed “rancheria” settlement pattern during the early phases, diminished material culture relative to later times, and a longer time for site burial. Based on these concerns, I eliminated the Red Mountain through Snaketown phase house counts from this analysis. Pit houses also have low visibility compared to some of the aboveground masonry structures of the Classic period and thus may be underrepresented. The number of houses in the Soho phase may be the result of a somewhat more ambiguous trait list for defining this phase. Civano phase houses may be either over or undercounted. Many Civano phase houses may have been in the “plow zone” of early Anglo farmers; or, the number of houses in the Civano phase may reflect an excavation bias toward monumental architecture common in the Classic period.

The representativeness of a sample is an inherent concern in all archaeological research where samples are relied upon to represent the total population of any artifact type or analytic unit. In this research, I do not see any systematic bias in the methods or locations from which the samples were derived. The research designs of the multiple excavation projects in Canal System 2 did not exclude some houses from excavation based on style or time period. Excavation locations were primarily the result of highway expansion projects that are distributed throughout Canal System 2. Although the size of the sample of houses from Canal System 2 will undoubtedly increase over time, increases are likely to be incremental. It is not the size of the sample, however, that influences its representativeness. It is the location of predefined development-related excavation project areas that potentially threaten the representativeness of the sample. Future excavations will be limited by the same spatial constraints on excavation as previous work. I rely on the existing sample of excavated houses because it is the best we have and the best we are likely to get in the near future.

**Population Growth Rates**

To infer population growth and decline, I use the number of houses in each temporal/cultural phase

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and compute the compound annual growth rate (CAGR). The CAGR describes population change as a constant percentage each year. The formula is: 
\[ \text{CAGR} = \left( \frac{p_2}{p_1} \right)^{\frac{1}{n}} - 1 \] 
where \( p_2 \) and \( p_1 \) are the number of houses at the end and beginning of the phase respectively and \( n \) is the number of years in the phase. The growth rate calculation uses the standardized house counts to account for different phase lengths. House use-life is not considered in this calculation. I prefer growth rates rather than changes in the absolute number of houses in each phase because growth rates capture the trends in population change. It does not seem reasonable to expect a linear relationship between the absolute number of houses in each phase and streamflow variation.

**Relationships between Streamflow and Population Growth Rates**

Examining the frequency, magnitude, and duration of high and low flows (variably defined), variability, and the channel-change indices results in 27 unique streamflow measures to compare to the compound annual growth rates. These streamflow measures are compared to the compound annual growth rates of each phase using Spearman’s rank correlation coefficient (\( r_s \)) procedure (Drennan 1996:227–234). This correlation procedure ranks each measure/variable from lowest to highest. The ranks are ordered by temporal phase. The correlation between the variables is then assessed using the computer program Statistica 6.1. Correlations may vary from −1 to 1 with positive numbers indicating a positive relationship between the variables and negative numbers revealing negative relationships.

Rank ordering the house and streamflow statistics by temporal phase may compensate for some weaknesses or inaccuracies of the house sample and streamflow data. For weaknesses or inaccuracies of the data to be analytically meaningful, the ranking of the measure/variable would have to be affected. For example, the closest population growth rates are the Soho phase at −.15 percent and the Sacaton phase at 0 percent. Growth rates are driven by the standardized house counts (number of houses divided by the number of years in each phase). The standardized house count for the Soho phase is .96 and the Sacaton phase is 1.2. To change the growth rate ranking, that is, for the growth rate of the Soho phase to exceed the 0 percent growth rate of the Sacaton phase thereby changing the growth rate ranking, 38.5 houses would need to be added to the Soho house count. This would be a substantial change as it represents a 5 percent change in the total house sample.

Results of the correlation analysis are presented for all phases considered and older phases are progressively removed to determine if the relationships substantially changed through time. Scatterplots of growth rates by each streamflow measure improve assessments of possible relationships between the variables. The expectation that as the frequency of high- and low-magnitude discharges and variability increased, population growth rates decreased will be supported if there is a strong negative relationship between the frequency of high, low, and variable flows and population growth rates.

**Results**

**Population Growth Rates**

Population growth rates and the standardized number of houses by phase are displayed in Figure 2. Cowgill’s (1975) examination of population change using worldwide regional-level data (up to some tens of thousands of square kilometers) provides a framework for examining growth rates in Canal System 2. Cowgill concludes:

> regional trends spanning a millennium or more show net population gains that are rarely more than what would have resulted from a steady rate of increase of 1 or 2 per 1000 per year... are perhaps never over 3 per 1000 per year...and rates of natural increase greater than about 6 or 7 per 1000 per year—that is, increase due entirely to excess of fertility over mortality, apart from increase due to migration—have occurred only very briefly and locally, or during the rapid colonization of uninhabited or very weakly defended new territory [Cowgill 1975:511].

It is important to note that Cowgill’s regional-level population growth data may not be completely comparable to growth rates in a portion of a region (e.g., Canal System 2) where internal mobility is
also a possibility. Assuming some comparability, substantial immigration and emigration can be inferred from the population growth rates and their fluctuations documented in Canal System 2. Based on the regional trends identified by Cowgill (1975), noted above, I infer that immigration is implied at growth rates greater than .7 percent (7 per 1000). Only the Sacaton and Soho phase growth rates are close to the growth rates typically expected from natural increases in birth over death rates in the absence of substantial migration. Although this is not a site/village based analysis, comparison of site/village growth rates with those in Canal System 2 as a whole is provided in Note 9.

Streamflow Measures and Population Growth Rates

The prehistoric irrigation agriculturalists of the lower Salt River experienced considerable annual and long-term variation in streamflow discharge volume and variability. Descriptive statistics of streamflow from A.D. 572–1450 and by phase are presented in Table 3. The coefficient of variation is about one-half the mean and median annual discharges from A.D. 572–1450 indicating that annual discharge volumes are highly variable from year to year.

The relationship between the 27 streamflow measures and the compound annual population growth rates, using the Spearman’s r statistic, was combined with a visual inspection of the scatterplots of growth rates by each streamflow measure. I expected that as floods, droughts, and variability increased, population growth rates would decline. I expected this decline based on the Graybill et al. (2006) and Nials et al. (1989) model and an intuitive sense that unfavorable conditions for irrigation agriculture would increase out migration and mortality and decrease fertility—all conditions that affect population growth rates. Contrary to these expectations, as inferred floods, droughts, and variability increased, so did population growth rates. More specifically, as annual streamflow discharge frequency, magnitude, duration, and variability increased, so generally did population growth rates.

The calculated results of each streamflow measure are presented in Table 4. The Spearman’s rank correlation coefficients for each measure by population growth rates are presented in Table 5 with results also provided with older phases eliminated to consider possible changing relationships through time between the variables. Positive correlation coefficients indicate that as population growth rates increased so did the streamflow measure; negative correlation results indicate that as population growth rates increased, the streamflow measure result decreased. I also present scatterplots of pop-

Figure 2. Standardized number of houses and population growth rates of temporal/cultural phases.
ulation growth rates by the frequency, consecutive magnitude, and duration of high flows one SD above the mean (Figures 3, 4, 5) and for low flows one-half SD below the mean (Figures 6, 7, 8). Scatterplots are also presented for the relationship between growth rates and variability (Figure 9) and the channel change indices (Figures 10, 11). Straight lines are fit to the data points in the scatterplots to aid visual identification of the relationship between growth rates and the streamflow measure.

Population Growth Rates and High Discharge

Table 3. Lower Salt River Streamflow Summary Statistics.

<table>
<thead>
<tr>
<th>Streamflow Statistics</th>
<th>A.D. 572-1450</th>
<th>Sweetwater 600-699</th>
<th>Snaketown 700-774</th>
<th>Gila Butte 775-874</th>
<th>Santa Cruz 875-974</th>
<th>Sacaton 975-1174</th>
<th>Soho 1175-1324</th>
<th>Civano 1325-1450</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean discharge</td>
<td>1.15</td>
<td>1.27</td>
<td>1.10</td>
<td>1.24</td>
<td>1.21</td>
<td>1.09</td>
<td>1.12</td>
<td>1.12</td>
</tr>
<tr>
<td>Median discharge</td>
<td>1.06</td>
<td>1.16</td>
<td>.98</td>
<td>1.15</td>
<td>1.08</td>
<td>1.03</td>
<td>1.07</td>
<td>.99</td>
</tr>
<tr>
<td>Maximum discharge</td>
<td>5.38</td>
<td>4.74</td>
<td>5.38</td>
<td>4.44</td>
<td>5.25</td>
<td>2.45</td>
<td>2.60</td>
<td>4.82</td>
</tr>
<tr>
<td>Coefficient of variation</td>
<td>.55</td>
<td>.59</td>
<td>.72</td>
<td>.59</td>
<td>.62</td>
<td>.44</td>
<td>.47</td>
<td>.55</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>.64</td>
<td>.74</td>
<td>.79</td>
<td>.73</td>
<td>.75</td>
<td>.48</td>
<td>.52</td>
<td>.61</td>
</tr>
</tbody>
</table>

Note: All statistics in million acre feet per year computed from retrodicted annual streamflow discharge data.

Table 4. Measures of Population and Streamflow, Calculated Results.

<table>
<thead>
<tr>
<th>Population and Streamflow Measures</th>
<th>Gila Butte 775-874</th>
<th>Santa Cruz 875-974</th>
<th>Sacaton 975-1174</th>
<th>Soho 1175-1324</th>
<th>Civano 1325-1450</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Population growth rates</td>
<td>.65</td>
<td>1.3</td>
<td>0</td>
<td>-.15</td>
<td>.47</td>
</tr>
<tr>
<td>II. High flow frequencies, magnitudes, and durations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency: Percent of years with flows above the mean</td>
<td>50</td>
<td>45</td>
<td>57</td>
<td>43</td>
<td>39</td>
</tr>
<tr>
<td>Frequency: Percent of years with flows above one SD</td>
<td>18</td>
<td>18</td>
<td>9</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>Frequency: Percent of years with flows above two SD</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>1.3</td>
<td>2</td>
</tr>
<tr>
<td>Magnitude: Sum of all discharge volume Z scores above the mean</td>
<td>.49</td>
<td>.48</td>
<td>.26</td>
<td>.31</td>
<td>.32</td>
</tr>
<tr>
<td>Magnitude: Sum of all discharge volume Z scores above one SD</td>
<td>.35</td>
<td>.36</td>
<td>.12</td>
<td>.16</td>
<td>.20</td>
</tr>
<tr>
<td>Magnitude: Sum of all discharge volume Z scores above two SD</td>
<td>.18</td>
<td>.16</td>
<td>.02</td>
<td>.03</td>
<td>.09</td>
</tr>
<tr>
<td>Magnitude: Sum of consecutive discharge volume Z scores above the mean</td>
<td>.446</td>
<td>.448</td>
<td>.191</td>
<td>.257</td>
<td>.255</td>
</tr>
<tr>
<td>Magnitude: Sum of consecutive discharge volume Z scores above one SD</td>
<td>.22</td>
<td>.24</td>
<td>.05</td>
<td>.02</td>
<td>.16</td>
</tr>
<tr>
<td>Magnitude: Sum of consecutive discharge volume Z scores above two SD</td>
<td>.13</td>
<td>.05</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Duration: Percent of years with consecutive flows above the mean</td>
<td>40</td>
<td>40</td>
<td>27</td>
<td>33</td>
<td>26</td>
</tr>
<tr>
<td>Duration: Percent of years with consecutive flows above one SD</td>
<td>9</td>
<td>11</td>
<td>3</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Duration: Percent of years with consecutive flows above two SD</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>III. Low flow frequencies, magnitudes, and durations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency: Percent of years with flows below the mean</td>
<td>50</td>
<td>55</td>
<td>43</td>
<td>57</td>
<td>61</td>
</tr>
<tr>
<td>Frequency: Percent of years with flows below one-half SD</td>
<td>31</td>
<td>38</td>
<td>33</td>
<td>32</td>
<td>34</td>
</tr>
<tr>
<td>Frequency: Percent of years with flows below one SD</td>
<td>11</td>
<td>14</td>
<td>13</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>Magnitude: Sum of all discharge volume Z scores below the mean</td>
<td>-.349</td>
<td>-.388</td>
<td>-.358</td>
<td>-.362</td>
<td>-.369</td>
</tr>
<tr>
<td>Magnitude: Sum of all discharge volume Z scores below 1/2 SD</td>
<td>-.29</td>
<td>-.35</td>
<td>-.293</td>
<td>-.30</td>
<td>-.294</td>
</tr>
<tr>
<td>Magnitude: Sum of all discharge volume Z scores below one SD</td>
<td>-.138</td>
<td>-.164</td>
<td>-.145</td>
<td>-.148</td>
<td>-.112</td>
</tr>
<tr>
<td>Magnitude: Sum of consecutive discharge volume Z scores below the mean</td>
<td>-.314</td>
<td>-.347</td>
<td>-.308</td>
<td>-.336</td>
<td>-.345</td>
</tr>
<tr>
<td>Magnitude: Sum of consecutive discharge volume Z scores below 1/2 SD</td>
<td>-.24</td>
<td>-.26</td>
<td>-.196</td>
<td>-.186</td>
<td>-.199</td>
</tr>
<tr>
<td>Magnitude: Sum of consecutive discharge volume Z scores below one SD</td>
<td>-.049</td>
<td>-.106</td>
<td>-.042</td>
<td>-.034</td>
<td>-.043</td>
</tr>
<tr>
<td>Duration: Percent of years with consecutive flows below the mean</td>
<td>43</td>
<td>48</td>
<td>47</td>
<td>51</td>
<td>55</td>
</tr>
<tr>
<td>Duration: Percent of years with consecutive flows below 1/2 SD</td>
<td>25</td>
<td>28</td>
<td>21.5</td>
<td>21</td>
<td>22.2</td>
</tr>
<tr>
<td>Duration: Percent of years with consecutive flows below one SD</td>
<td>4</td>
<td>9</td>
<td>3.5</td>
<td>2.7</td>
<td>3.9</td>
</tr>
<tr>
<td>VI. Variability – coefficient of variation</td>
<td>.59</td>
<td>.62</td>
<td>.44</td>
<td>.47</td>
<td>.55</td>
</tr>
<tr>
<td>VII. Change change indices</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency: Percent of inferred geomorphically significant years</td>
<td>32</td>
<td>27</td>
<td>2</td>
<td>1</td>
<td>18</td>
</tr>
<tr>
<td>Magnitude: Sum of discharge volume Z scores of geomorphically signif yrs</td>
<td>.17</td>
<td>.14</td>
<td>.03</td>
<td>.02</td>
<td>.1</td>
</tr>
</tbody>
</table>

Notes: All measure results have been standardized by using percents or by dividing the measure result by the number of years in each phase. Measure results that are similar in value are carried out an additional decimal place to allow ranking of the results for the correlation analysis.
Table 5. Streamflow Measures and Population Growth Rates, Spearman’s Rank Correlation Coefficients.

<table>
<thead>
<tr>
<th>Streamflow Measures</th>
<th>Gila Butte through Civano A.D. 775–1450</th>
<th>Santa Cruz through Civano 875–1450</th>
<th>Sacaton through Civano 975–1450</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. High-flow frequencies, magnitudes, and durations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency: Percent of years with flows above the mean</td>
<td>.10</td>
<td>0</td>
<td>−.50</td>
</tr>
<tr>
<td>Frequency: Percent of years with flows above one SD</td>
<td>.67</td>
<td>.40</td>
<td>−.70</td>
</tr>
<tr>
<td>Frequency: Percent of years with flows above two SD</td>
<td>.87</td>
<td>.80</td>
<td>.50</td>
</tr>
<tr>
<td>Magnitude: Sum of all discharge volumes above the mean</td>
<td>.80</td>
<td>.80</td>
<td>.50</td>
</tr>
<tr>
<td>Magnitude: Sum of all discharge volumes above one SD</td>
<td>.90</td>
<td>.80</td>
<td>.50</td>
</tr>
<tr>
<td>Magnitude: Sum of all discharge volumes above two SD</td>
<td>.80</td>
<td>.80</td>
<td>.50</td>
</tr>
<tr>
<td>Magnitude: Sum of consecutive discharge volumes above the mean</td>
<td>.70</td>
<td>.40</td>
<td>−.50</td>
</tr>
<tr>
<td>Magnitude: Sum of consecutive discharge volumes above one SD</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Magnitude: Sum of consecutive discharge volumes above two SD</td>
<td>.78</td>
<td>.77</td>
<td>n/a</td>
</tr>
<tr>
<td>Duration: Percent of consecutive flows above the mean</td>
<td>.50</td>
<td>.20</td>
<td>−1.0</td>
</tr>
<tr>
<td>Duration: Percent of consecutive flows above one SD</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Duration: Percent of consecutive flows above two SD</td>
<td>.78</td>
<td>.77</td>
<td>.50</td>
</tr>
<tr>
<td>II. Low-flow frequencies, magnitudes, and durations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency: Percent of years with flows below the mean</td>
<td>−.10</td>
<td>0</td>
<td>.50</td>
</tr>
<tr>
<td>Frequency: Percent of years with flows below one-half SD</td>
<td>.40</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Frequency: Percent of years with flows below one SD</td>
<td>.20</td>
<td>.40</td>
<td>−.50</td>
</tr>
<tr>
<td>Magnitude: Sum of all discharge volumes below the mean</td>
<td>.30</td>
<td>.80</td>
<td>.50</td>
</tr>
<tr>
<td>Magnitude: Sum of all discharge volumes below one-half SD</td>
<td>.10</td>
<td>.40</td>
<td>−.50</td>
</tr>
<tr>
<td>Magnitude: Sum of all discharge volumes below one SD</td>
<td>.10</td>
<td>.20</td>
<td>−1.0</td>
</tr>
<tr>
<td>Magnitude: Sum of consecutive discharge volumes below the mean</td>
<td>.50</td>
<td>.80</td>
<td>.50</td>
</tr>
<tr>
<td>Magnitude: Sum of consecutive discharge volumes below one-half SD</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Magnitude: Sum of consecutive discharge volumes below one SD</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Duration: Percent of consecutive flows below the mean</td>
<td>−.30</td>
<td>0</td>
<td>.50</td>
</tr>
<tr>
<td>Duration: Percent of consecutive flows below one-half SD</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Duration: Percent of consecutive flows below one SD</td>
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<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>V. Variability – coefficient of variation</td>
<td>.90</td>
<td>.80</td>
<td>.50</td>
</tr>
<tr>
<td>VI. Change change indices</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency: Percent of geomorphically significant years</td>
<td>.90</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Magnitude: Sum of discharge volumes of geomorphically significant years</td>
<td>.90</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Years. Population growth rates increased as the frequency (percent) of annual discharge volumes one and two standard deviations above the mean increased. The relationship between growth rates and flows at or above one SD resulted in a Spearman’s $r$ correlation coefficient of .67 (Figure 3). At the threshold of two SD above the mean, the correlation coefficient is .87 although there are only five or fewer discharge years in each phase above 2 SD. There was no relationship between growth rates and the frequency of all flows above the mean.

Streamflow magnitudes by phase are calculated by both the sum of all discharge volumes and all consecutive discharge volumes at or above the mean, one SD, and two SD. Population growth rates are strongly related to the magnitude of all high flows and all consecutive high flows at each threshold. The relationship between growth rates and the magnitude of all flows above the mean resulted in a Spearman’s $r$ statistic of .8, above one SD was .9 (Figure 4), and above two SD was .8. The magnitude of consecutive discharge volumes revealed the same strong positive relationship. The relationship between population growth rates and consecutive high flows above the mean resulted in a Spearman’s $r$ statistic of .7, above one SD was 1.0, and above 2 SD was .78.

Population growth rates were also strongly related to the duration of consecutive high annual flows in each phase. As the percentage of consecutive years with flows above the mean and one SD increased, population growth rates increased. The relationship is strongest between growth rates and consecutive high flows above one SD ($r_s = 1.0$, Figure 5). The correlation between growth rates and the duration of all flows above the mean is .5. There were no occurrences of consecutive high flows two SD above the mean in the Sacaton, Soho, or Civano
phases, so the relationship between growth rates and the duration of flows above this threshold should probably be disregarded.

When the Gila Butte phase (A.D. 775–874) is removed from the analysis and the Santa Cruz through Civano phases are solely considered, the relationship between growth rates and the frequency, magnitude, and duration of high flows remains generally the same. When the Gila Butte and Santa Cruz phases (A.D. 775–974) are removed and only the Sacaton through Civano phases are considered, some negative relationships emerge.
from the analysis. These negative relationships are between population growth rates and the frequency (percent) of high flows above the mean and above one SD. Negative relationships also occur between growth rates and the magnitude of consecutive discharge volumes above the mean and the duration of consecutive flows above the mean. These negative relationships may indicate some change in the relationship between growth rates and high discharge volumes during the Sacaton through Civano.
phases. The possibility that the relationship between high flows and growth rates changed during these phases should be viewed cautiously, however, as only three cases/phases are considered.

*Population Growth Rates and Low Discharge Years.* The frequency (percent) of low-flow discharge years in each phase does not appear to be related to population growth rates, based on the low Spearman’s $r$ coefficients and ambiguous scatterplots. The strongest relationship ($r_s = .4$) is between
growth rates and the frequency of flows one-half SD below the mean (Figure 6).

Population growth rates are strongly related to consecutive discharge magnitudes one-half and one SD below the mean. In other words, as the sum of consecutive discharge magnitudes below one-half and one SD increased, population growth rates increased. The Spearman's $r$ statistic is a strong 1.0 for consecutive magnitudes one-half (Figure 7) and one SD below the mean. There is no relationship between growth rates and the sum of nonconsecutive low-flow discharge magnitudes. Isolated low-
flow years probably had little effect on demographic behavior because any negative effects of lower agricultural productivity could have been mitigated by storage, trade, and gathered/hunted foods. When low-flow years become consecutive; that is, when drought conditions prevailed over multiple years, buffering strategies become strained and demographic behavioral changes begin to take place.

Population growth rates were also strongly related to the duration of consecutive low flows. As the number of consecutive years with flows below one-half (Figure 8) and one SD increased, population growth rates increased. The Spearman’s $r$ statistics are a strong 1.0 for the relationship between growth rates and the duration of flows below one-half and one SD.

When the Gila Butte phase (A.D. 775–874) is removed from the analysis and the Santa Cruz through Civano phases are solely considered, the relationship between growth rates and low flow frequencies, magnitudes, and consecutive magnitudes somewhat strengthens. When the Gila Butte and Santa Cruz phases (A.D. 775–974) are removed and only the Sacaton through Civano phases are considered, a few negative relationships emerge from the analysis. These negative relationships are between population growth rates and the frequency of low flows below one SD and between growth rates and magnitudes one-half and one SD below the mean. These negative relationships are probably anomalous as most of the relationships between growth rates and low flows remain consistently positive through time.

**Population Growth Rates and Streamflow Variability.** Population growth rates are strongly related to increasing streamflow variability as measured by the coefficient of variation of each phase. The Spearman correlation coefficient is .9 and the scatterplot (Figure 9) shows a strong linear relationship. This strong positive relationship is consistent but decreases slightly when the Gila Butte and Santa Cruz phases are removed from the analysis.

**Population Growth Rates and Channel Change Indices.** These indices exclusively characterize the geomorphically significant years most likely to have negatively impacted irrigation agriculture based on the Graybill et al. (2006) and Nials et al. (1989) model. I, therefore, expected that as the frequency and magnitude of geomorphically significant discharge events decreased and streamflow and channel-change induced damage to canal systems declined, population growth rates would increase. However, the opposite occurred. Results
indicate that as the frequency and magnitude of these geomorphically significant discharge years increased, population growth rates increased. The Spearman’s $r$ correlation coefficient is .9 for the relationship between growth rates and the frequency of geomorphically significant discharge years and the magnitude of these discharge years (Figures 10 and 11). These relationships remain strong when the Gila Butte and Santa Cruz phases are removed from the calculation of the correlation coefficient.

**Discussion**

The research presented has systematically compared the available demographic data in Canal System 2 with the frequency, magnitude, and duration of high and low annual streamflow discharges and variability over 675 years. Results indicate that population growth rates generally increased as the frequency, magnitude, and duration of high annual flows (inferred flooding), low annual flows (inferred drought), and discharge variability increased. Periods characterized by infrequent high- and low-magnitude discharges and low variability (often called climatically stable periods) have lower growth rates than periods characterized by more extreme streamflow events and patterns.

I propose two plausible interpretations of the results documented in this research. First, floods, droughts, and variability resulted in favorable conditions for irrigation agriculture rather than unfavorable conditions. Second, population growth rates in the lower Salt River valley are the result of substantial in and out-migration and are strongly related to agricultural conditions for canal farmers along the lower Salt River and for noncanal farmers living beyond the Salt River. These interpretations do not exhaust the possible explanations for the results of this study. They are, however, reasonable first steps in enhancing our understanding of the relationship between streamflow discharge volumes, conditions for irrigation agriculture, and population change in the lower Salt River valley. Discussion of each plausible interpretation follows.

The first interpretation proposes that floods, droughts, and variability resulted in favorable conditions for irrigation agriculture. The notion that floods and variability created unfavorable conditions for irrigation agriculture is reasonably intuitive and has been well developed by Graybill et al. (2006) and Nials et al. (1989). Furthermore, the assumption that climatic extremes and variability resulted in subsistence stress and stable climatic conditions were salubrious for human populations is well entrenched in Southwestern prehistory and beyond (see Cashdan 1990; Halstead and O’Shea 1989). Irrigation agriculture may represent a notable exception to this axiomatic relationship between variable climatic conditions and subsistence stress in agriculturally marginal environments for the reasons discussed below.

Favorable conditions for irrigation agriculture and agricultural productivity would explain why immigration increased as floods, droughts, and variability increased. In the few years during or after flooding, drought, and high variability, it seems reasonable to assume that agricultural productivity declined and subsistence stresses increased. However, the effects of these extreme events could have increased agricultural productivity relatively quickly and provided ecological and social benefits that enhanced the long-term sustainability of irrigation agriculture within the canal system. According to Henderson and Clark (2004:182), “the geological floodplain of the Salt River represents the premier tract of arable land in the valley precisely due to its susceptibility to flooding.” Flooding recharges soil nutrients and flushes away accumulated salts common on heavily irrigated lands (Ackerly et al. 1987; Cable and Doyel 1985; Forbes 1902) so that years or seasons immediately following over-bank flooding could have been particularly productive in floodplains. Canal relocation—resulting from flood damaged canals or fields—may have prevented soil degradation and substantial productivity losses by forcing the development of new field locations. Droughts force fallow field time, delaying depletion of soil resources or waterlogging. Cooperative labor necessary for canal repair (Russell 1975) may have enhanced social and economic ties, promoted food sharing, and mitigated conflict by binding people together out of necessity. Ecologically, both floods and droughts are part of the natural flow regime of a river and maintain channel and floodplain dynamics that are essential to aquatic and riparian species (Poff et al. 1997). Riparian plant and animal species undoubtedly provided a wide variety of resources for the Hohokam. Assuming the benefits described
above, high streamflow variability (frequent floods and drought) may have provided a robust mix of beneficial agricultural, social, and ecological conditions.

In the process of reconsidering the relationship between floods, droughts, and variability on conditions for irrigation agriculture, the changing nature of these relationships over time must also be considered. Specifically, the effects of floods, drought, and variability on irrigation agriculture in both aggrading and degrading stream channel regimes should be considered. A period of channel cutting and widening may have changed the relationship between streamflow discharge events and irrigation agriculture. A period of channel cutting and widening has been documented along the nearby Gila River sometime between A.D. 1020 and 1160 (Waters and Ravesloot 2000, 2001) and a similar alluvial history along the Salt River is also suggested by the available soil-stratigraphic evidence (Onken et al. 2004). Over-bank flooding during an aggrading streamflow regime could have provided the ecological goods and services I speculate on above. Flooding, drought, and variability during a degrading stream channel regime was likely deleterious. I base this conclusion on historic accounts of farming along the Salt River during the degrading regime of the late nineteenth and early twentieth centuries (Waters and Ravesloot 2001; Zarbin 1980). During a regime in which the stream channel is degrading, over-bank flooding may have been less frequent due to the wider and more entrenched stream channel (Waters and Ravesloot 2001). Less over-bank flooding would not have allowed any of the positive benefits of flooding described above to have accrued and it is possible that agricultural, ecological, and social conditions began to degrade as a result.

Sorting out the complexities of the possible changing relationship between streamflow patterns and conditions for irrigation agriculture in aggrading and degrading streamflow regimes is beyond what has been attempted in this study but is necessary for advancing our understanding of the relationship between streamflow and population change in the lower Salt River valley.

The second interpretation proposes that population growth rates in the lower Salt River valley were the result of substantial in and out-migration and were strongly related to agricultural conditions for canal farmers along the lower Salt River and for noncanal farmers living beyond the Salt River. As discussed above, the population growth rates and their fluctuations documented in this study suggest substantial immigration and emigration. A motivator of this movement may have been regional precipitation patterns affecting agricultural conditions for noncanal farmers in addition to the streamflow conditions along the lower Salt River valley. Tree-rings provide the basis for the streamflow retrodictions and also reflect regional precipitation conditions. That is, high streamflow discharge years are also years in which precipitation conditions in the watershed (and likely the region) are higher overall. As a result, streamflow patterns documented in this analysis also generally reflect patterns in regional precipitation. Farmers, away from the major canal systems, practiced riverine and non-riverine agricultural strategies from both perennial and intermittent water sources. The relationship between precipitation patterns, agricultural conditions, and the demographic behavior of noncanal farmers is beyond the scope of this study. However, a few speculations will provide a general picture of the possible relationship between agricultural conditions for noncanal farmers and population growth rates in Canal System 2.

Agricultural conditions for noncanal farmers were likely directly related to precipitation conditions. When rainfall was sufficient, noncanal farmers were probably able to subsist on some combination of rain fed agriculture, gathered, and hunted foods. Intermittent water sources and rivers also allowed small-scale water control strategies including irrigation. When drought conditions prevailed regionally, intermittent water sources probably failed and small-scale rivers experienced drastic reductions in flow. During these stressful periods, perennial water sources such as the Salt River would have been a major attraction. Although conditions for canal farmers along the lower Salt River would also have been compromised during droughts, conditions may not have been as unfavorable as those for noncanal farmers away from the perennial rivers. Thus, in-migration into the lower Salt River valley and Canal System 2 seems a reasonable coping strategy as the frequency, magnitude, and duration of low-magnitude streamflow discharges (drought) increased. During these periods, precipitation conditions throughout the region
were also low.

As the frequency, magnitude, and duration of high-magnitude annual streamflow discharges increased, why would in-migration to Canal System 2 also increase? The precipitation conditions that caused the high-flow events should also reflect high and favorable precipitation conditions for noncanal farmers away from the lower Salt River valley. In-migration into Canal System 2 seems especially unlikely if the floods disrupted canal irrigation. Noncanal farmers should have had few incentives to migrate into the canal systems during these periods. One explanation is that high-flow discharges resulted in the disruption and destruction of irrigation agriculture and thus created opportunities for in-migration for noncanal farmers. Canal repair and rebuilding would have created significant labor demands. These labor demands could have created opportunities for noncanal farmers to participate in canal rebuilding and thus secure future irrigation rights or portions of future harvests. Russell (1975) documented in the early 1900s that work on canals entitled the Pima to irrigation rights. Significant canal work also may have been a collective activity that attracted extended and possibly distant relations and indebted or socially obligated individuals to provide assistance. Disruption of canal irrigation may have also resulted in diminished social controls on immigration and land tenure. Canal rebuilding in locations not subject to previous ownership claims could have created economic, political, and social opportunities for noncanal farmers when irrigation agriculture was disrupted. Alternatively, if high-flow conditions created favorable conditions for irrigation agriculture, as suggested above, rising agricultural productivity could have sustained increasing populations and in-migration to some increasing level.

The results of this study also indicate that when streamflow discharge volumes tended toward long-term averages and variability was minimal, population growth rates decreased. These relatively stable conditions are argued to be the most favorable for irrigation agriculture (Graybill et al. 2006; Nials et al. 1989). If they were the most favorable, it seems reasonable to expect that agricultural productivity could have supported increasing population growth over time. Instead, population growth rates decreased as the frequency, magnitude, and duration of both high and low flows decreased and tended toward long-term means. The stable streamflow conditions combined with stable precipitation conditions regionally may simply have kept canal and noncanal farmers in place with no incentive for in or out migration. Population growth rates during these stable periods were likely driven by changes in fertility and mortality in the absence of significant in or out migration. Alternatively, if floods, droughts, and high variability provided necessary ecological goods and services for irrigation agriculture, agricultural conditions during stable periods would have slowly declined. Mechanisms for this decline include nutrient depletion caused by less over-bank flooding, salinization due to less soil flushing by flooding, and riparian resource degradation through the absence of ecologically beneficial flood disturbances.

In addition to the motivations of migration and resettlement presented above, immigration into Canal System 2 could have been the result of population movements within the lower Salt River valley. Canal System 2 may have been more attractive or less affected by streamflow events at certain times based on geologic, topographic, or other advantages. If so, growth rates along other canal systems may have declined as expected during periods of frequent high, low, and variable discharges while they increased along Canal System 2. Canal System 2 villages all share a common headgate location just below a bedrock mass created by the Papago and Tempe Buttes. This bedrock mass may have minimized the effects of high-magnitude discharges on stream channel change (Nials and Gregory 1989:57–58). The heads of 10 of 16 canal systems that served Classic period communities in the lower Salt River valley were placed at and immediately below bedrock masses so Canal System 2 was not the only system to take advantage of these locations (Gregory and Nials 1985; Gregory 1991:177–178).

In summary, advancements in understanding the relationship between streamflow discharge volume, agricultural productivity in irrigated areas, and population change in the lower Salt River valley should focus on the following themes: a re-examination of the inference that floods, droughts, and variability created unfavorable conditions for irrigation agriculture; a consideration of the effects of floods, drought, and variability on irrigation agriculture in both aggrading and degrading stream
channel regimes; and, agricultural conditions for both canal and noncanal farmers and the relationship of these conditions to migration in and out of the lower Salt River valley.

**Conclusion**

This analysis has been concerned with the relationship between streamflow discharge variation and changes in long-term population growth rates. The results are limited by the resolution of both the streamflow and house data as well as the representativeness of the sample of houses available for consideration. Extending the geographical scope of the study in the future will provide more evidence for evaluating the relationship between streamflow and population change and continue to lessen potential biases introduced by variation in the extent of excavation at each site. If the analysis were truly compromised by the resolution of the data sets and representativeness of the sample, I would expect most measures to result in little to no relationship between streamflow and growth rates or to yield mixed results. Instead, moderate to strong positive relationships exist between most measures of streamflow and the population growth rates.

The results of this analysis challenge commonly held assumptions regarding the negative effects of floods, droughts, and high variability on irrigation agriculture and settlement in the lower Salt River valley. To interpret my results, I have speculated on the positive benefits of frequent floods, drought, variability, changes in the effects of these events over time, and the effect of migration on population change. I conclude that the relationship between streamflow discharge variation and population change is a complex multivariate problem. Expanding our understanding of the effects of annual streamflow variation on irrigation agriculturalists offers an exciting opportunity to advance our knowledge of the coupled human and natural system created by irrigation agriculture.

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Flagstaff and Tucson.


Notes

2. Refinements of the sequence and definitions of buff ware ceramics by Wallace (2001, 2004) are remedying this deficiency. When his definitions are used it is possible to segregate contexts into two or more temporal subphases within the existing phases.

3. The annual discharge rededications were provided by the Laboratory of Tree-Ring Research, University of Arizona. These data were developed and interpreted in the Graybill et al. 1989 and Graybill et al. 2006 analyses.

4. A variety of thresholds to define high- and low-flow years may be computed. The mean is highly sensitive to extreme high and low flows so it may not represent the typical amount of water available for canal irrigation. The median is probably the best indicator of typical discharge volumes adapted to by Hohokam irrigation agriculturalists but is used less frequently in analyses of streamflow regimes. In my exploratory analysis of the data, I used the median and upper and lower quartiles to define high and low flows and repeated each analysis described in this paper. The results were largely the same as those using the mean and standard deviation units above/below the mean to define high and low flows. Therefore, I am confident my results and conclusions do not depend on my choice of high and low flow thresholds.

5. For example, in the Gila Butte phase, the years 873 and 874 are above the mean discharge. In the adjacent Santa Cruz phase, the years 875, 876, 877 are also above the mean discharge. As the majority of years occur in the Santa Cruz phase, I add the two Gila Butte phase years to the adjacent and consecutive three years in the Santa Cruz phase for a total of five years. I do not count 873 and 874 in the Gila Butte phase. In this example, the five consecutive years above the mean from 873 to 877 are only one of twelve periods that meet the criterion of consecutive years above the mean in the Santa Cruz phase. In addition to this instance of truncation, one low-flow year from the Santa Cruz phase was added to the Sacaton phase, and one low-flow year from the Sacaton phase was added to the Soho phase. The effects on the resulting calculation of duration in each instance and this analysis as a whole were therefore trivial.

6. A majority of the project reports are available on CD Rom in Shears et al. 2002.

7. Several researchers have developed reasonable use-life estimates for different house types in several regions.

In a study of tree-ring dates from 28 well-dated pit houses in the Mogollon and ancestral Puebloan area, Ahlstrom (1985:631–642) concluded that construction and repair intervals indicate that pit houses typically survived for less than 20 years and typical pit house use-life is no more than 15 to 20 years. Based on the argument that a historic Pima round house standing near Snaketown in 1934 was architecturally similar to older Hohokam buildings, Haury (1976:75) determined from the occupant of the house a use-life of 25 years for the structure. Layhe (1988), in a reconstruction of the population of Las Colinas (a Canal System 2 village), estimated an average Hohokam pit house use-life of about 10 years and Henderson (1987) in the La Ciudad (a Canal System 2 village) study used a 25–year pit house use-life. At the Grewe site near Snaketown (in the nearby Gila River valley), using stratigraphic data to identify episodes of house replacement, Craig (2000:149–153) concluded that 25 years was a reasonable use-life figure for pit houses. The use-life of Hohokam aboveground, freestanding, adobe houses/rooms, has not been systematically estimated. Abbott and Foster (2003) assumed that since compound rooms were more substantial and durable than pit houses, that use-life of these rooms may have been greater. For purposes of their analysis, they use a use-life assumption of 20 and 40 years for compound rooms. In an examination of adobe rooms at Pot Creek Pueblo in northern New Mexico, Crown (1991:305) examines the repair interval of the rooms with tree-ring data and determines a use-life of 19 years. In the absence of evidence indicating a longer use-life for Hohokam aboveground adobe houses/rooms, I treat these houses as equivalent in use-life to pit houses. As a result, the number of pit houses does not need to be adjusted or standardized to be comparable to the number of adobe rooms/ houses. It is important to note that if the compound rooms common in the Civano phase have a longer use-life than pithouses, the likelihood that the relatively higher number of houses in the Civano phase represents an actual increase over the Soho and Sacaton phases is increased.

I also examined the floor area of each type of house through time. Pit houses (more accurately, houses in pits) had an average floor area of about 16 m² from the Gila Butte through Civano phase. Pit house floor area values (m²) by phase were: Gila Butte 14, Santa Cruz 15, Sacaton 16, Soho 19, Civano 15. Floor area in aboveground free-standing houses averaged about 19 m² in both the Soho and Civano phases. The floor area of all aboveground contiguous houses/rooms during the Civano phase was about 16 m². Based on these results, the number of people living in each type of house was probably reasonably constant through time so an adjustment to the growth rate computations based on house type does not seem warranted. A more detailed analysis than I have conducted here of changes in floor area by house type by location through time should be pursued and the results might yield some important insights into changing household demography.

8. The basic method described in this section is substantially similar to the method presented by Kintigh et al. (2004:440) for demographic modeling of Zuni towns. However, I do not use the more sophisticated method they developed to find the population growth rate by simulating each year’s room construction and abandonment activities, taking into account the use-life of rooms.

9. Some readers may want to know how the growth rates at individual locations compare with the aggregated growth rate data for Canal System 2. As previously noted, based on my reading of the project reports, only four projects resulted in excavated samples that likely represented individual site/village trajectories at certain time periods. Growth rates at these locations compared to growth rates in the Canal System as a whole are as follows. El Caserío follows the significant growth of the rest of Canal System 2 with a growth rate of 1.96 percent from the Gila Butte to Santa Cruz period. La Ciudad also followed the trends within the Canal System with significant growth in the Santa Cruz phase (1.26 percent) followed by negative growth rates in the Sacaton phase (−.52 percent). Growth rates at La Lomita Pequeña (2.3 percent) indicate that this location experienced more growth than the
rest of the Canal System during the Sacaton phase. Pueblo Grande does not follow the growth trends in the rest of Canal System 2. Growth rates there increased in the Soho phase (.66 percent) then slowed in the Civano phase (.33 percent). Rapid population growth at Pueblo Grande at the start of the Classic period (Soho phase) has also been documented by Abbott and Foster (2003). I see no reason to expect growth rates within Canal System 2 as a whole to be reflected in the demographic trajectory of all individual sites. Significant differences in size, access and proximity to water and other resources, and individual site histories all must have been a factor in the demographic trajectory of individual locations.

10. For consistency with the other streamflow measures, I converted the low-flow discharge magnitude results to positive numbers prior to computing the correlation coefficients. Leaving the values negative is confusing because negative values such as -.31 are greater (closer to zero and closer to the mean annual streamflow discharge value) than larger negative values such as -.34. Without converting the low-flow discharge magnitude results to positive numbers, negative correlation coefficients result because as growth rates increase, low-flow discharge magnitudes decrease (are further from zero). Because the magnitude values, as Z scores, represent departures below the mean, the greater the number the greater the departure. With this measure, the greater the magnitude value (distance from zero) the lower the streamflow discharge amount. Converting the low flow discharge magnitude results to positive numbers more clearly represents the relationship between increasing population growth rates and increasingly low streamflow magnitudes.

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