STREAMFLOW AND POPULATION DYNAMICS ALONG THE MIDDLE GILA RIVER

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ABSTRACT

Floods, droughts, and periods of high streamflow variability continue to influence archaeological interpretations of Hohokam demographic and sociopolitical change. In most instances, extreme streamflow events have been linked to canal system failure and a decline in agricultural productivity. It has been further hypothesized that catastrophic floods and associated geomorphic channel changes contributed to settlement movement and population decline. Contrary to these expectations, a recent study of population change along Canal System 2 in the lower Salt River valley found that as flooding, drought, and streamflow variability increased, population growth rates also increased. We build on the Canal System 2 analysis in this paper by comparing changes in inferred population levels at the Grewe site to annual streamflow patterns along the middle Gila River. Extensive excavation data from Grewe provide a unique opportunity to evaluate the long-term relationship between streamflow and population dynamics at the scale of an individual settlement. Although the Grewe results differ from those observed along Canal System 2, we attribute these differences primarily to scalar factors. We suggest that it is unreasonable to assume that one model or set of expectations regarding the relationship among streamflow, potential agricultural productivity, and human demographic behavior is adequate. Different scales of analysis should yield differences in results.

The purpose of the research presented here is to advance our understanding of the influence of environmental variation on human behavior in the Hohokam region. The specific problem considered is the influence, if any, of annual Gila River streamflow discharge variation on the population dynamics of Grewe, a major Pre-Classic settlement along the Gila River. Prevailing hypotheses regarding the influence of streamflow variation on population dynamics, developed primarily by the pioneering work of Donald Graybill, David Gregory, and Fred Nials[1] (Graybill 1989; Graybill and Gregory 1989; Graybill and Nials 1989; Graybill et al. 2006; Nials and Gregory 1989; Nials et al. 1989), predict that high magnitude annual discharges and pronounced variability may have resulted in changes in river channel position and/or morphology. These studies have linked extreme streamflow events and inferred channel changes to challenges to irrigation systems and declines in irrigated agricultural productivity. They have also hypothesized that catastrophic floods and associated geomorphic channel changes contributed to settlement and population movement and the substantial depopulation of the Phoenix Basin after A.D. 1400.

The general outlines of their model have been effectively applied by a number of researchers (e.g., Ackerly 1989; Craig 2001; Gregory 1991; Kwiatkowski 2003; Masse 1991; Van West and Altschul 1997). For example, Craig (2001) modeled changes in the productive potential of the Grewe irrigation system using the Gila River streamflow retrodictions and found that the population dynamics at Grewe matched well with the model. That is, a dramatic decline in population at Grewe during the late Colonial period (A.D. 875–949) occurred in the context of a concentration of high and low flows when productivity would presumably have been the worst. Likewise, Grewe's population peak during the middle Colonial (A.D. 825–874) is associated with a period of sustained high productivity associated with low streamflow variability and higher than average annual flows.[2]

Similarly, population declines along the nearby lower Salt River have been linked to poor conditions for irrigation agriculture caused by extreme streamflow events. Nials et al. (1989:66) hypothesized that population declines during the Colonial period (ca. A.D. 750–950) were related to destructive streamflow events and patterns during the A.D. 798 to 899 inter-

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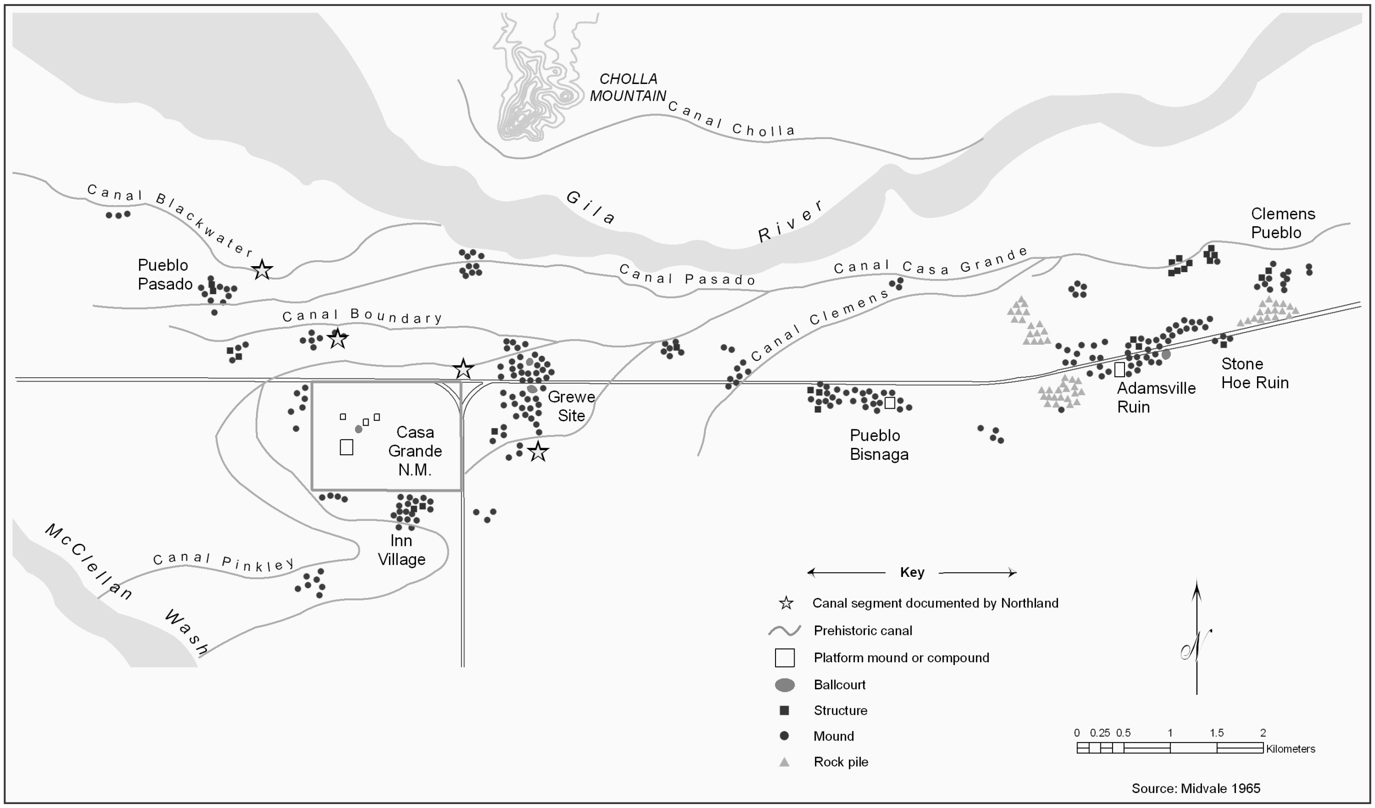

Figure 1. Location of Grewe.

val. Gregory (1991:187) also considers the possibility that floods along the lower Salt River 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. Furthermore, Masse (1991:217) argues that as a result of the presumed disastrous flooding of A.D. 899, settlements on the terminus of irrigation community networks may have been abandoned due to the absence of potable and agricultural water and moved to new settlements in areas favorable to *ak-chin* and dry-farming techniques.

Contrary to expectations derived from the Graybill et al. (2006) model, however, Ingram (2008) recently demonstrated a strong positive relationship between population growth rates within Canal System 2 along the Salt River and extreme streamflow events from A.D. 775 to 1450. In that work, population growth rates increased as the frequency, magnitude, and duration of inferred flooding, drought, and variability increased. Specifically, when the productive potential of irrigation agriculture in Canal System 2 was expected to be the least due to these extreme streamflow events, people moved into the canal system rather than out of it. This pattern of movement challenges commonly held assumptions regarding the negative effects of extreme streamflow events on population growth and out-migration and our understanding of the long-term relationship between annual streamflow discharge volumes and population change in the Phoenix Basin.

The research presented here is intended to further identify and clarify the relationship between streamflow discharge variation and the population dynamics of the Phoenix Basin. Although streamflow and its ef-effect on agricultural productivity is not expected to be the sole influence on the population dynamics of any riverine community practicing irrigated agriculture, we expect it had some effect and seek to identify and describe the extent of its influence. We consider this ef-effort critical for evaluating Graybill and colleagues' (2006) hypotheses and model, which play a prominent role in many cultural-historical interpretations of the Hohokam trajectory in the Phoenix Basin and beyond.

BACKGROUND

This study further explores the relationship between streamflow discharge volumes along the Gila and population dynamics at Grewe, where we have particularly strong and relatively complete data to infer changes in population growth rates (Craig 2001). The Grewe site is a large Pre-Classic period village located along the Gila River near Casa Grande Ruins National Monument (Figure 1). Archaeologists generally consider Grewe and Casa Grande to have been part of the same settlement complex, with Grewe the main locus of occupation during the Pre-Classic period and Casa Grande the main locus of occupation during the Classic period. Grewe is located on the lower terrace of the Gila just outside of the floodplain and towards the end of a main canal.

Between 1995 and 1997, large-scale excavations were carried out at Grewe by archaeologists from Northland Research, Inc. in connection with a road construction project sponsored by the Arizona Department of Transportation. More than 1,300 prehistoric features were uncovered as a result of this work, including 270 houses, close to 900 outdoor pits, segments of 10 canals, and a portion of a large ball court. Most of these features were associated with a residential district situated in the heart of Grewe. This residential district was occupied for virtually the entire Pre-Classic period. Temporal control for this roughly 600-year time span from A.D. 500 to 1100 was established by first assigning individual features to one of nine age groups based on ceramic and stratigraphic evidence. Absolute dates were then assigned to the various age groups based on an analysis of 110 radiocarbon and 52 archaeomagnetic samples. In total, more than 700 features, including 180 houses, were assigned to discrete age groups. The overall distribution of features suggests that Grewe was occupied on a continuous basis for hundreds of years, though not always at the same level of intensity. Grewe was abandoned by about A.D. 1100, corresponding to a shift in settlement over to the Casa Grande Ruins area.

Model

The relationship between streamflow discharge variation and irrigated agriculture productivity employed in this study is informed by the Graybill et al. (2006) model. We have extended their model by linking variation in irrigated agriculture productivity to changes in population growth rates. Variation in agricultural production is also linked to the risk of resource shortfalls. The synthesized model used in this analysis is summarized as follows.

Streamflow events and patterns of these events may induce major changes in stream channel position and/or morphology and negatively impact gravity-fed irrigation systems by changing the location and/or height of the water within the channel relative to the canal infrastructure (Graybill et al. 2006; Nials et al. 1989). Streamflow events and patterns considered in this analysis are floods, wet and dry periods, and periods of high temporal variability. Floods (inferred from high annual discharges) likely damaged and or destroyed canal infrastructure and agricultural land due to erosion or the deposition of impermeable silts. Dry periods reduced water availability to irrigated fields and may have increased the potential for stream channel change during subsequent high magnitude events. Periods of high temporal variability are associated with greater variability in channel morphology due to the effects of both floods and dry periods. Periods of low temporal variability are associated with geomorphic stability and favorable conditions for agricultural production.

Streamflow is not the only variable that likely af-affected agricultural productivity along the Gila. Temperature affects productivity by increasing or decreasing evapotranspiration and associated plant water needs. In general and within limits, periods of warm temperatures are assumed to have decreased resource productivity by increasing evapotranspiration and plant water requirements, and periods of cool temperatures are assumed to have increased resource productivity by decreasing evapotranspiration and plant water requirements. Higher temperatures also create earlier onsets of springtime snow melt and associated streamflow, higher peak streamflows, and lower summer streamflow (Stewart et al. 2005 and references contained therein). These events may have decreased productivity by decreasing streamflow for irrigation during the growing season and challenged irrigation with flood-related stream channel changes and canal damage. Other factors, such as soil type and quality (e.g., Sandor et al. 2007), affect resource productivity but are beyond the scope of this study.

Negative impacts on irrigation systems due to streamflow and temperature extremes likely decreased agriculture production and may have increased the risk of resource shortfalls. Shortfalls occur where there is not enough food to eat, and starvation became a possibility. To lessen the real or perceived risk of shortfalls, people use a variety of strategies such as storage, trade, exchange, and mobility (Halstead and O'Shea 1989). Population movement, a type of mobility, from areas of lesser to greater productivity is the strategy considered in this model. Population movements affect population growth rates through out-migration (decrease growth rates) and in-migration (increase growth rates). Changes in fertility and mortality also affect growth rates. Increases in productivity are assumed to increase fertility and decrease mortality, thereby increasing growth rates. Decreases in productivity are assumed to decrease fertility and increase mortality, thereby decreasing growth rates.

The real or perceived risk of resource shortfalls can also be affected by the climate-related year-to-year (temporal variability) and place-to-place variation (spatial variability) in resource productivity. Variation in resource productivity is often viewed as riskier if it has greater variance (Cashdan 1990:2-3). Temporal variability has been used either explicitly or implicitly as a proxy for variation in risk in a number of studies in

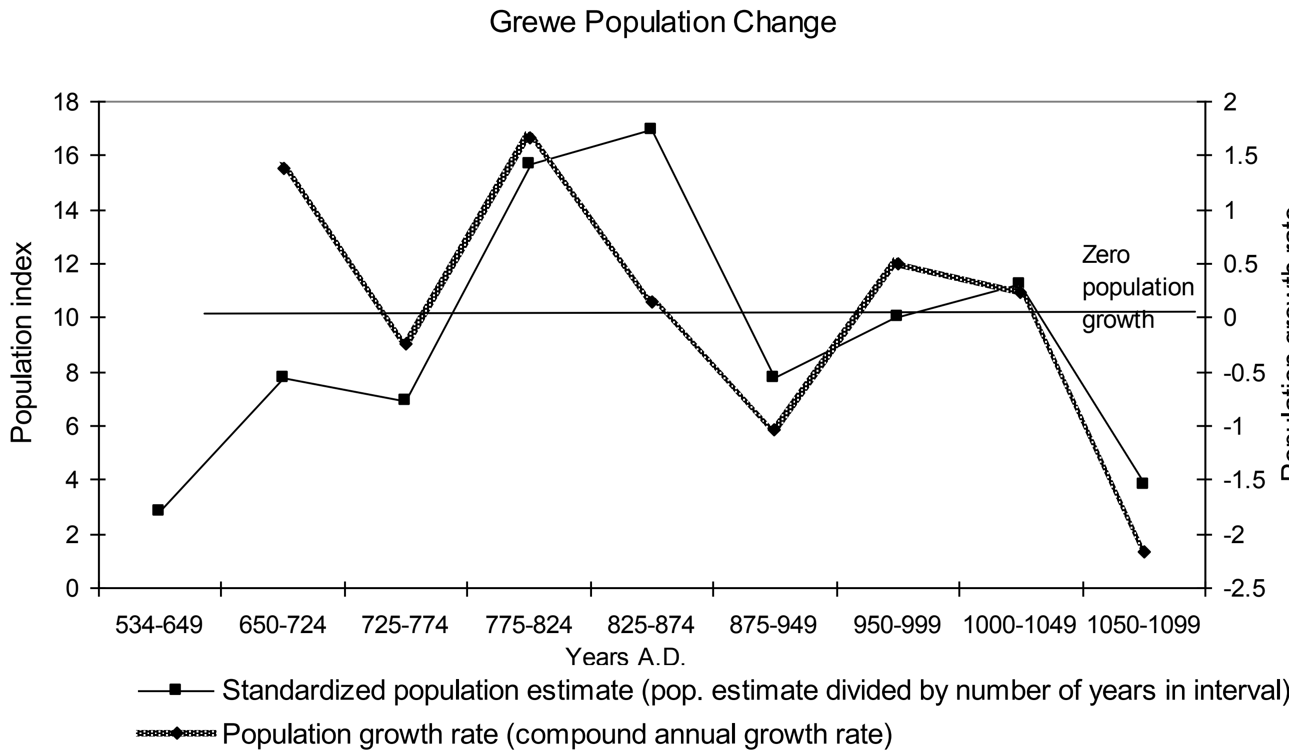

Figure 2. Grewe population change.

the American Southwest to explain buffering strategies, including population movements (e.g., Kohler and Van West 1996; Larson et al. 1996; Nials et al. 1989; Graybill et al. 2006). Periods of low temporal variability are often considered less risky as conditions are considered stable and predictable, while periods of high temporal variability are more risky due to increased uncertainty.

The spatial variability of annual precipitation (Dean et al. 1985:542) is assumed to have influenced the viability of exchange, interaction, and population movements to lessen the negative effects of shortfall (e.g., Braun and Plog 1982; Cordell et al. 2007; Plog et al. 1988). Substantial differences among conditions, during periods of high spatial variability, could have lessened the risk of shortfall if opportunities for exchange, interaction, or movement existed. Periods of low spatial variability, when conditions are the most uniform, that co-occur with dry periods were probably periods when opportunities for movement, exchange, and interaction with others experiencing different conditions were greatly reduced.

Therefore, the expected relationships between streamflow and temperature extremes and population growth rates are as follows: (1) as flooding (inferred), dry and warm periods, and periods of high temporal variability and low spatial variability increased in duration or frequency, population growth rates decreased; (2) and as wet and cool periods, periods of low temporal variability, and periods of high spatial variability increased in duration or frequency, population growth rates increased.

DATA AND METHODS

Population Data

Population estimates were derived for Grewe utilizing architectural evidence and methods that have become fairly standard in Hohokam archaeology (see discussion in Craig 2001). The basic strategy was to apply information learned about the houses in the ADOT right-of-way to other parts of the site. It was further assumed that roughly 10 percent of the houses at the site were investigated by Northland and that the average pithouse was occupied for 25 years. The population figures used for our analysis here represent midpoints of the population ranges previously discussed by Craig (2001).

Using the population estimates derived for Grewe, population growth rates are presented in Figure 2. Population growth rates were calculated using a standard compounded annual growth rate (CAGR) formula:

$$\text{CAGR} = (\text{ending amt}/\text{beginning amt})^{(1/\#\text{of years})} - 1).$$

This formula uses the number of rooms occupied in an earlier interval as the beginning amount and the number of rooms occupied in the next interval as the ending amount and the number of years in the latter interval as the interval duration. We use the average of the high and low population estimates to calculate growth rates. Due to varying durations of the temporal/cultural periods, we standardize the population estimates by dividing the population estimate by the number of years in the temporal interval. The growth rates are calculated from these standardized estimates.

As is evident in Figure 2, there was substantial variation in growth rates at Grewe. Steady increases or decreases in growth rates due to natural increases or decreases in mortality do not explain the range of variation observed. Using the zero population growth line as a reference, negative growth rates are inferred to be periods of out-migration. These periods occurred during the Pioneer to Colonial transition (A.D. 725–774), late Colonial (A.D. 875–949), and middle to late Sedentary (A.D. 1050–1099). Periods of relatively rapid population growth due to in-migration as opposed to accelerated internal demographic changes are difficult to differentiate, but population growth was the greatest during the late Pioneer (A.D 650–724) and the early Colonial period (A.D. 775–824).

Streamflow Data

Gila River streamflow retrodictions were developed by Donald Graybill and others at the University of Arizona's Laboratory of Tree-Ring Research. The lab graciously provided these data for our use. Methods used to develop the streamflow retrodictions are detailed in Graybill (1989) and Graybill et al. (2006). It is beyond the scope of this study to review the strengths and weaknesses of tree-ring retrodicted discharge variation. However, several points are noted that were clearly discussed by Graybill (1989; 2006) but seldom presented by others. First, single flood events are not captured in the tree-ring records. Floods are inferences based on some evidence of the relationship between flooding and high annual discharge years observed in modern streamflow records (Ackerly 1989:61–83; Smith 1981 as cited in Smith and Stockton 1981). Second, the timing of flooding during the agricultural calendar will largely determine the extent of effects on food production. Spring discharge conditions are betbetter detected by the tree-ring records than summer conditions. This implies that we know little about the effects of streamflow conditions on food production during the second half of the annual planting season.

Temperature Data

The San Francisco Peaks temperature reconstruction (Salzer 2000; Salzer and Kipfmueller 2005) can be used to identify warm and cool periods across the region. In that study, the annual mean maximum temperature was reconstructed from 250 B.C. to A.D. 1997. This variable can be considered a general measure of how warm it gets during the daytime of a given year (Salzer and Kipfmueller 2005:470) and, while most accurate locally, is also applicable on a regional scale (Salzer 2000:63 as cited in Bradley 1980).

Identification of Climate Extremes

To identify patterns in the streamflow data, we identify multiple types of climatic extremes. These extreme events capture the range of patterns that are expected to have affected changes in the productive potential of irrigated agriculture along the Gila. Climate extremes are identified using a centered nine-year interval running average throughout the duration of the streamflow retrodiction, A.D. 534–1988. Extreme periods are defined as those intervals in the lowest and highest quartile and decile of the distribution of all nine-year intervals in each reconstruction. Quartile and decile threshold values are arbitrary but are assumed to represent values and periods with sufsufficient rarity to have substantially influenced resource productivity. A similar approach has been used with standard deviation units by Dean (1988), and percentile approaches to identify thresholds are currently used by the U.S. Drought Monitor (www.cpc.noaa.gov) and others to track drought severity across the U.S. (e.g., Hirshboeck and Meko 2005; Steinemann et al. 2006; Smakhtin 2001). Using several threshold values to identify the extremes acknowledges the uncertainty inherent in projecting a threshold above which shortshortfalls were unlikely (thus a behavioral response is not expected) and below which they were likely (thus a behavioral response is expected). Use of a single threshold presumes a shortfall threshold is known and introduces the possibility of failing to detect a relationship, if one existed, at a slightly higher or lower threshold.

Climate Extremes Considered and Methods of Identification

1. Inferred flooding is identified by counting the number of discharge years in the seventy-fifth and ninetieth percentiles per temporal/cultural period.

2. Wet periods are defined as those nine-year intervals in the seventy-fifth and ninetieth percentile of the distribution of nine-year interval averages calculated using the streamflow reconstructions.

3. Dry periods are defined as those nine-year intervals in the tenth and twenty-fifth percentile of the distribution of nine-year interval averages calculated using the streamflow reconstructions.

4. Temporal variability is assessed by calculating a nine-year centered moving standard deviation of the streamflow annual values. The nine-year standard deviation intervals are divided by the nine-year interval

averages to produce a coefficient of variation for each interval. Periods of low temporal variability are defined as those nine-year intervals in the lowest decile and first quartile, and periods of high temporal variability are in the third quartile and highest decile of the distribution of interval coefficient of variation values.

5. We combine wet/very wet and dry/very dry periods into a single index. This index differs from the other indices as the pattern of the wet and dry years are not considered; that is, this index identifies the number of wet and dry years in each temporal/cultural period, not the duration of prolonged wet and dry periods. If these extremes in streamflow are assumed to negatively impact productivity, then this measure identifies the proportion of years within each interval in which productivity was relatively low.

6. The spatial variability considered in this analysis is the difference in discharge patterns between the lower Salt River and the middle Gila River. In other words, this variability represents the extent to which discharge patterns were "in-sync" or "out-of-sync" with each other. Spatial variability is assessed by calculating the annual standard deviation of the Salt and Gila discharge volumes for each year of the reconstructions. The annual standard deviations are divided by the associated annual averages to produce an annual coefficient of variation. The coefficients of variation are smoothed by nine-year centered moving averages that are then ranked and assigned percentile values. Periods of low spatial variability are defined as those nine-year coefficient of variation intervals in the lowest decile, and first quartile and periods of high spatial variability are in the third quartile and highest decile of the distribution of coefficient of variation intervals.

7. Cool periods are defined as those nine-year intervals in the tenth and twenty-fifth percentile of the distribution of interval averages calculated using the temperature reconstructions.

8. Warm periods are defined as those nine-year intervals in the seventy-fifth and ninetieth percentile of the distribution of interval averages calculated using the temperature reconstructions.

To allow comparison of the climate extremes with population growth rates, the number of years within each temporal/cultural interval (e.g., late Pioneer period) of each type of climate extreme (e.g., wet, warm, cool, etc.) is calculated. Because the intervals are different lengths, the number of years in which a climate extreme occurred during each interval is divided by the number of years in the interval to create a standardized and interpretable index that allows each interval to be compared and ranked. These indices are the percent of extreme years within each interval.

Summarizing the annual climate data by temporal intervals is appropriate because tree-ring based climate reconstructions are the strongest and most reliable when they are used to represent relative changes in climate conditions rather than absolute (year-to-year) changes. Relative changes are better represent-because of the biological characteristics of trees, such as food storage, that create time lags in growth responses to moisture variations and the statistical approaches used in climate reconstruction used to reduce autocorrelation (Fritts 1976; Meko and Graybill 1995; Meko et al. 1995). The statistical correlation between tree growth and climate is also always less than perfect; therefore, an emphasis on individual retrodicted years gives a false sense of precision to an analysis. Numerous climate studies have also documented persistence in climate patterns on decadal scales in both the modern instrumental and proxy records (Cayan et al. 1998; Dettinger et al. 1998; Fritts 1991; Gray et al., 2004; Grissino-Mayer 1995). In sum, analyses and explanations based on year-to-year change are not as reliable and well grounded in the data as investigations of multi-year wet and dry or warm and cool periods (e.g., Salzer and Kipfmueller 2005:472-473).

Relationship Between Climate Extremes and Growth Rates

We conduct correlation analyses and inspection of associated scatterplots to assess the long-term relationship between the climate extremes and population growth rates. A rank order correlation procedure, Spearman's *r*, is used for the correlation analyses. High correlation coefficients (positive or negative) are evidence of a long-term relationship and one wherein the magnitude of change in growth rates is related to the duration of the extreme period. A strong correlation coefficient indicates a long-term pattern of sensitivity and vulnerability to a climatic extreme. Low correlation coefficients do not provide evidence of long-term climatic sensitivity and vulnerability because they imply an uneven relationship, if any, between climatic extremes and population movement. We argue that the 566 years or roughly 22 human generations represented by the population and streamflow data we are considering represent a sufficiently long sample capable of detecting a relationship, if any existed, between discharge variation and human demographic behavior at Grewe.

RESULTS

The correlation coefficients representing the relationships between the population growth rates and climate extremes at several thresholds are presented in Table 1. Some representative scatterplots are presented in Figure 3. Straight lines are fit to the data points in the scatterplots to aid visual identification of

Table 1. Correlations between climate extremes and population growth rates.

Climate extremes	Percentile threshold	Population growth rates
High annual discharge years	75	-0.50
Very high annual discharge years	90	-0.45
Wet periods	75	-0.74
Very wet periods	90	-0.64
Very dry periods	10	-0.26
Dry periods	25	-0.01
Combined very wet and very dry years	10 and 90	-0.90
Combined wet and dry years	25 and 75	-0.74
Years between median and fourth quartile	50 and 75	0.06
Periods of very low temporal variability	10	-0.57
Periods of low temporal variability	25	-0.10
Periods of high temporal variability	75	0.00
Periods of very high temporal variability	90	0.05
Periods of very low spatial variability	10	0.10
Periods of low spatial variability	25	-0.40
Periods of high spatial variability	75	0.31
Periods of very high spatial variability	90	0.17
Very cool periods	10	0.57
Cool periods	25	0.83
Warm periods	75	-0.68
Very warm periods	90	-0.48

the relationship between growth rates and the streamflow and temperature indices.

High Annual Discharge Years

Population growth rates at Grewe decreased as the frequency of high magnitude annual discharge years (inferred floods) increased. That is, periods with frequent inferred floods were periods with generally lower population growth rates. The correlation coefficients are moderately strong at the seventy-fifth (r = -.50) and ninetieth percentiles (r = -.45). This relationship supports the prevailing model (Graybill et al. 2006) wherein flooding threatened agricultural productivity through challenges to the canal infrastructure. These declines in productivity then likely led to out-migration or declining internal growth rates. This finding is inconsistent with the relationship identified within Canal System 2, wherein high magnitude discharge years were associated with increases in growth rates (Ingram 2008).

Wet Periods

The relationship between wet periods and population movement has not been previously considered in the Phoenix Basin. Population growth rates at Grewe decreased as the duration of wet periods increased. Wet periods are prolonged periods of relatively high annual streamflow related to relatively wetter conditions throughout the watershed. These are periods when the productive potential of both irrigated and non-irrigated agriculture should have been the greatest as water availability was the greatest. Wet periods may have encouraged migration out of Grewe if the increased productivity was sufficient to support settlement elsewhere. Or, if the wet periods frequently damaged canals, then out migration fits with the prevailing model that damage to canals and crops influenced movement to more productive locations.

Dry Periods

There is no evidence for a long-term relationship between dry periods and population growth rates at

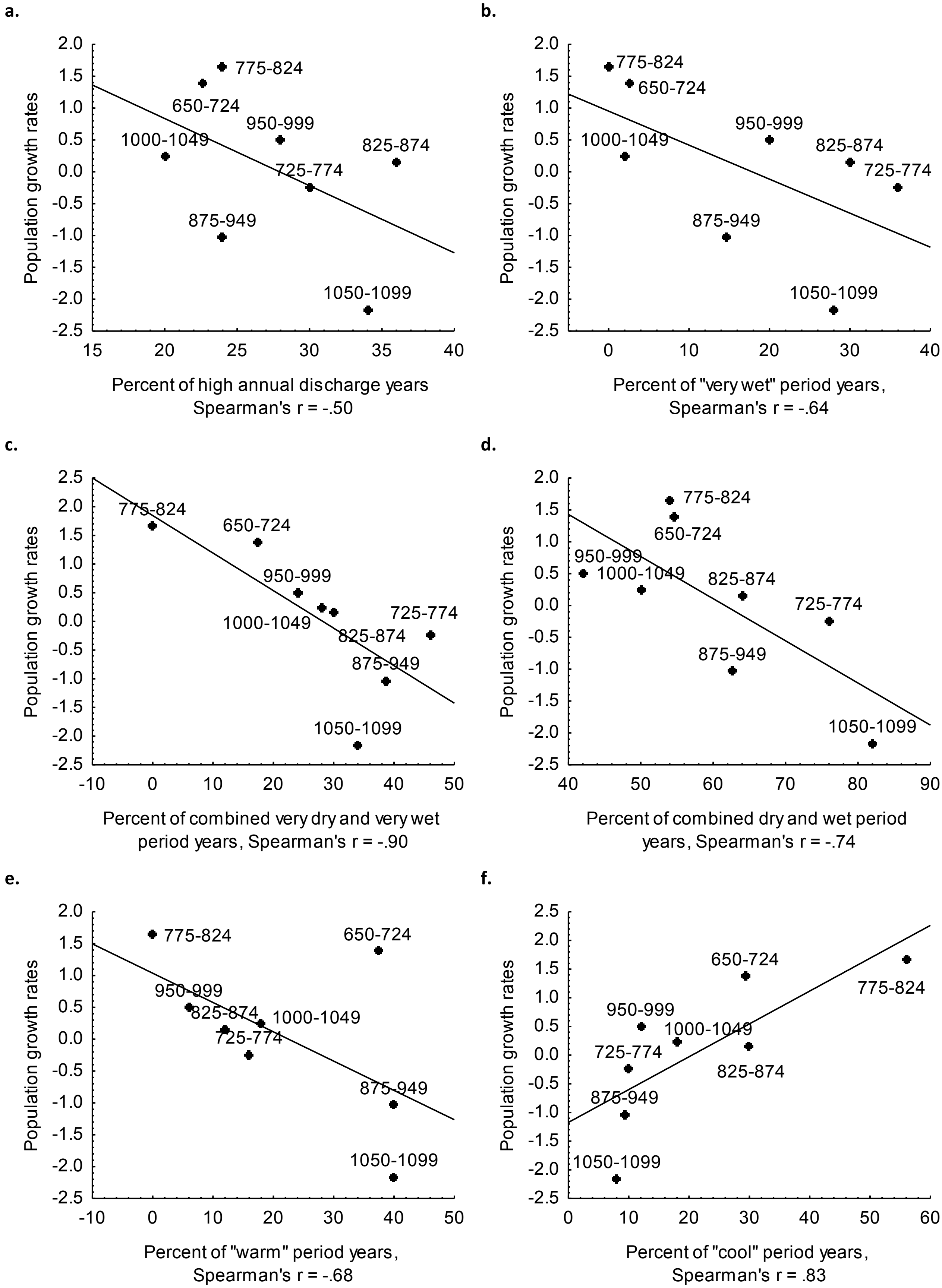

Figure 3. Some climate extreme and growth rate scatterplots.

Grewe. This suggests that Grewe residents were able to maintain or acquire sufficient resources or ade-productivity during dry periods. Alternatively, it may indicate that low streamflow discharge years had a minimal impact on the productive potential of irrigation agriculture in and around Grewe, perhaps due to the favorable upstream position of the canals close to Grewe. If people suffered from dry-period related declines in productivity, they may have just suffered in place where conditions may have been bad but not as bad as elsewhere. Overall, this result implies that dry periods did not affect decisions to move into or away from Grewe. This result is inconsistent with findings in Canal System 2 where dry periods are related to increases in population growth rates.

Low and High Temporal Variability of Streamflow

There is no evidence that periods of high or low temporal variability affected growth rates at Grewe. To further examine this result, the frequency of years with discharge volumes between the median discharge level and the third quartile was calculated. These should have been optimal years for irrigated agriculture, neither especially low nor high. However, no influence on growth rates was detected. These results are inconsistent with expectations that equate high variability with geomorphic instability and greater risk of shortfalls and low variability with stability and lesser risks of shortfall. These findings are also inconsistent with results from Canal System 2 (Ingram 2008). Little influence of temporal variability on growth rates suggests that periods of high temporal variability were anticipated and effectively buffered by existing strategies. And, periods of low variability, if advantageous in any way, were not sufficient to influence decisions to move into or out of Grewe or to affect fertility or mortality substantially.

Combined Wet and Dry Years

Population growth rates decreased and the frequency of wet and dry years increased. With this index, both wet and dry years (not prolonged periods) are assumed to decrease resource productivity. Results indicate that as the frequency of these wet and dry years increased, growth rates decreased. The relationships are strong when extreme years are defined with the upper and lower deciles (r = -.90) and upper and lower quartiles (r = -.74). It may be that this index better represents the type of temporal variability that was most meaningful to irrigation agriculturalists rather than prolonged periods of low or high temporal variability.

Low and High Spatial Variability of Streamflow

Population growth rates at Grewe were not affected by patterns of similarity and difference in discharge volumes between the Gila and Salt rivers. This implies that if population movements occurred between the two riverine settlement areas, Grewe was not involved in this shifting, or that the movements were not related to prolonged variations in discharge volumes and associated changes in resource productivity.

Warm and Cool Temperatures

Population growth rates increased as periods of relatively cool temperatures increased, and growth rates decreased as warm periods increased. Expectations are met for both warm and cool temperatures, thereby strengthening the evidence for a strong relationship between temperature, productivity, and population growth rates. Given the long growing seasons throughout much of central and southern Arizona, it is unlikely that people moving to Grewe were seeking to reduce cool-temperature related risks of shortfalls. Rather, the cool temperatures may have increased productivity at Grewe by either decreasing evapotranspiration and associated plant water stress and/or lessening the potential problems of early snowmelt and streamflow, higher peak streamflow, and lower summer flows possibly associated with warm temperatures. More research needs to be done to understand the impact of the reconstructed temperature variable on the productive potential of irrigated agriculture.

Depopulation of Grewe

Grewe was abandoned by about A.D. 1100, corresponding to a shift in settlement over to the Casa Grande Ruins area. To examine potential climate-related influences on this settlement shift, conditions during the A.D. 1050 to 1099 period (the middle to late Sedentary period) are considered. The most anomalous change in streamflow patterns are the two wet periods (seventy-fifth percentile threshold), totaling 35 years or 70 percent of the years from A.D. 1050 to 1099. This proportion of wet period years was unprecedented throughout the 566 years considered in this analysis. This analysis has previously established a long-term and strong negative relationship (r = -.74) between growth rates and wet periods throughout the history of Grewe. It is possible that Grewe's position near the floodplain of the Gila made residents and the canal infrastructure vulnerable to potentially damaging effects of these frequently occurring and relatively high flows. If so, the shift in settlement to Casa Grande, nearby but further from the floodplain, makes sense as a reasonable remedy and response to the increased risks associated with the high flows.

DISCUSSION AND CONCLUSION

This effort has identified long-term relationships between specific Gila River streamflow discharge pat-patterns and population growth rates. Given the complexity of human demographic behavior and the necessity of a plethora of methodological decisions necessary to assess potential influences of streamflow on this behavior, we find the detection of long-term relationships remarkable and compelling. It is also notable that despite a range of potential buffering mechanisms, such as storage, trade, and abundant seasonally distributed wild foods, patterns of sensitivity and vulnerability to streamflow discharge variation persisted throughout the history of Grewe. In short, we cannot decouple the demographic trajectory of Grewe from the vagaries of Gila River discharge variation.

Relationships identified in this paper demonstrate that human decision-making at Grewe was consistently affected by specific types of climate-related streamflow discharge variation and associated changes in resource productivity. Patterns of movement as reflected in the growth rates indicate that high annual discharge years, wet periods, frequent wet and dry years, and warm periods influenced movements out of Grewe. It is impossible to conclude given the limited spatial scale of this analysis whether these movements were the result of declines in agricultural productivity related to high annual discharge events, geomorphic changes, and associated negative impacts on canal infrastructure; and/or, were the result of relatively better and attractive conditions in the watershed unrelated to streamflow-related threats to irrigated agriculture. During high annual discharge years, precipitation conditions were relatively high throughout the watershed. These precipitation conditions may have expanded settlement opportunities away from Grewe along smaller rivers and streams or in non-riverine locations (see Ingram 2008:157-160). This analysis has also demonstrated that decisions to move into and out of Grewe were not consistently related to dry conditions and periods of low and high temporal and spatial variability.

Three spatial scales of analysis have been considered in this research: 1) a river basin scale as used by Graybill and colleagues (Graybill et al. 2006); 2) a canal system scale as used with the Canal System 2 analysis of population change (Ingram 2008); and, 3) the settlement scale as considered in this analysis. Differing scales undoubtedly contribute to differences in results. There is no reason to expect population dynamics at an individual settlement will mirror dynamics within a canal system or within a river basin. Population dynamics in an individual settlement, if related at all to the productive potential of canal irrigation, are likely strongly influenced by the position of the settlement along a canal as it relates to access to water. Canal system population dynamics are probably strongly related to the up-stream or down-stream position of the canal in relation to other canals. River basin population dynamics are an amalgamation of shifting settlement canal locations and unique population histories responsive to a variety of local and regional factors through time. At each scale, the demand for water must be reconciled with the supply of water. Thus, adaptations and responses to climatic extremes cannot be expected to have been the same at each spatial scale of analysis.

We suggest that it is implausible that one model or set of expectations regarding the relationship among streamflow, the productive potential of irrigated agriculture, and human demographic behavior is adequate. Different scales of analysis should yield differences in results. Importantly, demographic factors that contribute to the vulnerability of people to climate-related declines in productivity should be considered. There is no basis for expecting everyone in a river basin to have been equally vulnerable to declines in productivity. Some people may have benefitted from changes in discharge patterns, while some likely did not. Demographic factors that affect the demand for resources (such as population levels) and productivity that affects the supply of resources should be considered when streamflow variation is expected or asserted to influence demographic behavior.

It is also important to acknowledge the fundamental assumption inherent in this and many other studies of the influence of environmental variation on human behavior. This is the assumption of productive resource marginality supported by relatively dry and variable conditions in the American Southwest. An assumption of marginality establishes the link between environmental variation (including climate and streamflow) and human behavior through the risk of short-shortfalls and the necessity of acting to prevent starvation. The assumption requires that shortfalls occurred and that productivity hovered around a threshold above which shortfalls did not occur and below which shortfalls were frequent. If resource shortfalls were rare, unrelated to climatic conditions, and/or effectively accommodated by existing buffering strategies, then there is little reason to expect or assume that climatic variation impacted human demographic behavior. Modeling and simulating irrigated agricultural production and projecting demand for this production through our best population estimates is likely the best way to identify how tightly coupled the people of the Phoenix Basin were to streamflow events that af-affected agricultural production.

We have more to learn about how people benefitted and coped with climate extremes. "Unpacking" streamflow discharge variation and its effects on human behavior is essential to understanding the cultural-historical trajectory of the Hohokam and evaluating the potential influence of discharge variation on the depopulation of the Phoenix Basin. It is also important that we search for insights into climate and human behavior informed by the long-term archaeological record so that we can contribute to the current search for understanding and to the guidance necessary to meet potential challenges related to projected global-scale climatic change.

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Notes

1. For convenience, this model will be referred to simply as the "Graybill model" and repetition of the six associated references will be omitted. The model is well summarized in the Graybill et al. (2006) publication and this will be used for subsequent in-text citation of the model.

2. These data are also compelling because the population changes identified occurred before evidence of channel cutting and widening along the nearby Gila River sometime between A.D. 1020 and 1160 (Waters and Ravesloot 2000, 2001). Channel cutting and widening could have altered the relationship between annual streamflow discharge variation and irrigated agricultural productivity.

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