Human Vulnerability to Climatic Dry Periods in the Prehistoric U.S. Southwest

by

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ABSTRACT

This study investigates the vulnerability of subsistence agriculturalists to food shortfalls associated with dry periods. I approach this effort by evaluating prominent and often implicit conceptual models of vulnerability to dry periods used by archaeologists and other scholars investigating past human adaptations in dry climates. The conceptual models I evaluate rely on an assumption of regional-scale resource marginality and emphasize the contribution of demographic conditions (settlement population levels and watershed population density) and environmental conditions (settlement proximity to perennial rivers and annual precipitation levels) to vulnerability to dry periods. I evaluate the models and the spatial scales they might apply by identifying the extent to which these conditions influenced the relationship between dry-period severity and residential abandonment in central Arizona from A.D. 1200 to 1450. I use this long-term relationship as an indicator of potential vulnerability to dry periods. I use tree-ring precipitation and streamflow reconstructions to identify dry periods. Critically examining the relationship between precipitation conditions and residential abandonment potentially sparked by the risk of food shortfalls due to demographic and environmental conditions is a necessary step toward advancing understanding of the influences of changing climate conditions on human behavior.

Results of this study support conceptual models that emphasize the contribution of high watershed population density and watershed-scale population-resource imbalances to relatively high vulnerability to dry periods.

Models that emphasize the contribution of: (1) settlement population levels, (2) settlement locations distant from perennial rivers, (3) settlement locations in areas of low average annual precipitation; and (4) settlement-scale population-resource imbalances to relatively high vulnerability to dry periods are, however, not supported. Results also suggest that people living in watersheds with the greatest access to and availability of water were the most vulnerable to dry periods, or at least most likely to move when confronted with dry conditions. Thus, commonly held assumptions of differences in vulnerability due to settlement population levels and inherently water poor conditions are not supported. The assumption of regional-scale resource marginality and widespread vulnerability to dry periods in this region of the U.S. Southwest is also not consistently supported throughout the study area.

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CHAPTER 1:

HUMAN VULNERABILITY TO CLIMTATIC DRY PERIODS IN THE PREHISTORIC U.S. SOUTHWEST

A fundamental challenge in studies that investigate the relationship between climate and human behavior is explaining climate's differential influence on human behavior over time and space. That is, why do particular climatic hazards, such as a dry periods, at some times and places appear to stimulate a particular behavioral response and at other times and places do not? In the arid and semi-arid prehistoric U.S. Southwest, this problem is especially evident in regional-scale studies when long-term paleoclimatic records of specific climatic hazards are compared to a record of expected behavioral responses. For example, dry periods that reduce resource productivity are expected to increase the risk of food shortfalls and stimulate a variety of responses to manage these risks. The movement of people out of areas of low productivity to areas of relatively higher productivity that often results in settlement abandonment is one potential response to these increases in the risk of shortfall. An investigation of population movement and settlement abandonment, however, reveals that some settlements are abandoned during dry periods, some are not, and many settlement abandonments show no relationship with climatic conditions. This uneven long-term relationship between climatic hazards and expected responses can be incorrectly interpreted as evidence of little to no influence of climate hazard on human behavior. This uneven relationship may be, instead, evidence of spatial and temporal variation in human vulnerability to the hazard. The specific conditions that contribute to or ameliorate this vulnerability are not, however, well understood. Deficiencies in understanding are caused by a lack of empirical scrutiny of existing conceptual models of vulnerability to climatic hazards and the reliance of these models on an unverified assumption of widespread resource marginality in dry climates.

The purpose of this study is to address this fundamental challenge of understanding climate’s differential impact on human behavior by advancing understanding of conditions that affect human vulnerability to dry periods in arid and semi-arid regions. I focus on dry periods because they are a common climatic hazard in these regions and are frequently argued to influence human behavior through increasing the risk of food shortfalls. My approach to this study is to evaluate prominent and often implicit conceptual models of vulnerability to dry periods used by archaeologists and other scholars investigating past human adaptations in dry climates. These models are used to explain and predict spatial and temporal variation in human vulnerability to dry periods. Each model emphasizes different demographic and environmental conditions assumed to influence this vulnerability. A contribution of this study is the identification of these largely implicit models of vulnerability to dry periods used in archaeological studies of the U.S. Southwest and elsewhere. In this study, I make these models explicit, subject them to empirical scrutiny to evaluate their veracity, and identify the spatial scales they might apply. This is the most spatially and temporally comprehensive examination of vulnerability to dry periods, and factors that contributed to this vulnerability, yet conducted in the U.S. Southwest.

I evaluate four conceptual models of vulnerability to dry periods. These models, discussed in detail in Chapter Three, are as follows.

1. Aridity Model. The aridity model emphasizes resource marginality and widespread vulnerability to dry periods across all demographic and environmental conditions because of low precipitation conditions inherent in dry regions. In this model, differences in vulnerability over time are expected to be directly related to differences in dry-period severity. Vulnerability to dry periods is expected to be highest when dry-period severity is greatest. Evaluating this model also identifies the spatial distribution of vulnerability to dry periods allowing the regional-scale resource marginality assumption to be evaluated throughout the study area.
2. Demand model. The demand model emphasizes the influence of settlement population levels and catchment population density on differences in vulnerability to dry periods. These demographic conditions affect resource demands, the rate of consumption of resources, and the extent of labor available to invest in strategies to manage the risk of shortfalls. People living in large settlements and/or densely populated watersheds are expected to be the most (and sometimes the least) vulnerable to dry periods.
3. Supply model. The supply model emphasizes the influence of settlement proximity to perennial rivers and long-term average precipitation levels of settlement locations to explain differences in vulnerability to dry periods. These environmental conditions affect the local-scale potential supply of resources and thus the extent of resources people may have access to during

dry periods. Greater access to and availability of water is expected to decrease vulnerability to dry periods.

4. Demand and supply model. The demand and supply model emphasizes the combination of demographic (settlement population levels, catchment population density) and environmental conditions (proximity to perennial rivers, precipitation levels) to differences in vulnerability to dry periods. These conditions affect the balance between resource demands and supplies and the extent of resources people have access to during dry periods. Vulnerability to dry periods is expected to be greatest where and when demands were high and supplies low.

I evaluate these models using data on demography, residential abandonment, environment, and dry periods for central Arizona during the A.D. 1200 to 1450 period. Central Arizona during this period is an excellent context to investigate the vulnerability of subsistence agriculturalists to dry periods because of the diverse cultural, environmental, climatic, and social conditions. I use the Coalescent Communities Database (Wilcox et al. 2003), the most comprehensive source of settlement data for central Arizona, to identify demographic conditions and residential abandonments. I use modern environmental data to identify local-scale differences in potential resource productivity among settlements and watersheds. I use tree-ring precipitation and streamflow reconstructions to identify dry periods during the period of study. As vulnerability is not a directly observable phenomenon, I use residential abandonment and associated population movement as an indicator of potential vulnerability to dry periods. To evaluate the models, I assess the long-term relationship between dry-period severity and residential abandonment among settlements by differences in their demographic and environmental conditions as emphasized by the vulnerability models. If differences in the relationships are detected when conditions are varied (e.g., high vs. low settlement population levels), I attribute these differences to the influence of these conditions on vulnerability to dry periods. This long-term approach is in contrast to studies that rely on single space-time coincidences to suggest a relationship between climatic conditions and potential behavioral responses (M. Ingram 1981:19). A long-term approach is valid because the effectiveness and use of residential abandonment and movement as a response and strategy for managing dry-period risks of shortfall is assumed to be consistent over the 250-year study period.

Evaluating models of vulnerability to dry periods is important because the specific conditions that contribute to or ameliorate this vulnerability, now or in the past, are not well understood or are in dispute (e.g., Cutter et al. 2003; Knight and Jager 2009; Meyer et al. 1998:238-243; Ribot 1995). Furthermore, no standard framework exists for identifying the fundamental sources of differential vulnerability (Meyer et al. 1998:240). In the absence of such a framework, archaeologists in the U.S. Southwest rely on common sense notions and unverified models that are logical and intuitively appealing but lack systematic empirical scrutiny. For example, it is reasonable to expect that people living distant from perennial rivers or in areas of relatively low precipitation should be the most vulnerable to dry periods in arid climates because they have the least access to water. Likewise those living near perennial rivers or in areas receiving the highest precipitation levels should be least vulnerable to dry-period declines in resource productivity. Does a long-term settlement history demonstrate this relationship between access to water and vulnerability to dry periods? In the U.S. Southwest, after 100 years of archaeological study of climate-human behavior relationships, this question has not been systematically addressed. Similarly, increasing population levels can be argued to increase stress on local environments thereby increasing vulnerability to dry periods and the number of people at risk. More people, however, can reduce vulnerability because larger populations may have more resources (human and environmental) to cope with climatic challenges. Both climatic and archaeological datasets in the U.S. Southwest are now sufficiently detailed that we can empirically address these questions and evaluate models and assumptions that rely on unverified notions.

Singular among these unverified notions is the assumption of resource marginality that equates low annual precipitation conditions inherent in arid and semi-arid regions with widespread resource marginality and vulnerability to dry periods. This assumption treats vulnerability to dry periods as a "pre-existing condition" (Cutter 1996: 530-531) of living in an arid region. Resource marginality, by definition, occurs where and when resource productivity (wild and cultivated) is inherently low relative to human food needs and oscillates around a threshold above which there was enough food to eat and below which there was not. Where resources are marginal, changes in any condition that increases the demand or decreases the supply of resources can increase the risk of food shortfalls and motivate a behavioral response. Models of vulnerability to dry periods rely on a marginality assumption to make variation in demographic (demand), environmental (supply), and dry periods meaningful for human behavior. Where resources are not marginal, changes in these conditions cannot be linked to changes in the risk of food shortfalls, thus, human behaviors argued to be linked to changes in demographic or environmental conditions cannot be interpreted as responses to shortfall risks. As I discuss further in Chapter Two, there are a number of reasons to question the assumption of marginality in the U.S. Southwest. It is based primarily on perceptions of the challenges of living in a dry climate and supported by limited indirect evidence. Weaknesses in the marginality assumption imply weaknesses in models of vulnerability that rely on this assumption. In this study, by evaluating the long-term relationship between dry-period severity and residential abandonment at different spatial scales, I identify the spatial distribution of vulnerability to dry periods and by implication the extent of resource marginality across the study area.

Evaluating models of vulnerability to dry periods is also important because it allows us to appraise arguments that rely on these models. For example, the depopulation of the northern Southwest during the late 1200s is coincident with a well-known dry-period and the impact of this dry-period on the depopulation has been debated for almost a century (e.g., Ahlstrom et al. 1995; Benson et al. 2007; Douglass 1929; Jett 1964; Judge 1989, Kohler et al. 2008; Lipe 1995; Varian et al. 1996; Van West and Dean 2000). Among the many factors now considered influential in the depopulation are decreased mobility options due to increased settlement population levels and increases in catchment population density caused by settlement aggregation (Van West and Dean 2000; Varien et al. 1996). Decreased mobility could have increased vulnerability to dry periods by increasing reliance on limited local productive capacities and decreasing access to arable land. This explanation suggests that the effects of the late 1200s dry-period could have been greater than similar or more severe dry periods because of, at least in part, these changes in demographic conditions. I consider this a ‘demand model’ of vulnerability to dry periods because it uses changes in demographic conditions that affect the demand for resources to explain changes in vulnerability to dry periods over time or differences in vulnerability among settlements. While the model is plausible and well reasoned, it is also partially amenable to testing using a long-term paleoclimatic record of dry periods and a demographic history of mobility. That is, do we have any evidence that settlement population levels or catchment population density influenced mobility or vulnerability to dry periods? If so, the argument is strengthened; if not, we cannot lessen the possibility that the changing demographic conditions, the dry-period, and the depopulation were simply space-time coincidences.

This identification and empirical evaluation of prevailing conceptual models of vulnerability to dry periods will affect the use of and confidence we have in these models. It will affect the use of the models by identifying the spatial scales at which they might apply. For example, I examine differences in potential resource productivity and the effects of these differences on vulnerability at the scale of individual settlements (e.g., near or far from a perennial river) and at the scale of entire watersheds (e.g., averaged watershed precipitation levels). I also examine the influence of differences in the demand for resources at the settlement scale with settlement population levels and at the watershed scale with population densities (rooms per square kilometer). Our confidence in the models should be affected by the results of this study. Whether our confidence increases or decreases, results should stimulate other methods and places for evaluating these and other models. Finally, this study demonstrates the opportunity and necessity of empirically examining models and notions regarding vulnerability to dry periods and the assumptions upon which they rely.

Organization of this Study and Summary of Results

This study of the influence of demographic and environmental conditions on vulnerability to dry periods and the models of vulnerability that rely on these conditions is presented in ten chapters. I first define and describe the relationship between the key concepts of vulnerability, risk, dry periods, and resource marginality. I argue that there are reasons to question the resource marginality assumption and discuss the consequences the assumption has had on interpretations and analyses of the challenges and opportunities of living in a dry climate (Chapter Two). I also argue that residential abandonment is an appropriate indicator of potential vulnerability to dry periods. Next, I describe the four vulnerability models I evaluate and provide examples of their use in archaeological studies in the U.S. Southwest and elsewhere and in modern studies of vulnerability to natural hazards (Chapter Three). I then describe the cultural, demographic, and environmental context of the central Arizona study area during the 1200 to 1450 period. I argue that the diversity within each of these domains benefits this study by providing a range of social and environmental conditions to investigate vulnerability to dry periods (Chapter Four).

My approach to evaluating the vulnerability models is to identify the extent to which demographic and environmental conditions influenced the relationship between dry-period severity and residential abandonment in central Arizona from A.D. 1200 to 1450. This evaluation involves data on demography, environment, dry periods, and residential abandonment (Chapter Five). I identify demographic conditions with this database by using the number of identified rooms in each settlement to represent settlement population levels and the number of identified rooms in each watershed divided by each watershed's area to represent watershed population density. I identify the environmental conditions of each settlement and watershed with modern GIS datasets of the location of perennial rivers and average annual precipitation and streamflow levels. I identify dry periods during the period of study with tree-ring precipitation and streamflow reconstructions. I identify residential abandonment from reductions in the number of settlements and rooms using settlement data from the Coalescent Communities Database (Wilcox et al. 2003). If differences in the sensitivity and strength of the relationship (as identified by the slopes of regression lines and correlation coefficients) between dry-period severity and residential abandonment among settlements with different demographic and environmental conditions are detected, I attribute these differences to the influence of these conditions on vulnerability to dry periods. Results support or challenge the veracity of the models to the extent that the long-term relationship between dry-period severity and residential abandonment is an effective indicator of potential vulnerability to dry periods.

I find that, for most of central Arizona during the 1200 to 1450 period, results (Chapters Six through Nine) support conceptual models that emphasize the contribution of high watershed population density and watershed-scale population-resource imbalances to relatively high vulnerability to dry periods. Models that emphasize the contribution of: (1) settlement population levels, (2) settlement locations distant from perennial rivers, (3) settlement locations in areas of low average annual precipitation; and (4) settlement-scale population-resource imbalances to relatively high vulnerability to dry periods are, however, not supported by this study. Results also suggest that people living in watersheds with the greatest access to and availability of water were the most vulnerable to dry periods, or at least most likely to move when confronted with dry conditions. Thus, commonly held assumptions of differences in vulnerability due to settlement population levels and inherently water poor environmental conditions are not supported. The assumption of regional-scale resource marginality and widespread vulnerability to dry periods due to low average precipitation in the region is also not consistently supported throughout the study area. Critically examining the relationship between precipitation conditions and migration sparked by the potential risk of resource shortfall due to demographic and environmental conditions is an essential step toward advancing understanding of the variable influences of changing climate conditions on human behavior in dry climates. I discuss the contribution of this effort to archaeological research in the U.S. Southwest, climate and human behavior studies, and analytical methods in the final chapter (Chapter Ten).

CHAPTER 2:

VULNERABILITY TO DRY PERIODS: KEY CONCEPTS AND METHODS OF ASSESSMENT

In this chapter, I define and describe the relationship between vulnerability, risk, dry periods, and resource marginality. I use the concept of vulnerability to refer to the potential for subsistence agriculturalists to be negatively impacted by dry-period declines in resource productivity. Where resources are marginal, dry-period declines in productivity are expected to increase the risk of food shortfalls and prompt a behavioral response to manage these risks. Resource marginality, by definition, occurs where and when resource productivity is inherently low relative to human food needs. As I discuss in this chapter, resource marginality is a foundational assumption in the U.S. Southwest but there are reasons to question this assumption. Importantly for this study, our models of vulnerability to dry periods (discussed in the next chapter) rely on a marginality assumption to make variation in demographic (demand), environmental (supply), and dry periods meaningful for human behavior. Reliance on a questionable assumption of resource marginality is a primary reason our models of vulnerability need to be evaluated. I conclude the chapter by describing my method of assessing vulnerability to dry periods.

Key Concepts: Vulnerability, Risk, and Dry Periods

Vulnerability is a composite concept "incorporating environmental, social, economic, political, cultural, and psychological factors" (Meyer et al. 1998:239-240). The study of "vulnerability of populations and activities is the most widely used umbrella concept for those factors that mediate between geophysical events and human losses” (Meyer et al. 1998:239). There are many specific definitions of vulnerability (see Cutter 1996:531-532 for a summary), but it is commonly understood as the "potential for loss" (Cutter 1996:529), the “capacity to be wounded” (Kates 1985:17), or the “potential for negative outcomes or consequences” (Meyer et al. 1998:239). More specifically, it is “the degree to which a system [such as a human-environment system], subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation or stress/stressor” (Turner et al. 2003:8074). Hazards are defined as threats to a system and the consequences they produce (Turner et al. 2003:8074). Differences in definitions reflect different disciplinary knowledge domains and emphases (Adger 1996; Fussel 2007; Jannsen and Ostrom 2006).

I follow most closely the definition of vulnerability and the associated "vulnerability as hazard of place" approach developed by Cutter (1996:533). Cutter (1993 as cited in Cutter 1996:532) defines vulnerability as "the likelihood that an individual or group will be exposed to and adversely affected by a hazard. It is the interaction of the hazards of place (risk and mitigation) with the social profile of communities." Vulnerability, in this model, is "conceived as both a biophysical risk as well as a social response, but within a specific areal or geographic domain. This can be geographic space, where vulnerable people and places are located, or social space, who in those places are most vulnerable" (Cutter 1996:533). In other words, "It is the intersection and interaction of both the social vulnerability and biophysical/technological vulnerability that create the vulnerability of places" (Cutter 1996:537). The hazard of place approach to vulnerability is appropriate for my study because it combines characteristics of social units (such as the demographic conditions I consider) with exposures to biophysical hazards or stressors (the dry periods and their severity I consider) and the geographic space (such as the settlement locations and watersheds) where vulnerable people and places may be located.

Other conceptualizations of vulnerability within the hazard of place model appropriate for my study include those developed by the National Research Council and the World Food Programme. The National Research Council (2001:114) defines vulnerability as the "Extent to which a population is liable to be harmed by a hazard event. Depends on [sic] the population's exposure to the hazard and its capacity to adapt or otherwise mitigate adverse impacts." In the context of food insecurity, or what I refer to as the risk of food shortfalls, the World Food Programme (2009) considers vulnerability a “forward-looking concept aimed at assessing community and household exposure and sensitivity to future shocks.” Vulnerability to food insecurity is expected to be “determined by their [households or communities] ability to cope with their exposure to the risk posed by shocks such as droughts, floods, crop blight or infestation, economic fluctuations, and conflict. This ability is determined largely by household and community characteristics, most notably a household’s asset base and the livelihood and food security strategies it pursues” (World Food Programme 2009:27-28). These conceptualizations of vulnerability are also appropriate for my study because they combine 'internal' factors of a vulnerable system with its exposure to 'external' hazards (Fussel 2007:160).

Vulnerability and risk are closely related concepts. Risk has been defined and used in a number of ways (e.g., Cashdan 1990; Tainter and Tainter 1996; Winterhalder et al. 1999) but is generally understood as the probability of a loss (Cashdan 1985; Wiessner 1982; Winterhalder 1986) or negative consequence (such as a food shortfall) multiplied by the magnitude of the consequences. These risks can be real or perceived as human perceptions of changing conditions and associated risks may differ from actual changes in conditions (Burton et al. 1993; Ortiz 1979; Powell 1988:82-86; Whyte 1985). In this study, I do not address perceptions of risk, relying instead on relative changes in key climate, demographic, and environmental variables to indicate relative changes and differences in risk of shortfall. Brooks (2003:6-7) argues that studies of risk and vulnerability are essentially examining the same processes because both are “ultimately interested in the physical hazards that threaten human systems, and in the outcomes of such hazards as mediated by the properties of those systems, described variously in terms of vulnerability, sensitivity, resilience, coping ability and so on" (Brooks 2003:7). In this study, I use a vulnerability framework, while recognizing my analysis is also about risk.

Vulnerability to dry periods is the focus of this study. [Note that a different type of vulnerability is not implied if “to dry periods” is omitted in the text of this study]. Dry periods are multi-year periods of relatively low precipitation and streamflow (see Chapter Five for methods of identifying these dry periods). Dry periods decrease resource productivity (wild and cultivated) in arid and semi-arid regions because water is a primary limiting factor on plant growth (Fischer and Turner 1978) and precipitation levels are typically below the moisture requirements of most cultivated crops such as maize (Muenchrath and Salvador 1995; Shaw 1977). Animals that rely on plant foods are also affected by changes in climate that influence plant growth (Bright and Hervert 2005; Osborn 1993). Hence, animals that rely on these herbivores are also affected. Since my concern is with vulnerability to dry periods and an associated risk of food shortfalls for humans, I define shortfalls as those conditions insufficient to meet human food needs. The focus is multi-year shortfalls associated with multi-year dry periods that likely stress or exhaust typical buffering strategies and necessitate a response to prevent the negative effects of long-term food deprivation. The risk of food shortfalls is the same as the concept of "food insecurity"--terminology often used outside of archaeology (e.g., Bohle et al. 1994; World Food Programme 2009). Decreases in resource productivity created by decreased precipitation or streamflow can increase the risk of food shortfalls (create a "hazard") among subsistence agriculturalists in dry climates. Although I focus on dry-period-related risks of food shortfalls, it is important to note that many factors affect the risk of shortfall. For example, Sen (1999) has shown that famines (food shortfalls) are also a consequence of social, political, and economic inequalities that affect access to food. In my study area, environmental factors, such as soil type and quality (Sandor et al. 2007), temperatures (Salzer 2000b), insects and plant diseases, and the extent of arable land all affect resource productivity and can also affect shortfall risks. I do not analyze these. Instead, for this study, I consider select demographic and environmental conditions that influence the potential risk of shortfall as identified by the models of vulnerability I evaluate.

Identifying the reasons why people may be vulnerable to dry-period risks of food shortfall is difficult because of the complexity of factors, and changes in these factors, that may contribute to or ameliorate this vulnerability. In general, vulnerability is a function of the exposure and sensitivity of a system to a hazard and the adaptive capacity or resilience of the system to cope, adapt, or recover from the effects of the hazard (Adger 2006:269; Smit et al. 2001:893-895; Smit and Wandel 2006:286; Turner et al. 2003). Specific contributors to vulnerability to dry periods include such factors as population levels and density, subsistence strategies, social stratification, technologies, poverty, health, landlessness, poor soils, social relations including political weakness, gender, occupation, race/ethnicity, immigration status, extent of social networks, and especially combinations of these factors (Blaikie et al. 1994; Liverman 1990a:49; Meyer et al. 1998:238-243; Ribot 1995; Wisner et al. 2004:11-12). Because the states of these potential contributors to vulnerability to dry periods change over time, vulnerability will also vary. Changes in strategies to manage the risk of shortfalls and changes in the extent of implementation and effectiveness of these strategies are also responsible for changes in vulnerability over time. Furthermore, "no standard framework exists for identifying the fundamental sources of differential vulnerability, but clearly they are numerous and complex" (Meyer et al 1998:240). In brief, "To be vulnerable to drought is to lack environmental, technological, economic, or political defenses against its impacts (Liverman

1990a:50).

Resource Marginality

The U.S. Southwest, like many arid and semi-arid regions, is often considered a “fragile and marginal environment for agriculture” (Diamond 2005:137) and a "harsh and variable region" (Dean et al. 1994:86). This widespread perception was, at least in part, promoted by early 20th century scholars in the Southwest whose perspectives were shaped by the agriculture of the temperate eastern states, the technology of the industrial era, and ultimately European traditions (Fish and Fish 2004:187; Fish 2004:116-117). “By comparison, the hard-won harvests of Indian peoples served mainly to illustrate the vicissitudes that these cultivators had to overcome” (Fish 2004:117). Most Southwestern archaeologists have adopted this perception and seem to accept the view that populations in the region were always undergoing a moderate amount of stress because of the region’s aridity and variability in the timing of rainfall (Cordell 1996:253). Lekson et al. (1994:16) asserts that 2,000 years of human occupation in the Southwest including associated technological, social, and ideological changes were "constrained by a harsh and unpredictable natural environment." Fish and Fish (1994:88) refer to this focus on resource marginality and its consequences as "a unifying theme throughout southwestern archaeology." Similar notions of native Southwestern peoples struggling to survive in a marginal and harsh environment prevail in the popular imagination as well (e.g., Childs 2007).

This perception of climate-related resource marginality, widespread vulnerability to dry periods, and risks of food shortfalls has been informed by:

1. ethnohistoric accounts of harvest failures and crop damage due to both flooding and drought (Abruzzi 1989; Bradfield 1971; Castetter and Bell 1942; Russell 1975 [1908]; Slatter 1979; Zarbin 1980);
2. archaeological evidence of extensive water control strategies to manipulate and maximize available precipitation (Fish and Fish 1984; Vivian 1974);
3. skeletal evidence of nutritional deficiencies (El-Najjar et al. 1976; Martin 1994; Sheridan 2003);
4. crop and climate studies indicating that annual precipitation levels are mostly below the moisture requirements of major crops such as maize (Muenchrath and Salvador 1995; Shaw 1977); and,
5. climate studies that demonstrate low mean and highly variable precipitation conditions (e.g., Sheppard et al. 2002).

An abundance of space-time coincidences between dry periods and potential human responses such as settlement abandonment have also supported this perception (e.g., Ahlstrom et al. 1995; Adams 1998; Cordell 1975; Cordell et al. 2007; Dean et al. 1985; Euler et al. 1979; Gumerman 1988; Judge 1989; Lipe 1995; Minnis 1985; Orcutt 1991; Schlanger 1988; Van West and Dean 2000).

There are reasons to question the extent of resource marginality and the prevalence of climate-related food shortfalls. First, inferences of shortfall risk that rely on ethnohistoric examples of dry-period challenges to agriculture may not be valid because the scale, complexity, social organization, and technology of prehistoric groups changed over time and differ from those observed historically. For example, historically-observed indigenous irrigated agriculture in the Phoenix basin was substantially smaller-scale than irrigated agriculture practiced prehistorically (see Howard 1993 for a description of Hohokam irrigation systems). Larger-scale systems increase the potential for agricultural surplus, depending on the size of populations relying on these systems. Second, much of the ethnographic evidence supporting climate-related shortfalls (e.g., Slatter 1979) is from upland portions of the Southwest without extensive perennial rivers and where climatic conditions, especially cool temperatures and shorter growing seasons, are more agriculturally limiting. Third, wild foods in central Arizona were "predictable, storable, and abundant…and harvest times for staples are spread over much of the year" (Fish 1989:22). Thus, wild foods could have substantially offset declines in cultivated crop productivity and reduced the risk of shortfall if these foods were less sensitive to dry-period declines in productivity or located in less affected areas. Fourth, cultural trajectories in the region spanning at least a millennium suggest effective adaptations to prevailing climatic and environmental conditions including a repertoire of strategies to manage shortfall risks (e.g., Fish 1989). Finally, empirical validation of resource marginality and endemic shortfalls is lacking, except for the few skeletal studies of nutritional deficiencies (El-Najjar et al. 1976; Martin 1994; Sheridan 2003). Such validation might come from agricultural production models that demonstrate recurring patterns of caloric insufficiency. Production models, however, are difficult to construct and defend due to the plethora of assumptions required and inadequate information about the essential variables (e.g., number of people, water requirements and yields of prehistoric maize varieties, field sizes, etc.). That resource marginality led to endemic risks of shortfall, then, is a plausible hypothesis rather than a well supported assumption.

Consequences of the Marginality Assumption

The perception of resource marginality has transformed over time into a foundational assumption of many Southwestern archaeological studies (e.g., Doyel and Dean 2006; Gumerman 1988; Larson et al. 1996; Minnis 1985; Rautman 1993; Tainter and Tainter 1996). For example, the assumption allows climate-related decreases in resource productivity to be strongly linked to the increasing risk of food shortfalls and responses to these risks. Marginality implies a strong linkage because resource levels are assumed to always be minimal and fluctuate around a threshold above which there was enough food and below which there was not. Thus, dry-period declines in productivity are expected to have increased the risk of shortfalls and stimulated behavioral responses to manage these shortfall risks. Marginality, then, provides a critical linking argument between climate and human behavior by making climate-related variation in resource productivity meaningful to people because of the risk of shortfalls.

Importantly for this study, models of vulnerability to dry periods in the U.S. Southwest rely on the marginality assumption to link changes and differences in demographic and environmental conditions to differences in vulnerability to dry periods. The marginality assumption implies that any condition that affects the demand or supply of resources will also meaningfully influence shortfall risks and prompt human responses. For example, people living in settlement areas of relatively low inherent productivity (e.g, in an area of low precipitation) should be more vulnerable to dry periods than people living in areas of relatively high inherent productivity. This is because people living in areas of low productivity are assumed to be closest to the threshold above which there is enough food to eat and below which there is not. Thus, when dry periods decrease productivity, the risk of shortfalls is assumed to increase in all areas but be most meaningful in areas of low productivity where resource supplies may have declined below a threshold so that there was not enough food to eat. However, if resources were abundant (not marginal) and dry-period declines in productivity in areas of both relatively low and high productivity did not approach the threshold below which food needs were unable to be met, then differences in inherent productivity among settlements would not have meaningfully influenced shortfall risks. Any change in human behavior associated with dry-period declines in productivity, then, could not be interpreted as responses to the risk of shortfalls.

The marginality assumption inappropriately obviates considerations of the role of human action in ameliorating or contributing to vulnerability. People have a variety of strategies for living in dry climates, managing vulnerability, and responding to shortfall risks. Such strategies include mobility, resource diversification, physical storage, exchange, and population distribution on the landscape (e.g., Braun and Plog 1982; Burns 1983; Dean 2006; Halstead and O'Shea 1989b:3-4; Minnis 1985; Rautman 1993; Slatter 1979:80-84). These strategies can address shortfall risks and ameliorate vulnerability by increasing resources or access to resources. These strategies and responses are choices among available opportunities (Burton et al. 1993) and their ameliorating or contributing influence on vulnerability can be evaluated. Variation in the effectiveness or implementation of these strategies over time may also explain variation in vulnerability to dry periods. That is, why at some places and times climate appears to have influenced human behavior and at other times it does not. When marginality, shortfalls, and vulnerability are assumed, however, the influence of these choices and changes in their implementation or effectiveness are not adequately considered.

Uncritical acceptance of the marginality assumption can slow the pace of theoretical and methodological advancement in climate-human behavior studies in the U.S. Southwest. The pace can be slowed by failing to identify *if* serious vulnerabilities existed and/or by failing to stimulate rigorous efforts to identify non-demographic and non-environmental causes of this vulnerability if it existed (e.g., disease, conflict, social stratification). Without a consideration of multiple factors that influence vulnerability to dry periods, we cannot effectively explain the diversity of responses including no response to dry periods evident when the paleoclimatic record of dry periods is compared to the archaeological record of behavioral change (Nelson et al. 2010). Weaknesses in our ability to account for a diversity of responses to dry periods including no response can result in frustration with current approaches that discourage analytical and interpretive advancements. The marginality assumption is at least partly responsible for current limitations in archaeological understanding of climatic influences on human behavior because it has focused attention on developing more refined identification and characterization of climatic events and on mostly demographic and environmental explanations of differences in vulnerability. This study’s challenge to the marginality assumption is inspired by and builds on previous work that has questioned the role of drought as the primary cause of abandonments at various times and places in the U.S. Southwest (e.g., Dean 1996; Hill et al. 2004; Lipe 1995; Kintigh 1985; Van West 1990; Van West and Dean 2000; Kohler and Van West 1996; Varien et al 1996).

The impact of the marginality assumption is not limited to climate-human behavior studies. Yoffee (1994:350) observed that at a conference on prehistoric social complexity in the Southwest, the major theme was "bad weather". In support of his claim he listed multiple references to resource marginality among the papers that comprised the edited volume that resulted from the conference (Yoffee 1994:350; in Tainter and Tainter 1994). It was clear that the shared assumption of marginality had a strong influence on approaches to the problem of complexity. Elsewhere, Harry (2005) examined the influence of agricultural marginality on ceramic specialization at six areas in the prehistoric U.S. Southwest. She found little evidence supporting the influence of agricultural marginality on the adoption of part-time ceramic specializations. Rather than question her method of differentiation of settlements into more or less marginal, she argues that attention must be focused on the differing social and economic contexts between prehistoric and historic/modern-day peasants to understand why agricultural marginality did not influence ceramic specialization. I suggest that her reliance on environmental criteria alone (e.g., potential for floodplain agriculture, precipitation levels and variability) to identify differences in marginality among settlements did not allow an effective consideration of the research problem she considered.

Assessing Vulnerability with Residential Abandonment

Understanding the influence of dry periods on vulnerability requires a method of assessing vulnerability, and changes in vulnerability, during the period of interest throughout the study area. Vulnerability, however, is not a directly observable phenomenon (Moss et al. 2001:8) making measurement and quantification difficult (Leurs et al. 2003:256). A number of studies have developed a set or composite of proxy indicators to quantify vulnerability (e.g., Moss et al. 2001; see Leurs et al. 2003:256-267 for other examples) and the development of vulnerability assessment tools is now a significant research emphasis. For example, the Pacific Northwest Laboratory Vulnerability Assessment Program developed a composite of sixteen variables such as life expectancy, percent of the population with access to safe water, and the percent of non-managed land to assess vulnerability to climate change for 38 countries (Moss et al. 2001).

In some case studies, however, the “relative impacts of stressors in a region” (e.g., dry-period risks of shortfall) and responses can be used as an objective ex-post facto measure of vulnerability (Leurs et al. 2003:256-257). I follow this approach and use one potential response to dry periods to assess vulnerability: residential abandonment. In the nomenclature of modern vulnerability studies, residential abandonment is referred to as "persons displaced" and it has been used as a quantitative index of hazard impacts (Meyer 1998:242). I do not use single abandonment events at any spatial scale as a measure of vulnerability to dry periods; such events may be simply time-space coincidences with a dry-period. Rather, I use the long-term (250-year) relationship between changes in dry-period severity and changes in residential abandonment at the scale of settlements, watersheds, and the total study area as an indicator of potential vulnerability to dry periods (as discussed further in Chapter Five). That is, if over the 1200 to 1450 period of study, changes in dry-period severity were strongly associated with proportionate changes in residential abandonment, then dry-period influences on this abandonment may be reasonably concluded.

Residential abandonment is an archaeological signature of population movement. This movement is a reasonable indicator of potential vulnerability to dry periods for several reasons. First, people can take advantage of the spatial and temporal structure of resource failure across a landscape by moving away from areas of food scarcity and low productivity to areas of higher productivity (Halstead and O’Shea 1989a), reducing their vulnerability to the dry climate conditions. Second, ample ethnohistoric evidence in the U.S. Southwest has documented residential abandonment in response to climate-related resource shortfalls (Abruzzi 1989; Slatter 1979). Third, dry-period influences on residential abandonment (often in combination with other factors) have been identified in a number of archaeological studies in the U.S. Southwest (e.g., Ahlstrom et al. 1995; Adams 1998; Cordell 1975; Cordell et al. 2007; Dean 1988; Dean et al. 1985; Euler et al. 1979; Gumerman 1988; Jett 1964; Judge 1989; Lipe 1995; Minnis 1985; Orcutt 1991; Schlanger 1988; Slatter 1979; Van West and Dean 2000). Fourth, dry periods are among the climatic conditions understood to have led to population movements in many parts of the world (McLeman and Smit 2006; Meze-Hausken 2000). Note that archeologically identified residential abandonment in the prehistoric Southwest is a record of population movements, not a record of the relinquishment of places, ownership, or the disappearance of a people (Nelson and Schachner 2002:169).

Movements in response to dry-period shortfall risks can be either short (intra-watershed) or long-distances (inter-watershed) when reductions in shortfall risk (real or perceived) can be achieved by either (as discussed below). In recent migration studies of living peoples in Ecuador (Gray 2008), Burkina Faso (Henry et al. 2004), and Nepal (Massey et al. 2007), data show that movement out of communities with adverse environmental conditions (e.g., low rainfall, rainfall variability, environmental degradation) resulted more often in short rather than long-distance moves. Short-distance movements can reduce dry-period shortfall risks when there is substantial local-scale spatial heterogeneity of topographic and environmental conditions that affect potential resource productivity (Massey 2007:7). Short-distance movements to new settlement areas and uncultivated lands can also be sufficient to increase productivity and decrease dry-period shortfall risks if these risks were created or exacerbated by declining productivity of continuously cultivated lands.

Substantial spatial heterogeneity in conditions influencing potential productivity exists within central Arizona and the individual watersheds that comprise the study area (see Chapter Four for the study area description). For example, settlements in the study area were located in areas receiving an average of 7 to 35 inches of precipitation annually, both near and far from perennial rivers, and in areas with average annual temperatures ranging from 49 F to 71 F (based on modern climate data from the Western Regional Climate Center 2010). Areas settled range in elevation from 994 to 6,966 feet. The study area also includes seven of the thirty-four biotic communities identified in the Southwest (Brown et al. 1979; The Nature Conservancy in Arizona 2004) and forty-one soil classifications (Natural Resources Conservation Services 2008). In a single watershed covering 5,612 square kilometers (the Upper Salt), settlements were located in areas receiving an average of 15” to 35” of precipitation annually, both near and far from perennial rivers, and in areas with average annual temperatures ranging from 51 F to 69 F. Areas settled range in elevation from 2,097 to 6,966 feet. The watershed includes five biotic communities and fourteen soil classifications. Thus, movements to destinations outside of the study area were not necessary to substantially change environmental conditions and influence potential productivity. This heterogeneity also implies that dry periods impacted neighboring communities differently, creating a mosaic landscape of vulnerability.

Residential abandonment and movement from settlement areas is, however, an imperfect indicator of vulnerability to dry periods because movement, like vulnerability, is a complex phenomenon that lacks a single cause. Thus, any assessment of the extent of movement over time conflates a variety of factors and potential causes (Meze-Hausken 2000). I do not attempt to identify these factors or causes by, for example, distinguishing between moves to places that are far or environmentally different from ones that are close and environmentally similar. Factors that affect decisions to move include “push” factors at the population origin, “pull” factors at the population destination, and the transportation costs between the two (Anthony 1990; Herberle 1938; Lee 1966). If people are vulnerable to dry periods and dry-period risks of shortfall provide a “push” to move, people may decide not to move if more productive locations are limited, or perceived to be limited, or the real or perceived costs of moving are greater than the benefits of remaining in place.

Population movement is also understood as “a strategy of resituating, both socially and ecologically, and perhaps even ideologically” (Nelson 1999:22; see also Nelson and Hegmon 2001 and Nelson and Schachner 2002). People can move for "religious, kinship, trade, artistic, and personal obligations" (Kelley 1992:48) and movement itself can be culturally valued (Naranjo 1995). Vulnerability to dry periods may also be addressed by a variety of strategies that do not include residential abandonment. People may diversify their resources and diets, increase physical food storage, acquire food through exchange, decrease food consumption, and socially reorganize (e.g., Bawden and Reycraft 2000; Braun and Plog 1982; Burns 1983; Dean 2006; Halstead and O’Shea 1989b:3-4;

Minnis 1985; Rautman 1993; Slatter 1979:80-84). Decisions to move, then, are not simply a function of vulnerability and risk but of real or perceived opportunities, costs and benefits, and the effectiveness of other strategies to manage declines in resource productivity and the risk of shortfall.

In sum, the intersection of different economic, social, and environmental conditions creates different potentials for vulnerability. Some of these conditions are those considered in this study: dry periods, population levels and density, and local-scale resource productivity. If residential abandonments were a response to dry periods, these movements should correlate over the 250-year period of study with the worst combinations of conditions.

Conclusion

In this chapter, I define and describe the relationships among vulnerability, risk, dry periods, and resource marginality. In both practice and thinking in the U.S. Southwest and other dry climates, these concepts are often closely linked and sometimes difficult to distinguish. One of the contributions of this study is to demonstrate the value of considering each of these concepts separately and questioning the relationship among them. For example, people are vulnerable to dry-period risks of shortfall in dry climates only to the extent that resources were marginal and existing strategies to manage these risks ineffective. Thus, there is not a necessary and direct linkage between dry periods, risk, vulnerability, and human response. I have argued that a questionable assumption of resource marginality has informed this linkage and our models of vulnerability. Questions regarding the validity of the marginality assumption are a strong reason why our models of vulnerability need to be evaluated. In the next chapter, I describe these models that inform our thinking about the challenges of living in dry climates.

CHAPTER 3:

CONCEPTUAL MODELS OF VULNERABILITY TO DRY PERIODS

My approach to advancing understanding of conditions that affect human vulnerability to dry periods is to evaluate four prominent and often implicit conceptual models used by archaeologists and others investigating past human adaptations in dry climates. These models are used to explain and predict spatial and temporal differences in vulnerability to dry periods and they each emphasize different demographic and environmental conditions assumed to influence this vulnerability.

Neither I nor the researchers that have employed the models I evaluate assume that demographic and environmental conditions are the only conditions that contribute to vulnerability to dry periods. These conditions and changes in these conditions, however, are often emphasized (individually or in combination) and form an important link in the chain of causal argument regarding climatic influences on human behavior. The individual contribution of a specific condition to dry-period vulnerability has been argued because in the context of assumed resource marginality, changes in either resource demands (represented by demographic conditions) and/or changes in resource supplies (represented by environmental conditions) may have created population-resource imbalances that increased vulnerability to dry periods. The indicators I use to represent differences in these conditions (settlement population levels, watershed population density, settlement locations relative to perennial rivers, and average annual precipitation levels) are also only a subset of characteristics that may influence resource demand and supply.

I identified these models by considering arguments, expectations, and assumptions regarding climatic influences on human behavior prevalent in U.S. Southwestern archaeological studies and in modern studies of vulnerability to natural hazards conducted by researchers in other disciplines. This is the first archaeological effort in the U.S. Southwest or elsewhere, to my knowledge, to explicitly identify these models and systematically examine over an extended period the influence of demographic and environmental conditions on vulnerability to dry periods in order to test the validity of these models. It is important to evaluate these models because they lack empirical scrutiny, are seldom identified explicitly but are rather embedded in other arguments, and rely on an unverified assumption of widespread resource marginality due to low precipitation in the region.

In this chapter, I describe these models and provide examples of their use and discuss how they have affected interpretations of vulnerability to dry periods as well as important events in the prehistory of the U.S. Southwest. The models are summarized in Table 3. I also provide an initial description of how I evaluate each model with greater detail provided in Chapter Five.

Table 3.1. Summary of Conceptual Models, Expectations, and Relationships to be Evaluated.

Conceptual Models	Conditions Expected To Influence Vulnerability To Dry Periods	Expected Influence Of Conditions On Vulnerability To Dry Periods	Actual Relationships To Be Evaluated In This Study And Results That Will Support Model Expectations
Aridity	regional scale aridity	increase as dry-period severity increases	strong and sensitive relationship[1] between dry-period severity and residential abandonment in all watersheds in study area
Demand models	settlement population levels	increase as settlement population levels increase	relationship between dry-period severity and residential abandonment increases in sensitivity and strength as settlement population levels increase
	watershed population density	increase as watershed population density increases	stronger, more sensitive relationship between dry-period severity and residential abandonment in watersheds with higher density than in watersheds with lower density
Supply models	settlement proximity to perennial rivers	greater among settlements far from perennial rivers than among those near perennial rivers	stronger, more sensitive relationship between dry-period severity and residential abandonment in settlements far from perennial rivers than among settlements near perennial rivers
	settlement area precipitation and streamflow levels	increase as precipitation and/or streamflow levels decrease	relationship between dry-period severity and residential abandonment increases in sensitivity and strength as settlement area precipitation and/or streamflow levels decrease

Conceptual Models	Conditions Expected To Influence Vulnerability To Dry Periods	Expected Influence Of Conditions On Vulnerability To Dry Periods	Actual Relationships To Be Evaluated In This Study And Results That Will Support Model Expectations
Demand and supply models	population-resource imbalances (watershed-scale)	increase as resource demands exceed supplies	stronger, more sensitive relationship between dry-period severity and residential abandonment where demand was high and supply low than where demand was low and supply high
	population-resource imbalances (settlement-scale)	increase as resource demands exceed supplies	same as above

[1] Strength of the relationship is assessed with correlation coefficients and the sensitivity with the slope of regression lines, as discussed at the end of Chapter Five.

Aridity Model of Vulnerability to Dry Periods

Aridity models emphasize the contribution of low precipitation and resource marginality to vulnerability to dry periods. Vulnerability in this model is understood in terms of the biophysical conditions of the environment (resource marginality and aridity), ignoring characteristics of human populations (Liverman 1990b). Biophysical vulnerability "is a function of the frequency and severity (or probability of occurrence) of a given type of hazard" (Brooks 2003:4) such as a dry period. Social, demographic, and other conditions of human populations exposed to dry periods and the contribution of these conditions to their vulnerability to dry periods are either ignored, not emphasized, or assumed to be small in biophysical models of vulnerability to natural hazards.

An emphasis on the contribution of biophysical conditions to vulnerability to climatic hazards is widely applied by engineers and economists in the technical literature on disasters (Fussel 2007) and within global environmental change studies (Liverman 1990b:30). An emphasis on biophysical conditions has its theoretical origins in the risk-hazard vulnerability approach originating in geography. Two examples of this approach are vulnerability to sea level rises and vulnerability to floods. Topographic contours are used almost exclusively to identify the extent of vulnerability to these hazards (e.g., Titus and Richman 2001). Regarding vulnerability to global environmental change, a biophysical approach "implies that in order to understand and delimit vulnerability, we just need to know how and where the physical environment will change. Physical indicators will then provide adequate insight into the populations at risk"

(Liverman 1990b:30).

Archaeological acceptance of a biophysical model of vulnerability to dry periods (and other climatic conditions) is pervasive in the U.S. Southwest because of the assumption of resource marginality and widespread vulnerability to relatively low precipitation in the region (as I discuss in the "Resource Marginality” section in Chapter Two). The assumption of resource marginality when employed to explain social and cultural changes in the U.S. Southwest essentially draws the contours of vulnerability to dry periods around the entire region due to relatively low and variable precipitation. As a result, studies of human-environment interactions and climatic influences on human behavior in the U.S. Southwest are usually studies of risk and the contribution of marginality and climatic event severity to this risk (e.g., Doyel and Dean 2006; Graybill et al. 2006; Gumerman 1988; Larson et al. 1996; Minnis 1985; Nials et al. 1989; Rautman 1993; Tainter and Tainter 1996).

Studies that emphasize quantitative estimates of precipitation levels relative to "normal" or average conditions and compare severe conditions to coincident behavioral changes signal the use of an aridity model. For example, Stahle et al. (2007) and Cook et al. (2007) use tree-ring reconstructed summer Palmer Drought Severity Indices (PDSI) to identify decadal droughts more severe and prolonged than any witnessed during the modern instrumental period. Cook et al. (2007; and references contained therein) identify temporal correlations between severe dry periods and a number of important socio-cultural events including the 14th century decline of complex Mississippian chiefdoms and famine, disease, and village abandonment in the Puebloan region of New Mexico in the 16th century. Stahle et al. (2007:136-140) also use the temporal coincidence between identified droughts and historical information on the environmental conditions and activities of Euroamerican and Native American societies throughout the U.S. to validate the PDSI reconstructions. Although Stahle et al. (2007:136) find a number of temporal correlations between severe dry periods and social and environmental events, they also find a number of "disagreements" between these dry periods and known historical events. Stahle et al. (2007:136) attribute these disagreements to climate proxy reconstruction errors or the fact that “tree-ring data integrate moisture conditions during and sometimes preceding the growing season, and may not well represent fall or winter conditions.” I suggest that these disagreements between dry periods and known historical events also strongly suggest variation in human vulnerability to dry periods driven by other factors in addition to weaknesses in the climate reconstruction's ability to accurately identify relevant precipitation conditions and their severity.

Explanations of regional-scale abandonments that attribute them to catastrophic climate events, such as dry periods, treat vulnerability as a regional-scale biophysical condition and assume endemic shortfalls and widespread vulnerability due to low precipitation. This assumption of widespread vulnerability ignores or over-rides any intra-regional social and environmental diversity that influences vulnerabilities. For example, abandonment of the San Juan Basin in the mid-1100s and the Mesa Verde region in the late 1200s has been (Douglass 1929; Judge 1989, and others) and continues to be (Benson et al. 2007) attributed to severe dry periods. Differences in vulnerability across these regions due to varying demographic and environmental conditions and how these differences might have affected dry-period impacts and responses are often not systematically considered. Van West's (1994) spatially detailed study of soil types and modern crop yields and potential variation in impacts of the late 1200s drought on agricultural productivity is an early and notable exception (see also recent work by Axtell et al. 2002, Kohler et al. 2007, and Schollmeyer 2009). In central Arizona, dry periods combined with catastrophic flooding and associated stream channel changes along the Lower Salt River in the late 1300s have been hypothesized as the cause of the depopulation of settlements irrigating from the Lower Salt River (Graybill et al. 2006, Nials et al. 1989; Gregory 1991). Again, differences in vulnerability based on settlement locations (e.g., near or distant from the floodplain) and settlement-scale demographic conditions that affected the demand for resources are typically not considered.

Dry-period influences on regional abandonments have been argued for many places and times (e.g., Weiss and Bradley 2001). Examples include the Maya of Mesoamerica ca. A.D. 1200 (Gill 2000; Hodell et al. 1995), Cahokia and associated settlements of the American Bottom and Mississippi River Valley ca. A.D. 1100 to 1245 (Benson et al. 2009), the Tiwanaku of Bolivia-Peru ca. A.D. 1100 (Binford et al. 1997), and the Akkadians of Mesopotamia ca. 4200 B.P. (Weiss et al. 1993), to name only a few. Dry periods are seldom considered the only factor responsible for these regional depopulations; however, variability in vulnerability across a region is not addressed in aridity models that emphasize widespread vulnerability to dry periods due to low average precipitation conditions.

To assess the utility of an aridity model for explaining vulnerability to dry periods, I examine the relationship between dry-period severity and residential abandonment throughout central Arizona from 1200 to 1450. I use the relationship between dry-period severity and residential abandonment as an indicator of the extent of vulnerability to dry periods within six watersheds with a long-term history of occupation. By geographically disaggregating the study area into watersheds, I test the assumption of vulnerability to dry periods as a regional-scale, biophysical condition. The aridity model and the assumption of regional-scale resource marginality would be supported by strong and sensitive relationships between dry-period severity and residential abandonment in all watersheds.

Demand Models of Vulnerability to Dry Periods

Demand models emphasize the contribution of demographic conditions to vulnerability to dry periods. The demographic conditions I consider are settlement population levels and watershed population density. These conditions define, in part, resource demands, the rate of consumption of resources, and the extent of labor available to invest in strategies to manage shortfalls. Settlement population levels reflect the cumulative decisions of people to stay or leave a locale--a settlement or watershed area--and to allow others to move into that locale. Exploration of the role of population levels and density is a window into the role of human decisions in creating or ameliorating vulnerabilities to dry periods.

The effect of settlement population levels and areal population density on vulnerability to dry periods is complex and has been argued to both increase and decrease vulnerability (Meyer et al. 1998:241). For example, as population levels increase more resources are consumed and increases in production may not be able to keep pace (Malthus 2001 [1798]) especially during dry-period declines in productivity. Relatively high population density in an area can also increase vulnerability by limiting mobility as a strategy to manage shortfall risks (Binford 1983; Cordell 2000:183; Dean et al. 1994:85; Minnis 1996; Powell 1988). Population density can limit mobility if productive locations are already claimed, occupied, or hostilities restricted movement. Larger populations might also increase the tilling of relatively less productive plots of land to increase production (B. Nelson et al. 1994:61-62) and these plots could quickly become unproductive during dry periods. Thus, "as population density increases, more individuals are forced into areas of greater risk" (Reycraft and Bawden 2000:2). Larger populations can, however, intensify production and invest in infrastructure to increase resource supplies (Boserup 1965) and develop social strategies not as readily available to smaller populations, such as centralized leadership and alliances (McGuire and Saitta 1996; Wilcox et al. 2001a; 2001b), to manage shortfall risks.

Demand models are essentially 'population pressure' models wherein increasing population levels are considered responsible for some stress on humans or the environment (e.g., Smith 1972). Population pressure arguments assert that rising population levels at some point breach a threshold and behavioral responses become necessary. Where resources are assumed to be marginal, this threshold is expected to be easily and frequently breached. For example, Larson et al. (1996:219) assert "With the shift to primary reliance on domesticated crops, population levels and densities increased dramatically between A.D. 900 and 1100 and the Anasazi [northern Southwest] became increasingly vulnerable to climatic variability and extremes." Larson et al. (1996:218) describe this increase in vulnerability in the context of an "extremely marginal environment for prehistoric hunting and gathering and agricultural pursuits." Similarly, Plog et al. (1988:261) state "It is difficult to imagine environmental deterioration of sufficient severity to stimulate a long-distance move in the absence of high populations." High population levels, then, in these examples are a critical factor in understanding vulnerability to dry-period risks of shortfall.

It is important to empirically evaluate this model because expectations of the contribution of demographic conditions to vulnerability to dry periods (and other hazards) are often conflicting (as discussed above) or too ambiguous to be useful or convincing. For example, in a list of possible determinants of vulnerability to global environmental change (which includes increases in dry-period severity associated with global-scale climate change), Liverman (1990b:33) asserts "High population densities, population growth rates, and pressure on limited food, land, and water resources can make regions very vulnerable to global change." Similarly, Reycraft and Bawden (2000:2 citing work by White 1974 and Burton et al. 1978) state that "the greater the population density of a given area, the greater the damage potential of a given extreme event. Also, as population density increases, more individuals are forced into areas of greater risk." And, Cordell (2000:182), referring to upland areas of the northern Southwest, states "Population 'packing' [makes it] impossible to implement an agricultural strategy that depends on relocating fields and dwellings" thereby linking increases in population densities with agricultural vulnerability. These expectations and assertions though sometimes vague are logically appealing and amenable to empirical testing. Minimally, we need to understand at what spatial scales the suggested relationships might apply.

Investigations of the potential influence of increasing population levels on vulnerability to dry periods without considering the potential resource productivity of an area are unrealistic. Coupled with the assumption of region-wide resource marginality, however, these studies place population levels close to a threshold where changes in either population or resources may increase the risk of shortfall. Under this model, people living in settlements or watersheds with relatively high population levels would be more vulnerable to dry periods than those living in places with lower population levels. Thus, for the central Arizona study area, if vulnerability to dry periods was influenced by settlement population levels and watershed population density, the relationship between dry-period severity and residential abandonment will be stronger and more sensitive where population levels and density are highest and weaker where population levels and density are lowest. Results will clarify the influence of these demographic conditions on vulnerability to dry periods in the study area.

Supply Models of Vulnerability to Dry Periods

Supply models emphasize the contribution of the potential productivity of settlement locations to vulnerability to dry periods. The environmental conditions I consider are settlement locations relative to perennial rivers and areas of low to high average annual precipitation levels. Access to resources, as reflected by settlement locations, is one factor that affects the ability of human systems to adapt to and cope with dry periods and climatic conditions. Settlement locations reflect the decisions of people regarding where to live; thus, exploration of the role of settlement locations is a window into the role of human decisions in creating or ameliorating vulnerabilities to the risk of shortfall.

Settlement locations adjacent to perennial riverine resources, which include the associated riparian and aquatic resources, are assumed in this study and model to offer greater potential productivity than settlements located away from perennial riverine resources. The majority of wild plants used as resources by the Hohokam "are most densely and continuously distributed along riparian corridors" (Fish and Nabhan 1991:42). Agricultural potential is also greater in riverine areas where irrigated and floodplain agriculture are possible.

Likewise, settlements in areas receiving relatively more precipitation on average are assumed to have been relatively more productive than those areas that receive less. Differences in precipitation conditions are often used to explain settlement location shifting motivated by changing climatic conditions (e.g. Dean 1988; 1996). Similar assumptions regarding proximity to rivers and precipitation levels have been used to identify "agricultural primeness" in the arid regions of Africa (Miller et al. 2002). Other factors such as the extent of arable land or the quality of soils (Sandor et al. 2007) influence productivity but are beyond the scope of this study.

The influence of potential resource supplies on vulnerability to dry periods wherein vulnerability is considered a function of riverine proximity or precipitation levels is a common sense notion supported by the strong relationship between the distribution of water and settlement locations in dry climates. People living distant from perennial rivers rely on "dry-farming" or "rain-fed" farming and are widely assumed to be among the most vulnerable and sensitive to low precipitation in dry climates (e.g., Liverman and Merideth 2002:207). For example, Harry (2005:299) compares two settlement areas in the Tucson Basin (southern Arizona): one bordering a primary river with wide expanses of arable floodplain, the other along lesser watercourses and in an upland area. Harry (2005:299) "intuitively" expects that the settlements near the primary river were not agriculturally impoverished relative to the settlements along the lesser watercourses and in the upland area. In colonial Mexico, Florescano (1980, as translated by Liverman 1990a:50) argues that "the disastrous effects of drought, as in earlier times, are concentrated in the rainfed agriculture practiced by the poorest ejidatarios and campesinos, lacking credit, irrigation, fertilizers, and improved seeds."

The notion that riverine areas were less marginal than non-riverine areas and people living near perennial rivers were less vulnerable to dry periods than those living distant from perennial rivers lacks empirical verification and there are reasons to question its validity. For example, investments in irrigation infrastructure in riverine areas will increase productivity and resource supplies thereby potentially reducing vulnerability to dry periods. However, these investments in irrigation infrastructure may increase population, reduce mobility, and thereby increase vulnerability to dry periods as well as other social and environmental conditions (Anderies 2006; Ingram 2008; Janssen and Anderies 2007; Nelson et al. 2010). In a study of the impact of irrigation on drought losses in Mexico, Yates (1981) finds little support for the expectation that irrigation has the advantage of reducing climatic hazards compared with crops dependent on erratic rainfall. Rather, he finds "only a slightly smaller deviation from [agricultural] output trend in irrigated than in rainfed areas" (Yates 1981:77 as quoted in Liverman 1990a:58).

To assess the utility of a resource supply model for explaining spatial differences in vulnerability to dry periods in central Arizona from 1200 to 1450, I examine the relationship between dry-period severity and residential abandonment among rooms near and far from perennial rivers and in areas of low, moderate, and high precipitation. If vulnerability to dry periods was strongly related to the productivity characteristics of settlement locations as identified by differences in the availability and access to water, then the relationship between dry-period severity and rooms abandoned near perennial rivers or in areas with high average annual precipitation will be less sensitive and weaker than the relationship between dry-period severity and rooms abandoned distant from perennial rivers or in areas with low average annual precipitation.

Demand and Supply Models of Vulnerability to Dry periods

Demand and supply models emphasize the contribution of population-resource imbalances (at various spatial scales) to vulnerability to dry periods (Cordell and Plog 1979; Dean 1988; Dean 1996; Larson 1996; Larson and Michaelsen 1990). Population-resource imbalances were "probably a fact of life for most prehistoric groups, both because they sometimes grew too fast and because of unforeseeable decreases in the resources available to them" (Cordell and Plog 1979:411). Emphasis on population-resource imbalances are not limited to climate-human behavior studies. Rather, "Interpretations of Southwestern cultural patterns are frequently based on the assumption of high population density, low plant and animal biomass [resource marginality], and resultant population/resource imbalances" (Powell 1988:182).

Attempts to consider both potential resource supplies and demand to infer shortfall risks pose a substantial challenge in archaeological research. It is a challenge because we have inadequate information about the plethora of variables involved in inferring both supply (wild and cultivated food resources) and demand (population levels). For example, identifying the extent of a food supply involves an understanding of the water requirements of prehistoric maize varieties, the proportions of cultivated and wild foods that comprised diets, yields of cultivated and wild foods, and many other factors (Minnis 1985:99-155 provides an extended discussion of these problems).

Despite these challenges, reasonable attempts have been made that provide approximations of periods when population-resource imbalances likely resulted in increased vulnerability to food shortfalls. One such effort is a study developed by Minnis (1985) for the Mimbres region of southwestern New Mexico focused on the A.D. 600 to 1250 period. Minnis documented potential resource supplies over time with estimates of crop success, wild food productivity, and food stress using precipitation and streamflow reconstructions. He compared these estimates to potential resource demands identified by variation in population levels. The resulting effort identified periods when population-resource imbalances and associated vulnerability to dry periods were most likely.

Examining the influence of population-resource imbalances is important because it allows us to see if these imbalances emerge as a consistent influence on vulnerability to dry periods over time. As I discussed in Chapter Two, people have a variety of strategies for managing shortfalls risks and their vulnerability to dry periods. The effectiveness or changes in the effectiveness of these strategies might be a more important factor in vulnerability to dry periods than simple formulations of the potential balance between resource supply and demand. As stated by Dean et al. (1994:86), "Many congruences [between past environmental variability and regional demographic trends] establish the importance of demographic and environmental variables as integral factors in sociocultural stability, variability, and change in this harsh and variable region. On the other hand, many failures of the archaeological record to fulfill the expectations of the models indicate that the effects of population and environmental fluctuations were mediated and transformed by sociocultural factors." Evaluating models of vulnerability to dry periods that emphasize population-resource imbalances, then, help us understand the extent to which these imbalances consistently influenced vulnerability to dry periods.

To assess the utility of this model for explaining differences in vulnerability to dry periods, I combine elements of the demand and supply models (above). I test the expectation that the extent of population-resource imbalances influenced vulnerability to dry periods by comparing the strength of relationships between dry-period severity and residential abandonment where demands were relatively high (settlements located in watersheds with high population density and settlements with high population levels) and supply low (settlements located distant from perennial rivers and in areas of low precipitation) to the relationship where demands were relatively low (settlements located in watersheds with low population density and settlements with low population levels) and supply high (near perennial rivers and in areas of high precipitation). If vulnerability to dry periods was influenced by population-resource imbalances, then the relationship between dry-period severity and residential abandonment will be stronger and more sensitive where demands were high and supplies low (population-resource imbalances most likely) than where demands were low and supplies high (population-resource imbalances least likely).

Conclusion

In this chapter, I describe four conceptual models that emphasize the influence of aridity and demographic and environmental conditions on vulnerability to dry periods. These models reflect logical relationships between the demand and supply of resources and vulnerability to dry periods in areas where resources are considered marginal and the risk of food shortfalls endemic and widespread. The models, however, need to be evaluated because they lack empirical scrutiny and rely on an unverified assumption of widespread resource marginality in dry climates. This evaluation is important because the models and associated expectations have had a profound influence on how we think about the challenges and opportunities of living in dry climates.

CHAPTER 4:

CENTRAL ARIZONA FROM 1200 TO 1450

In this chapter, I describe the climatic, environmental, and cultural diversity of central Arizona during the 1200 to 1450 period. Climatic and environmental diversity--from the dry and hot desert to the wet and cool mountains--provides a range of conditions to evaluate the influence of environmental characteristics on vulnerability to dry periods. Cultural diversity--from sedentary irrigation agriculturalists to newly arriving immigrants--suggests that the findings of this study may be broadly applicable to other culturally diverse regions and not limited by the subsistence strategies or vulnerabilities of a particular society. It is important to consider vulnerability to dry periods during the 13th through 15th centuries so that we can advance our understanding of the complex social issues occurring during this time.

This chapter is organized into four sections. First, I delineate the spatial boundaries of the study area and the watersheds therein that are an important analytical unit of this study. Second, I describe the climatic diversity within central Arizona and focus on aspects of this climate that are shared across the study area. Third, I describe the cultural and environmental diversity within the study area. Fourth, I discuss why the 1200 to 1450 period is an important period to consider vulnerability to dry periods.

Study Area and Scales of Analysis

The central Arizona study area (Figure 1, all shaded polygons) includes the low and hot Sonoran desert in the south, a transition zone north to the

Colorado Plateau, and the cooler and wetter high mountains of eastern Arizona (Fish and Nabhan 1991; Turner and Brown 1982; Whittlesey and Ciolek-Torrello 1997). Populations throughout the study area were widely distributed throughout this landscape along perennial rivers, intermittent streams, ephemeral washes, and among mountains and mesas distant from perennial rivers.

The shaded polygons in Figure 1 are the watersheds that comprise the study area. A watershed is an area of land that drains water, sediment, and dissolved materials to a common outlet at some point along a stream channel (Dunne and Leopold 1978). Watersheds are also referred to as drainage basins or catchment areas and they occur at multiple scales. I identify the smallest watershed units ("cataloging units" or "sub-basins") identified by the U.S. Geological Survey (Seaber et al. 1987). Watersheds are a common spatial unit of analysis for archaeologists focused on central Arizona prehistory because these watersheds roughly correspond to differences in the material indicators used to infer cultural identity (as illustrated later in this chapter). Watersheds also delineate a reasonable spatial boundary that may approximate actual resource acquisition zones.

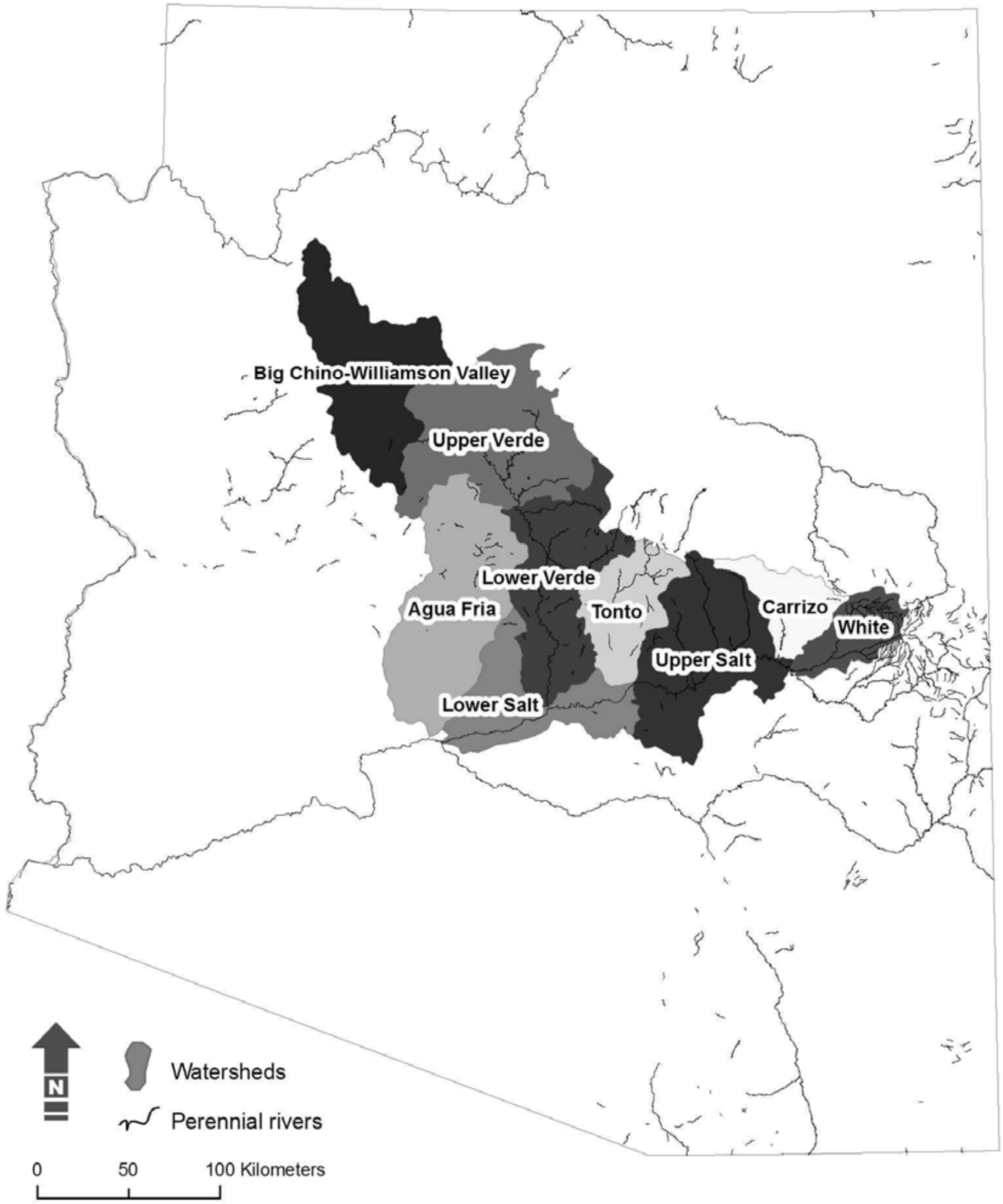


Figure 4.1. Study area watersheds within central Arizona identified with shaded polygons.

The primary unit of analysis of this study is settlement-scale residential abandonment examined at the watershed scale and at the scale of the entire central Arizona study area. The "central Arizona” scale includes the nine identified watersheds in Figure 4.1: Agua Fria, Big Chino-Williamson Valley, Carrizo, Lower Verde, Lower Salt, Tonto, Upper Salt, and Upper Verde, and White watersheds. I selected these watersheds for study because there have been thorough and targeted efforts to compile records of all identified settlements in these areas (Wilcox et al. 2001a, 2001b, 2003) and dry periods in these watersheds can be effectively identified by available tree-ring precipitation reconstructions (as discussed in Chapter Five). I evaluate the models, when possible, at the watershed scale as this allows each model to be tested in multiple locations. If the relationship between dry-period severity and residential abandonment differs among watersheds, then differences in watershed characteristics are examined to understand factors that may have contributed to differences in relationships (discussed further in Chapter Five).

I use the central Arizona scale to evaluate a few aspects of the models. For example, settlements in the Agua Fria watershed were located only in areas of low and moderate precipitation while settlements in the Upper Salt were located only in areas of moderate and high precipitation. Thus, neither watershed offers a comprehensive opportunity to evaluate the influence of precipitation levels on vulnerability to dry periods. When watersheds are aggregated at the central Arizona scale, however, problems of low numbers of settlements in particular classifications are avoided.

I focus this analysis on the Agua Fria, Lower Verde, Lower Salt, Tonto, Upper Salt, and Upper Verde because each of these watersheds has a long-term settlement history and sufficient numbers of settlements to represent a range of demographic and environmental conditions necessary to evaluate the vulnerability models. I exclude the Big Chino-Williamson Valley, Carrizo, and White watersheds from the watershed-scale analysis due to low settlement and/or room numbers and the limited duration of occupation in these watersheds. Settlements within these watersheds are, however, included in the all-central-Arizona scale analyses.

Climatic Diversity

The climatic diversity of central Arizona provides a range of environmental conditions to evaluate models of vulnerability to dry periods. I use this diversity to identify differences in potential productivity among settlements and watersheds and to evaluate models of vulnerability to dry periods that emphasize these differences to explain spatial variation in vulnerability to dry periods (as discussed in Chapter Five and in the Supply models). I focus exclusively on precipitation and streamflow conditions because water is the primary limiting factor on resource productivity in the region (Muenchrath and Salvador 1995). The precipitation and streamflow levels and ranges noted in this section are all modern average annual values calculated from historical climate records (United States Geological Survey 2010; Western Regional Climate Center (2010). Modern long-term precipitation averages are appropriate for characterizing average precipitation levels during the 1200 to 1450 period because the atmospheric and physiographic controls on Southwest climate have not changed since the period of study (Sheppard et al. 2002). Studies of pollen, plant and animal distributions, geology (Schoenwetter 1962), and the tree-growth response to climate over time also demonstrate that there has been no change in the type of climate prevalent for at least the past 2,000 years (Dean and Robinson 1982). [It is important to understand that I use modern climate data with relatively fine spatial resolution to characterize settlement-scale potential resource productivity and tree-ring precipitation reconstructions to identify central Arizona scale dry periods during the 1200 to 1450 period. These data are thoroughly discussed in Chapter Five.]

Precipitation levels varied among settlements and watersheds based largely on differences in elevation, topography, and location. Settlements during the period of study were located in areas that historically (ca. 1900 to 2000) receive an annual average of 8" to 35"of precipitation (Western Regional Climate Center 2010). Figure 4.2 displays the average annual precipitation levels of settlement locations within each watershed. In general, higher elevations receive more precipitation than lower elevations. While these spatial differences in precipitation levels are relatively constant, year-to-year changes in regional-scale precipitation levels will occur that change the absolute levels received at each location. That is, if a dry-period decreases precipitation across the region, the relative rank-ordering of settlements by precipitation levels will remain constant (I demonstrate this spatial consistency in Chapter Five). This is because the absolute precipitation levels are controlled by hemispheric atmospheric circulation patterns and will not vary substantially within the study area (McPhee 2004). The implication of the synchronicity is, if people used population movement from areas of lesser to greater productivity to manage dry-period shortfall risks, then these movements were likely between areas of inherently different productivity rather than to areas with a short-lived anomalous precipitation advantage. I use locations near and far from perennial rivers and areas receiving on-average low, moderate, and high precipitation as indicators of inherently greater or lesser inherent productivity.

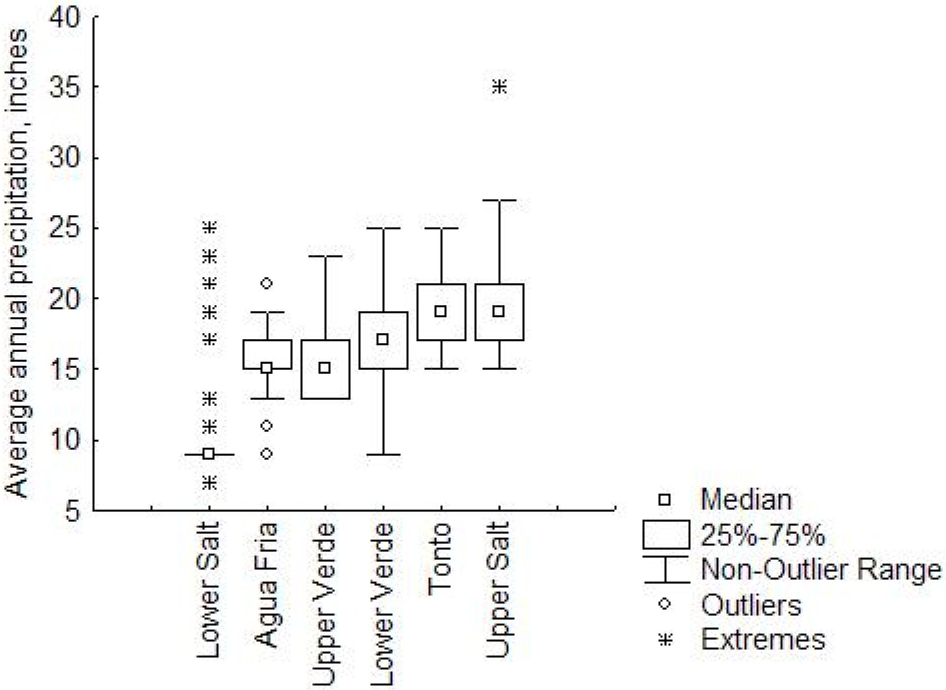


Figure 4.2. Average annual precipitation levels of central Arizona settlements occupied from 1200 to 1450, by watershed. Precipitation values of settlement locations calculated by combining a spatial layer of historical climate information (PRISM Climate Group 2007) with a spatial layer of settlement locations (Coalescent Communities Database, Wilcox et al. 2003).

Streamflow discharge levels also varied substantially throughout the study area (Table 4.1). Precipitation levels are a reasonable indicator of relative changes in these discharges because the source flows are entirely within the study area watersheds. The watershed of the Lower Salt River, however, extends outside of the study area and into northern and eastern Arizona. As a result, its flows will sometimes be out-of-sync with local precipitation patterns within the rest of the study area. Perennial rivers in the region trend north to south beginning in the high elevation mountain and plateau country then join the east to west flowing Lower Salt River in the Sonoran Desert. All rivers are subject to short and intense flooding possibly with changes in channel morphology (Graf 1988; Graybill et al. 2006; Nials et al. 1989). In addition to the irrigation potential of some perennial rivers, riparian vegetation adjacent to each river was probably an important source of food (Fish and Nabhan 1991).

Table 4.1. Annual Streamflow Discharge Levels Calculated from Historic Climate Records (Arizona Department of Water Resources 2010).

River, Stream	Annual Flow/Year (in acre-feet)				Years of Annual Flow Record
	Minimum	Median	Mean	Maximum	
Agua Fria (near Mayer)	976	9,197	16,327	103,555	63
Tonto Creek (above Gun Creek near Roosevelt)	2,853	66,297	113,232	469,256	62
Upper Verde (near Clarkdale)	54,529	104,279	128,062	458,393	40
Lower Verde (below Tangle Creek, above Horseshoe Dam)	131,073	294,733	409,875	1,583,014	57
Upper Salt (near Chrysotile)	128,176	393,581	474,817	1,456,907	78
Lower Salt (near Roosevelt)	152,798	518,499	644,942	2,422,315	89

Note: Salt River discharge levels in the settled portion of the Lower Salt River watershed are higher than identified here because the Verde River and Tonto Creek flow into the Salt above the settled area. The Salt River gage used for this figure is located above the confluence of the Salt, Verde, Tonto, and Agua Fria.

Although people lived in locations with widely different precipitation and streamflow levels, all watersheds shared a common biseasonal precipitation pattern. This biseasonal pattern allows for a greater structural diversity of the flora than in other North American deserts (Brown 1994:182). The wettest periods are winter (November through April) and summer (July through September) (Sellers and Hill 1974; Sheppard et al. 2002). Winter precipitation is strongly affected by westerly storm tracks originating over the Pacific Ocean.

Summer precipitation is the product of moisture from several oceanic sources moving into the region in July. Summer convective storms occur when local conditions cause these moist air masses to ascend (Sheppard et al. 2002). The proximity of Arizona to the Pacific Ocean, the Gulf of California, and the Gulf of Mexico also subject the region to atmospheric processes affected by changes in sea surface temperatures (i.e., El Nino, La Nina, Pacific Decadal Oscillation). The result of these complex processes interacting with the diverse topography of the region is high intra-annual and inter-annual precipitation variability. It seems likely that this variability challenged the successful scheduling of crop planting and made harvest success continually uncertain throughout the region (e.g., Dean 1988, 1996; Van West and Dean 2000).

Temperatures across the study area are, like precipitation, mostly a function of differences in elevation, topography, and location. In general, temperatures decrease with increasing elevation. Maximums are mid-summer and minimums are mid-winter. Temperature variations affect resource productivity by influencing water requirements of plants, growing season durations, and the timing and magnitude of snow-fed stream discharges relied on for irrigated agriculture. Throughout the study area the frost-free period exceeds 120 days, the approximate length of time necessary for a successful maize harvest (Muenchrath and Salvador 1995). I do not consider temperature variation in this study.

Archaeologically focused studies of climatic influences on human behavior in central Arizona have been dominated by a focus on changes in annual streamflow discharge volumes along the Lower Salt River (Graybill 1989;

Graybill et al. 2006; Nials 1989), the Verde River (Van West and Altshcul 1997), and Tonto Creeks (Waters 1998; 2006). Only two studies have considered precipitation changes. Rose (1994) reconstructed Palmer Drought Severity Indices for Climate Divisions 3, 4, and 6, which cover the central Arizona study area. His retrodictions stop in A.D. 1370 as the data were not available at the time for further retrodiction. Weaver (1972) used precipitation and environmental reconstructions developed for the Black Mesa area of northern Arizona to articulate a model of Hohokam collapse that relied on decreases in effective moisture beginning in the 1200s. Neither of these studies examined long-term patterns of population movement in relation to changes in dry-period severity. Regional-scale patterns have not emerged from these studies and there is no empirically driven consensus on the impact of climate extremes on population movement in central Arizona.

Cultural and Environmental Diversity

Archaeologically defined cultural traditions referred to as Hohokam, Salado, Mogollon, Sinagua, and ancestral Puebloan have been identified within the study area and throughout prehistoric Arizona (Cordell 1997; Reid and Whittlesey 1997). Distinct boundaries separating these traditions, however, did not exist and most material assemblages from particular locations share a number of common traits. As a result, archaeologists typically conceptualize the region by watersheds and associated river valleys. These watersheds contain roughly similar constellations of material indicators used to identify the cultural traditions of the region. This suggests that these watersheds, and particularly the perennial rivers that define them, may have been socially meaningful. I follow this watershed-scale approach in this selective summary of these traditions, some of their material indicators, and culture-historical events. I also note some specific environmental and climatic characteristics that distinguish each watershed.

Lower Salt Watershed

The Lower Salt River watershed was home to the "Hohokam" tradition for more than a thousand years (Bayman 2001; Crown and Judge 1991; Doyel 1987; Doyel et al. 2000; Gumerman 1991). People of this tradition transformed their hot and dry Sonoran Desert homeland into the "most populous and agriculturally productive valley in the [U.S.] West before 1500 CE" (Fish and Fish 2007:1). This transformation was the result of the development of large-scale irrigation systems and effective social strategies for managing these systems (Howard 1993; Howard 2006). Eight canal networks with separate intakes off of the Lower Salt River have been identified (Howard 1993). During the period of this study, these networks irrigated about 100,000 acres (Howard 1993:296) of maize, beans, squash, and cotton (Gasser and Kwiatkowski 1991). Residential stability, likely due to these extensive canal systems, was greater in the Hohokam area than in other parts of the U.S. Southwest (Dean et al. 1994:70).

In addition to irrigation agriculture, characteristic Hohokam cultural features 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 (Gumerman 1991). Many of these features are thought to signal

Mesoamerican origins or influences (McGuire et al. 1994; McGuire and Villalpando 2007). The extent of influence of the Hohokam tradition throughout the study area during the period of interest varied over time and is a matter of continuing inquiry (Van West and Altschul 1997:391-392; Whittlesey 1997b).

The 13th through 15th centuries, identified by archaeologists as the Classic Period, is characterized by significant sociocultural changes in the Lower Salt watershed. Following a retraction of the Hohokam interaction sphere in the 1100s, the people of the Lower Salt River valley developed new forms of residential and public architecture, modified existing mortuary practices, and developed new pottery styles and ceremonial objects, and severely restricted the extent of exchange relationships throughout the watershed (Abbott et al. 2003:8; Bayman 2001:280-283 and references contained therein). The transformation of a previously diffuse distribution of settlements across the watershed to walled, multi-family compounds after about 1100 suggests a more exclusionary pattern had developed (Fish 1989:50-51). The development of walled platform mounds placed at regular spatial intervals within the watershed also suggests increasing hierarchical social organization (Fish 1989:50-51). Sometime during the 15th century, the archaeological visibility of Hohokam (Dean 1991) and the other cultural traditions of central Arizona cease.

Based on retrodicted annual streamflow discharge volumes from tree-rings and analogies with historic irrigators in the watershed, Graybill et al. (2006) and Nials et al. (1989) have argued that catastrophic floods and associated geomorphic channel changes during the late 1300s contributed to settlement and population changes and ultimately the depopulation of the lower Salt River valley after A.D. 1400. Abbott and colleagues (Abbott 2003 ed.), however, develop a strong case for a change in Hohokam society around 1100 that initiated a gradual decline in sociopolitical conditions that ultimately led to the depopulation. Studies of dry-period impacts in the watershed have been limited to my (Ingram 2008) analysis of the relationship between droughts and changes in population growth rates in the most well documented canal system in the valley. I found that as dry periods increased in severity, population growth rates increased during a 700 year period. This relationship suggests that the Lower Salt may have been a refuge for people moving away from other areas.

The Lower Salt watershed is in the northern portion of the Sonoran Desert, a vast arid region that extends south and west into Mexico and California. The Sonoran Desert is classified as a "tropical-subtropical desertland" climatic zone (Brown 1994) similar to the Kalahari Desert of southern Africa, the Namib Desert of Saudi Arabia, and the Patagonian Desert of South America. Fish (1989:22) characterizes the Sonoran desert as "one of the major food-rich areas for a gathering economy in North America." The desert is within the Basin and Range physiographic province and consists of north-south trending faulted mountains and flat valley floors (Fenneman 1931). Precipitation, temperature, and streamflow conditions in the Lower Salt are more extreme than throughout the rest of the study area. Precipitation along the Lower Salt where settlement was concentrated is the lowest among all the watersheds--8.37" annually. Temperatures are high with daytime-high averages over 100 F during the summer

(Western Regional Climate Center 2010).

Agua Fria Watershed

Peoples living in the northern portion of the Agua Fria watershed have been difficult to assign to traditional Southwestern cultural traditions. Instead, they are sometimes referred to as the "Central Arizona tradition" (see Wilcox and Holmlund 2007:122, note 23, for a discussion of the possible origins of this concept) or "Perry Mesa tradition" (Stone 2000). Puebloan-style architecture and decorated ceramics in the northern portion of the watershed suggests residents were not closely affiliated with the Hohokam tradition. Perry Mesa is the locus of settlement in the watershed during the period of study and settlement patterns on and around the mesa are an integral part of the Verde Confederacy model, a prominent case study of endemic warfare and alliance formation in the late prehistoric Southwest (Wilcox 2005; Wilcox et al. 2001b). Further south along the intermittent Agua Fria River, the watershed is sparsely populated after 1300 and the people there were probably most strongly affiliated with the Hohokam of the Lower Salt River watershed.

The Agua Fria watershed is a transition zone that begins with the Sonoran Desert in the south and ends with high mesas covered with grasslands cut by canyons in the north. Settlements in the northern portion of the watershed were located in areas receiving an average of 15" to 17" of precipitation annually, twice as much as those living in the Lower Salt. Settlement patterns in the watershed include hill-top sites, dispersed small sites near field systems, and settlements on mesas (Wilcox et al. 2001a, 2001b). The Agua Fria watershed is distinct among the watersheds considered in this study because is has the least extensive perennial riverine resources. The Agua Fria River and its tributaries are perennial in only a few places.

Upper and Lower Verde Watersheds

The peoples of the Upper Verde watershed are archaeological known as the "Sinagua" (Colton 1939; Plog 1989). Material correlates include Alameda Brown Ware, paddle-and-anvil ceramic techniques, extended inhumation, alcove houses, deep pit houses, and masonry pueblos and cliff dwellings. Colton (1946) argued that the Sinagua were influenced by Mogollon, Hohokam, and Pueblo people who were drawn to the Flagstaff area after the eruption of the Sunset Volcano. Although the current status of Colton's concept of a distinct culture is unclear (Plog 1989:264), research supports the diversity and variety of influences in the area. Schroeder (1957, 1979) interprets the diverse material patterns of the upper Agua Fria, Verde, and Tonto watersheds as part of a single "Hakataya" culture. The Upper Verde includes the well-known archaeological sites (cliff dwellings) of Montezuma's Castle and Tuzigoot, both national monuments.

In the Lower Verde watershed, ceramics, architecture, and other material traits are diverse but share similar patterns with the Sinagua of the Upper Verde (Pilles 1976; Whittlesey 1997a). The Lower Verde watershed also has strong evidence of Hohokam influence and is often considered a part of the Hohokam periphery (Whittlesey and Ciolek-Torrello 1997). The Lower Verde is culturally similar to the Tonto Basin (Pilles 1976). Settlements in the watershed are mostly located along river terraces, alluvial fans, and along tributaries of the Verde.

There is evidence of prehistoric irrigation along the Verde although much of the valley is too steep and narrow for extensive irrigation (Van West and Altschul 1997; Whittlesey and Ciolek-Torrello 1997). Roughly separating the Upper from the Lower Verde watersheds is the Verde Valley, the greatest extent of arable land and biotic diversity in the watershed (Whittlesey 1997a).

Settlement patterns in the Verde watersheds, like those in the northern portion of the Agua Fria, are thought to be strongly influenced by the intentional creation of defensive clusters of settlements and buffer zones. A "Verde Confederacy" is argued to have existed that united Perry Mesa residents with residents of the Upper and middle Verde against populations located in the Tonto Basin (Wilcox et al. 2001b). In this model, the depopulation of the Lower Verde in the 12th century is thought to be the result of the intentional creation of a buffer zone against enemies in the Lower Salt or Tonto watersheds (Wilcox et al. 2001b).

The Lower and Upper Verde River watersheds are a mountainous transition zone between the Sonoran Desert in the south and the Colorado Plateau in the north. Unlike the wide and flat expanse of land along the Lower Salt River, the Verde River is constricted by a narrow valley throughout much of its length. The Verde River is one of the largest perennial rivers in Arizona (USGS 2010) and would have provided a reliable water supply for prehistoric irrigators. Settlements in the Lower Verde were located in areas receiving 9" to 23" inches of precipitation annually (Western Regional Climate Center 2010). Settlements in the Upper Verde received between 13" and 23" annually. Vegetation is dense along the floodplains and the river is bordered by a rich riparian zone. Plant communities in the watershed include semi-desert Grassland, Great Basin Conifer Woodland, and Sonoran Desertscrub (U.S. Fish and Wildlife Service 2010).

Tonto

The Tonto watershed and portions of the Upper Salt watersheds are considered "Salado" (Dean 2000). The material correlates of this pattern, particularly polychrome pottery, extend into western New Mexico and elsewhere in the Southwest (Crown 1994, 1995). Debate continues on the distinctiveness of a Salado culture or whether the traits are more of a "horizon" of styles shared by an amalgamation of peoples of varying backgrounds (e.g., Dean 2000; Doyel 1981; Rice 1998). In addition to polychrome pottery, some of these traits include walled residential compounds, monumental architecture, and in some cases irrigated agriculture. In the Tonto watershed, existing populations were strongly influenced by an influx of migrants during the late 13th century (Stark et al. 1995). These migrants, probably pushed by social and environmental changes in the north (Van West et al. 2000), formed multi-ethnic communities that ultimately proved relatively short lived. The watershed experienced substantial population loss in the mid to late 14th century, perhaps due to regional-scale changes in precipitation variability and more attractive social conditions elsewhere (Van West et al. 2000). The Tonto watershed was the first to be depopulated among the watersheds I focus on in this study.

The Tonto watershed is a transition zone from the Sonoran desert in the south to the mid-elevation mountains and uplands of the northern portion of the watershed. Vegetation ranges from Saguaro cactus to pine-forested mountains. Whittlesey et al. (2000:242) argue that a diversity of resources in the watershed created an island of resource advantage that attracted people of different ethnic and cultural traditions to the basin. The Tonto Creek is mostly perennial through the watershed and settlements were located in areas receiving from 15" to 25" of precipitation annually (Western Regional Climate Data Center 2010).

Upper Salt

The Upper Salt River watershed included people archaeologically referred to as Mogollon and Salado. Both traditions in the watershed were influenced by ancestral Puebloan (Anasazi) and Hohokam cultural traditions (Cordell 1997). Mogollon traits are widely distributed throughout the watershed and Salado characteristics are mostly along the Salt River in the southwestern portion of the watershed. The Mogollon, while sharing many similar characteristics with ancestral Puebloan (Anasazi) populations, maintained distinctive methods of pottery manufacture, architectural construction, residence location, and mortuary treatment (Cordell 1997; Haury 1936; Reid and Whittlesey 1997). Subsistence systems were initially focused on the use of wild plants and animals and the cultivation of small garden plots of corn, beans, and squash although an increasingly sedentary and agriculturally focused lifestyle developed during the period of study.

During the late 1200s and early 1300s, people living in the Upper Salt became increasing influenced by ancestral Puebloan immigrants fleeing the effects of deteriorating conditions in the northern Southwest (Reid and Whittlesey

1997). These immigrants substantially increased population levels and density in the watershed. Rapid population growth in the watershed has also been attributed to increases in opportunities for inter-community exchange (Graves et al. 1982). Rising social and economic tensions in the 1300s, as in other areas of the Southwest, are suggested by the selection of defensible locations for major and minor settlements and the use of cliff shelters for secure food storage (Reid and Whittlesey 1997:164). Following a period of population aggregation, population decline began sometime in the mid to late 1300s. Based on detailed study at a large pueblo in the watershed (Grasshopper), these declines may have been caused by dry-period decreases in resource productivity, increased population, reduced soil fertility, and depleted resources (Reid et al. 2006; Reid and Whittlesey 1997:164). Factors that may have influenced the decline of Salado populations include rising population levels in the context of climatic conditions unfavorable for irrigated agriculture (Waters 2006). Archaeological visibility of human occupation of the watershed ceases sometime during the early 1400s.

The Upper Salt River watershed is a mountainous environment characterized by extreme changes in elevation. Settlements occupied during the period of study are located between 2,000 and 7,000 feet in elevation. Average annual precipitation received at settlement locations ranges from 15" to 35" and the watershed average is about 18.7", greater than any other populated watershed in Arizona (Western Regional Climate Center 2010). Perennial rivers include the Salt with three tributaries (Cherry Creek, Canyon Creek, and Cibecue). Based on my GIS analysis of the slopes of land throughout the watershed, opportunities for floodplain and/or irrigated farming were probably restricted and minimal in most places except along the Salt River near the western edge of the watershed (slopes of between 0 and 5% are considered optimal for irrigation; Walker 1989). Assessing opportunities for floodplain and irrigated farming along perennial rivers of the watershed, however, requires further on-site evaluation.

Contributions to the Prehistory of Central Arizona

It is important to consider vulnerability to dry periods during the 13th through 15th centuries so that we can advance our understanding of the complex social issues occurring during this time. These issues include rising warfare and the 15th century regional depopulation. Each involves population movement on a large scale and over long-time periods. Models of increasing conflict and warfare explain movements out of particular places on the landscape as defensive responses to the real or perceived threat of violence (LeBlanc and Rice 2001). When settled areas are abandoned and unoccupied zones around clusters of settlements are observed, these patterns are interpreted as an effort to create defensive open spaces between socially distant peoples (DeBoer 1981; LeBlanc 1999; Wilcox et al. 2001b; Wilcox and Haas 1994). Models of regional depopulation need to explain large-scale population movements out of a region (unless in situ demographic decline is argued, e.g., Hill et al. 2004). Our current understanding of the process in central Arizona is limited to rising warfare (Wilcox et al. 2001b), demographic decline associated with community coalescence (Hill et al. 2004), and general notions of breaches in regional carrying capacity (e.g., LeBlanc 1999, 2006). Along the Lower Salt River, a prevailing depopulation hypothesis is technological and social challenges to irrigated agriculture related to streamflow variability, flooding, and channel change in the late 1300s (Graybill et al. 2006; Nials et al. 1989). In contrast to environmentally focused hypotheses, Abbott and colleagues (Abbott 2003 ed.) have made a strong case for a gradual, centuries-long decline of populations along the Lower Salt. Causes for this decline are complex and include demographic instability, truncated trade networks, political strife, environmental impacts and ultimately ineffective responses to these challenges (Abbott 2003).

Advancing our understanding of both warfare and depopulation in central Arizona requires a better understanding of the factors influencing population movements. This study focuses on a frequently considered explanation for population movement--dry periods--and asks whether or not and under what conditions there is long-term evidence that dry periods were related to population movements out of settlements and watersheds in central Arizona. If dry-period influences on movements are detected over long time periods, then explanations of warfare and depopulation must accommodate climatic contributions to these phenomena. It should not be sufficient that we gloss climatic influences as simply context in explanations of the major events during this period in prehistory. For example, Wilcox et al. (2001b:165) argue the role of conflict in the depopulation of central Arizona and suggest that "Environmental perturbations could have further exacerbated such a process." No further suggestions of what these perturbations might be were provided. I am not suggesting dry periods as the sole cause of any social phenomenon. Rather, I am suggesting that if population movements constitute an integral part of a social phenomenon being explained and if these movements are strongly related dry periods, then explanations that do not consider potential dry-period impacts on movement are incomplete.

In sum, the cultural, environmental, and climatic diversity of central Arizona during the 13th through 15th centuries provide an important context for evaluating models of vulnerability to dry periods and furthering our understanding of dry-period influences on population movement. Population movements were an integral part of some of the critical social issues of this period. At the conclusion of this study (Chapter Ten), I discuss the implications of the findings of this research for understanding both the depopulation and models of increasing warfare in the region.

CHAPTER 5:

DATA AND METHODS

Evaluation of the vulnerability models requires data on demography, environment, dry periods, and residential abandonment. I use these data to evaluate the vulnerability models by examining the extent to which each model's expectations are supported by patterns of residential abandonment in the study area. The data sets and variables include:

1. Demography: Demographic variables emphasized in vulnerability models include settlement population levels and watershed population density (Demand model and Demand/Supply model). I use both variables to identify differences in the demand for resources throughout the study area. I identify demographic conditions using settlement data in the Coalescent Communities Database (Wilcox et al. 2003).
2. Environment: Environmental variables emphasized in the vulnerability models include settlement locations near and far from perennial rivers and differences in precipitation levels among settlements (Supply model and Demand/Supply model). I use these variables to identify differences in potential resource supplies among settlements. I identify these conditions using a geographic information system to overlay a dataset of perennial river locations and modern precipitation contours on a map of all settlements in the study area. I also use average precipitation and streamflow discharge levels in each watershed to identify watershed-scale differences in potential resource supplies. I use modern streamflow records to quantify differences in

streamflow discharge levels.

3. Dry periods: I use paleoclimatic reconstructions of annual precipitation and streamflow levels from tree-rings to identify dry periods.
4. Residential abandonment: I identify residential abandonment from reductions in the number of settlements and rooms using settlement data from the Coalescent Communities Database (Wilcox et al. 2003). I use the long-term relationship between dry-period severity and residential abandonment and associated movement from settlements and watersheds as an indicator of potential vulnerability to dry periods.

In this chapter, I describe each of these data sets and my methods of calculating or identifying the variables. I summarize the data, variables, their spatial and temporal resolution, and sources in Table 5.1. I conclude the chapter by explaining how I assess the relationship between dry-period severity and residential abandonment. I also provide an example of the analytical methods.

Table 5.1. Summary of Data, Variables, Spatial and Temporal Resolution, and Sources.

Data Type	Variables	Spatial Resolution	Temporal Resolution	Sources
Demography	settlement population levels	settlement	five 50-year intervals, 1200 to 1450	calculated from Coalescent Communities Database, Wilcox et al. (2003)
	watershed population density	six watersheds in central Arizona study area	five 50-year intervals, 1200 to 1450 (averaged)	
Environment	settlement proximity to perennial rivers	settlements near (less than two kilometers) or far (more than two kilometers) from a perennial river	250 years (assumed to be constant from 1200 to 1450)	spatial dataset from The Nature Conservancy of Arizona (2006)
	settlement area precipitation levels	settlement and watershed, 2" precipitation intervals	250 years (assumed to be constant from 1200 to 1450)	PRISM, Oregon State University (2007)
	streamflow discharge levels	by watershed, ranked lowest to highest	250 years (assumed to be constant from 1200 to 1450)	United States Geological Survey (2010)

Data Type	Variables	Spatial Resolution	Temporal Resolution	Sources
Dry periods	identified from a regional-scale tree-ring precipitation reconstruction	central and northern Arizona including all study area watersheds except the Lower Salt River watershed	annual data summarized by 50-year intervals to match resolution of data identifying residential abandonment	San Francisco Peaks precipitation reconstruction, Salzer and Kipfmueller (2005)
	identified from a tree-ring streamflow reconstruction	only the Lower Salt River watershed	annual data summarized by 50-year intervals to match resolution of data identifying residential abandonment	Lower Salt River streamflow reconstruction, Graybill et al. (2006)
Residential abandonment	room and settlement abandonment	settlement (aggregated by watersheds and total study area)	five 50-year intervals, 1200 to 1450	identified using Coalescent Communities Database, Wilcox et al. (2003)

Demography: Indicators of the Scale of Resource Demands

I use the Coalescent Community Database to identify demographic conditions in the study area (Wilcox et al. 2003; see Wilcox et al. 2007 for a description of the development of the database). The demographic conditions I identify are settlement population levels and watershed population density (discussed further below). Sources of central Arizona settlement data in the Coalescent Communities Database include site file searches of major data repositories (Arizona State Museum [AZSITE], Arizona State University, Museum of Northern Arizona), literature reviews, national forests, and personal communications (Wilcox et al. 2001b:158, 162; Wilcox et al. 2007). The result is the most comprehensive source of settlement data available for the study area. The database has recently been employed in several studies with implications for the extent of warfare, alliances, and population decline in the U.S. Southwest (Hill et al. 2004; Wilcox et al. 2001a, 2001b; Wilcox et al. 2007). I follow Hill et al. (2004:693) and the Coalescent Communities Database authors (Wilcox et al. 2003) and consider only settlements with at least 13 rooms. Data on settlements with fewer than 13 rooms are less complete and reliable due to reduced surface visibility and detection. The A.D. 1200 start date for my study and the 50-year intervals (e.g., 1200 to 1249, etc.) used to identify residential abandonment are based on the strengths of the data and the realities of chronological resolution in the region (Hill et al. 2004). Documenting demographic changes at 50-year intervals is currently the best chronological resolution possible in most of the central Arizona study area (see also Dean 1991).

Limitations of the database, as with much archaeological settlement data, include unidentified rooms, poor chronological resolution, and differences in the quality and extent of archaeological survey and excavation in the study area. Interpretive challenges and inaccuracies are probably greatest with the settlement data from the Lower Salt River watershed (Phoenix basin). Urban developments on top of these settlements have prevented systematic survey and excavation. This especially challenges our ability to delineate settlement and community boundaries, population levels, and chronology in the Lower Salt (Howard 2006). Settlement data from Native American Indian community properties are also less complete. I rely on this database because, like Wilcox et al. (2007:169), "In the aggregate we [I] believe that a 'law of large numbers' applies from which we can make warranted inferences about general trends in the data revealed by the maps and their comparisons." These data are also the only regional-scale settlement data available for central Arizona. A regional-scale and long-term approach was required to identify trends in the data and eliminate the reliance on time-space coincidence that challenge other climate-human behavior studies. This spatially and temporally comprehensive approach should also diminish the impact of specific problems in the settlement data in particular places on the results of this analysis.

I infer settlement population levels from the total number of rooms identified in each settlement during each 50-year interval from 1200 to 1450. From these room counts, I classify all settlements by differences in settlement population levels (low, moderate, or high). I use these classifications and “bin” the room data because it accommodates uncertainties in the actual room numbers. Actual room numbers are always in dispute because of chronological issues and many settlement room counts are estimates based on reliable but incomplete information (as just discussed above). Settlement room counts in central Arizona are identified in the database as constant throughout a settlement’s period of occupation, in most cases.

To classify settlements by population levels, I examine a histogram of the number of rooms in all settlements occupied in central Arizona from 1200 to 1450 (Figure 5.1). I separate the number of rooms per settlement into low, moderate, and high settlement population levels based on inspection of the histogram. I classify settlements with 30 or few rooms "low population" settlements, 31 to 100 rooms "moderate population" settlements, and more than 100 rooms as "high population" settlements. I developed a separate histogram of settlement population levels for the Lower Salt River watershed as settlement sizes there were substantially larger than in the rest of central Arizona (Figure 5.2). I use these classifications as an indicator of differences in resource demands, the rate of consumption of resources, and the extent of labor available to invest in strategies to manage the risk of shortfalls. With these classifications, I evaluate models of vulnerability that emphasize the contribution of settlement-scale resource demands to vulnerability to dry periods (the Demand model and the Demand and Supply model).

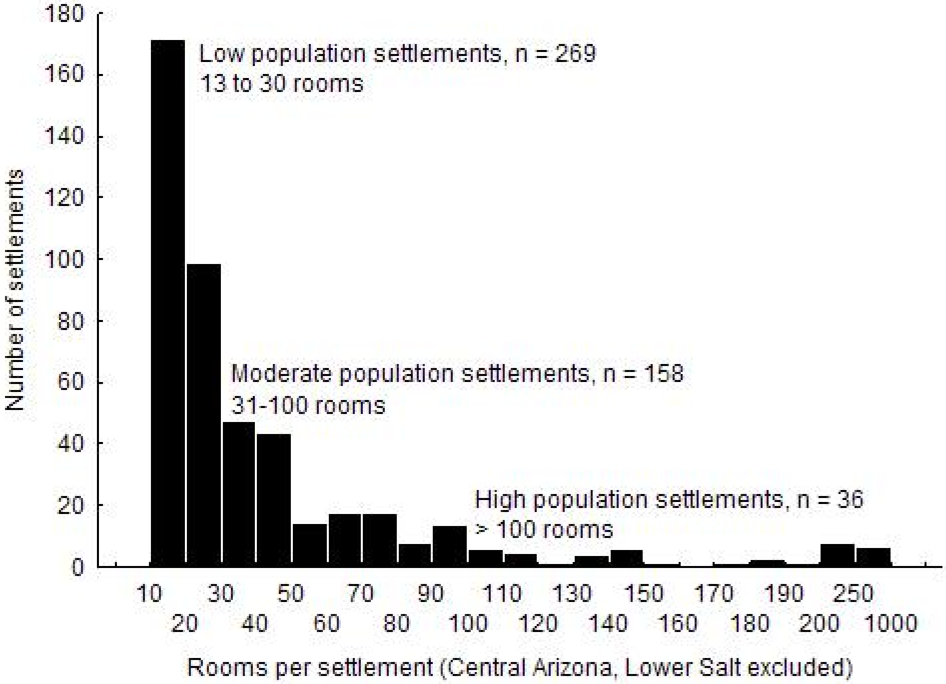


Figure 5.1 Histogram of settlement room counts in central Arizona (Lower Salt watershed excluded), 1200 to 1450.

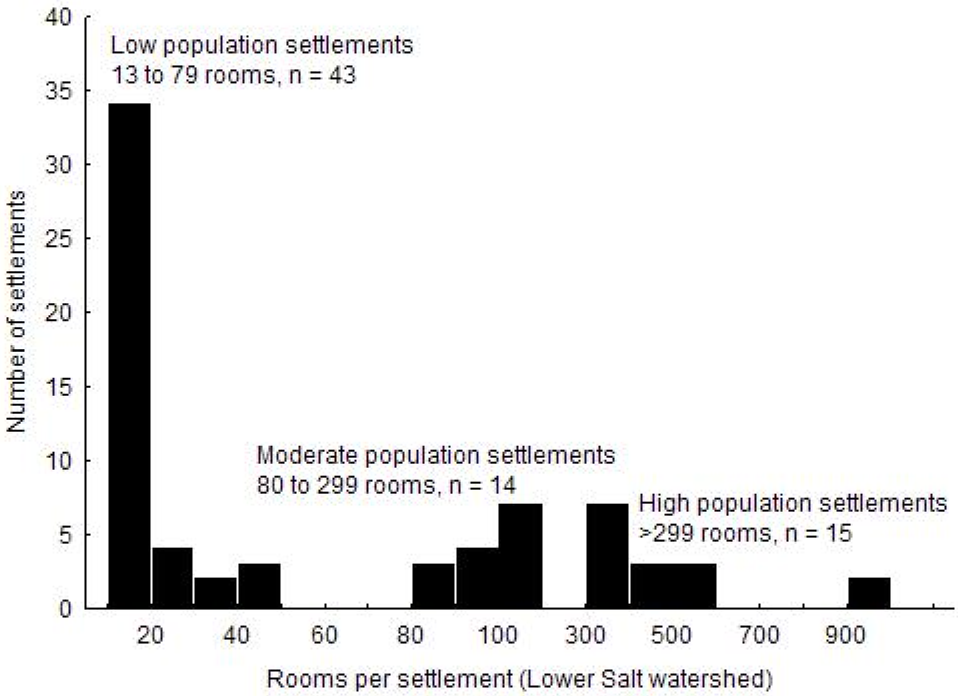


Figure 5.2. Histogram of settlement room counts in Lower Salt River watershed, 1200 to 1450.

To identify differences in watershed population density, I sum the number of rooms in each watershed during each of the 50-year intervals, and divide it by the number of square kilometers in the watershed (rooms per square kilometer) (Table 5.1). I then calculate the average population density of each watershed by summing the five density statistics from each watershed and dividing by five. Average watershed population density is a reasonable comparative measure of density because, although absolute density varies over time, relative density (i.e., each watershed's relative ranking) is mostly consistent over time. That is, density in the Upper Verde and Agua Fria watersheds was consistently lower than in the Lower Verde, Tonto, Upper Salt, and Lower Salt during the 250 year study period. For convenience in discussing differences in density, I classify each watershed as having low, high, or very high density. The cutoff between the designation of low and high density watersheds is based on the gap in density between the Agua Fria and Lower Verde watersheds (.19 and .37 rooms per square kilometer). This doubling of density is the largest gap in the distribution of density values among the watersheds (Figure 5.3), except the Lower Salt which is treated as a very high density outlier. With these classifications, I evaluate models of vulnerability that emphasize the contribution of watershed-scale resource demands to vulnerability to dry periods (the Demand model and the Demand and Supply model).

Table 5.2. Number of Rooms and Density (rooms/km^2) in All Central Arizona Watersheds.

Watershed	Size, Square Kilo-Meters	1200 to 1249		1250 to 1299		1300 to 1349		1350 to 1399		1400 to 1449		1200 to 1450 Average Density
		rooms	density	rooms	density	rooms	density	rooms	density	rooms	density	
Aqua Fria	6,355	787	.12	427	.07	1937	.30	1917	.30	860	.14	.19
Big Chino	5,640	102	.02									.02
Carrizo	1,786	165	.09	505	.28	555	.31	185	.10			.20
Lower Salt	3,442	6,317	1.84	7,121	2.07	8,126	2.36	6,888	2.00	486	.14	1.68
L. Verde	5,019	1,162	.23	1,764	.35	3,318	.66	2,750	.55	244	.05	.37
Tonto	2,694	1,601	.59	2,221	.82	1,444	.54	1,294	.48			.61
Upper Salt	5,612	2,081	.37	3,701	.66	4,922	.88	4,207	.75	361	.06	.54
Up. Verde	6,372	869	.14	1,115	.17	1,667	.26	1,507	.24	155	.02	.17
White	1,703	245	.14	430	.25	800	.47	800	.47			.33
TOTAL	38,623	13,329		17,284		22,769		19,548		2,106		

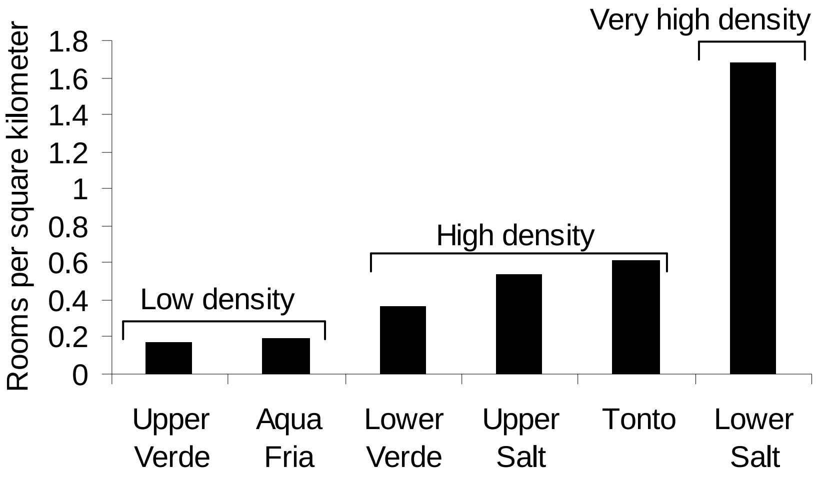


Figure 5.3. Average population density of focal watersheds.

Environment: Indicators of Differences in Potential Resource Supplies

I use both settlement and watershed-scale indicators of potential resources supplies in this study. At the settlement-scale, I identify each settlement's proximity to a perennial river and the average annual precipitation level the settlement location receives. At the watershed scale, I identify the weighted average annual precipitation level of all settlements in each watershed and identify the streamflow discharge level of each watershed's primary river. These indicators identify differences among settlements and watersheds in general or average water conditions supporting resource productivity. These differences are considered constant throughout the 1200 to 1450 period of study because the locations of perennial rivers and long-term, average annual precipitation levels have not substantially changed since the period of study. By identifying inherent differences in potential resource productivity (supply) among settlements and watersheds, I can examine the relationship between dry-period severity and residential abandonment under different resource conditions at two spatial scales. This effort allows conceptual models that emphasize the influence of differences in resource supplies on vulnerability to dry periods to be evaluated.

Proximity to Perennial Rivers

Data on the location of perennial rivers, and portions of perennial rivers, were developed by The Nature Conservancy (2006). The Conservancy's project synthesized and updated previous work and similar maps of perennial rivers developed by Brown et al. (1977, 1981) produced for the Arizona Game and Fish Department and the U.S. Forest Service, and Miller (1954). Although the Conservancy's study considered extensive historical resources, it is possible that diversions and ground water extractions decreased the extent of perennial resources with fewer perennial rivers identified now than there were in the past. However, perennial rivers identified in this study were certainly perennial in the past.

I consider settlements located within two kilometers of a perennial river (or a portion of a perennial river) to be "near" a perennial river. Those located more than two kilometers are considered "far" from perennial rivers. Two kilometers is an arbitrary cutoff but selected to accommodate changes in river channel positions over time and relatively easy walking distances. I also assumed that a strong reliance on irrigated agriculture, which I expect increased potential productivity, to be unlikely among settlements located more than two kilometers from a perennial river (except along the Lower Salt). Further efforts to identifying the potential for irrigated agriculture at each settlement would bring additional confidence but these efforts are beyond the scope of this study given the breadth of the spatial area considered in this analysis. I use two classifications (near and far) because the models I evaluate do not distinguish differences in vulnerability based on actual distances from perennial rivers. That is, the models do not expect vulnerability to dry periods to increase as distance from a perennial river increases. Differences are typically conceptualized as either/or: greater potential productivity near a perennial river and lesser potential productive far from a perennial river.

Using GIS analysis (ArcGIS 9.3), I identify each settlement's distance from the nearest perennial river with settlement location data from the Coalescent Communities Database (Wilcox et al. 2003). High proportions of rooms located both near and far from perennial rivers in the central Arizona study area (Figure 5.4) and in most watersheds (Figure 5.5) allow an effective examination of the influence of proximity to perennial rivers on vulnerability to dry periods.

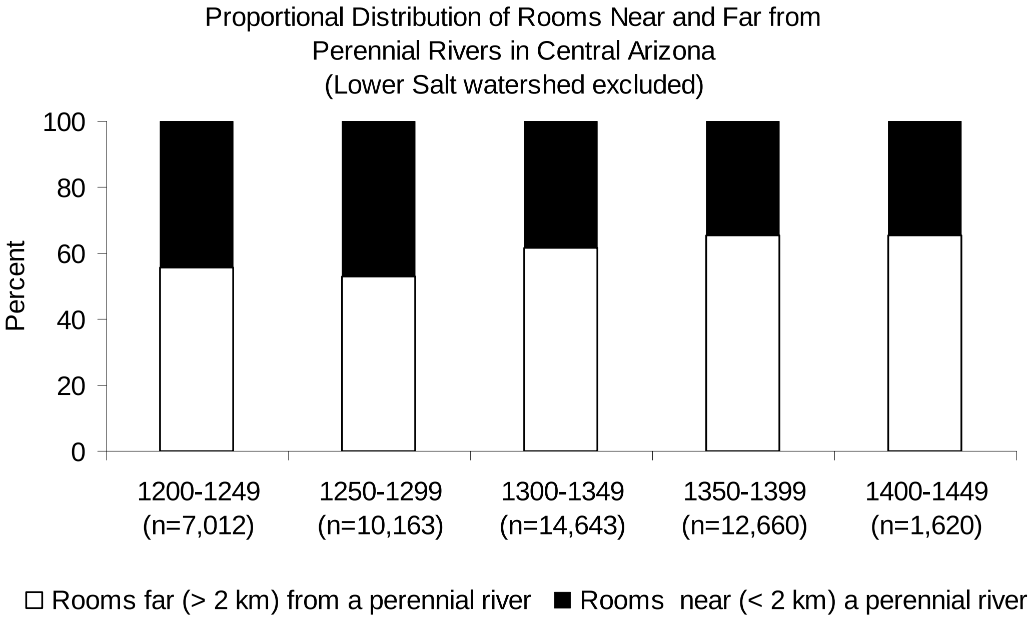


Figure 5.4. Proportional distribution of rooms near and far from perennial rivers.

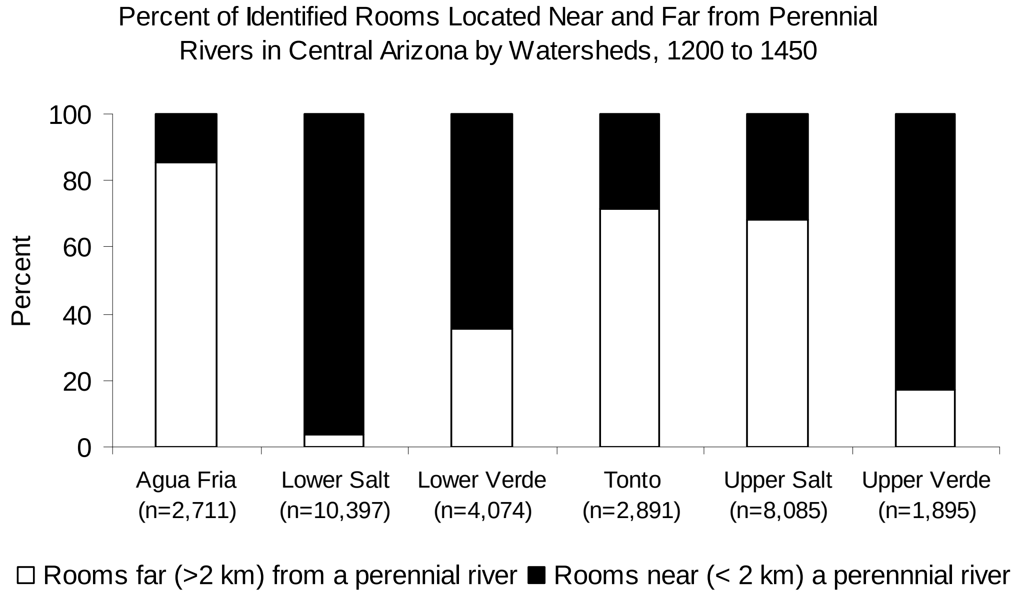


Figure 5.5. Proportional distribution of rooms near and far from perennial rivers by focal watersheds.

Streamflow Discharge Levels

To compare streamflow-related resource productivity among watersheds, I use the mean annual streamflow discharge level of each watershed's primary river calculated from modern discharge records (Arizona Department of Water Resources 2010; USGS 2010). The duration of each record varies by river but always exceeds 40 years. I rank discharge levels among the watersheds rather than use absolute values (acre feet/year) because differences in the absolute values are not necessarily a meaningful indicator of differences in the productive potential of perennial riverine areas. Unlike precipitation where moisture is stored in the soil and may be utilized by wild and cultivated plant foods over time, high annual discharge levels were likely not fully utilized by either irrigated agriculture or riparian plant communities. Ranking discharge levels from lowest to highest more effectively captures the intent of this analysis by identifying relative differences in water availability among the watersheds. In the evaluation of the supply models of vulnerability to dry periods (Chapter Eight) I use this ranking in combination with precipitation levels to approximate differences in potential water-related resource productivity among watersheds.

Table 5.3. Watersheds by Mean Annual Streamflow Discharge of the Watershed's Primary River.

Watershed	Mean Annual Flow/Year (in acre-feet)	
	discharge[1]	rank
Agua Fria	16,327	1
Tonto	113,232	2
Upper Verde	128,062	3
Lower Verde	409,875	4
Upper Salt	474,817	5
Lower Salt[2]	644,942	6

[1] Arizona Department of Water Resources (2010), United States Geological Survey (2010)

[2] Lower Salt River discharge levels in the settled portion of the Lower Salt River watershed are higher than identified here because the Verde River and Tonto Creek flow into the Salt above the settled area. The Salt River gage used for this figure is located above the confluence of the Salt, Verde, Tonto, and Agua Fria. See gage and other statistics: Chapter Four, Table 4.1.

Settlement Area Precipitation Levels

I use modern precipitation data to identify the average annual amount of precipitation received at each settlement's location. Tree-ring precipitation data cannot capture spatial differences in precipitation at the level of resolution of the site locale, which is needed for this analysis and which is possible with modern climate data. I use modern precipitation data from the PRISM Group, Oregon State University (2007), to identify average annual precipitation at each settlement location based on a 30-year climatic normal (Guttman 1989) from 1961 to 1990 (Figure 5.6). The PRISM (Parameter-elevation Regression on

Independent Slopes Model) climate mapping system incorporates instrumental point data, a digital elevation model, and expert knowledge of complex climatic extremes, including rain shadows and temperature inversions (Daly et al. 1994). PRISM data are recognized as the highest-quality climate data sets currently available and are the U. S. Department of Agriculture's official climatological data (PRISM 2010).

As also noted in the climatic description of the study area (Chapter Four), modern long-term precipitation averages are appropriate for characterizing average precipitation levels during the 1200 to 1450 period because the atmospheric and physiographic controls on Southwest climate have not changed since the period of study (Sheppard et al. 2002). Studies of pollen, plant and animal distributions, geology (Schoenwetter 1962), and the tree-growth response to climate over time also demonstrate that there has been no change in the type of climate prevalent in the Southwest for at least the past 2,000 years (Dean and Robinson 1982).

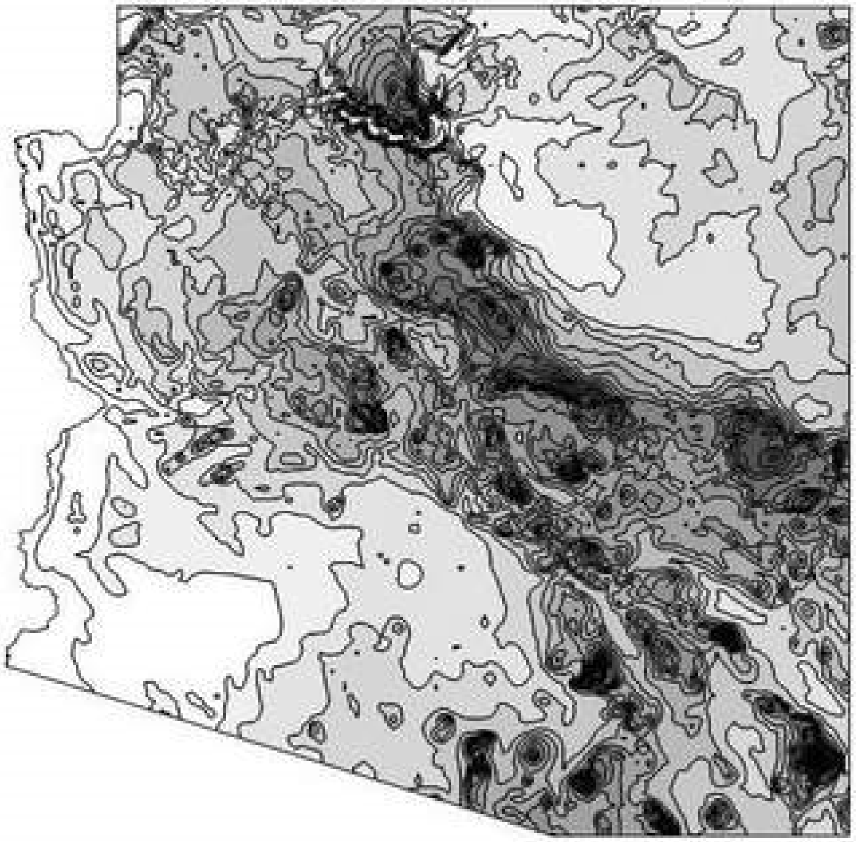


Figure 5.6. PRISM precipitation contours by 2” intervals. Lesser to greater precipitation represented with lighter to darker shading. Map produced using data from PRISM Climate Group, Oregon State University 2007, http://www.prismclimate.org.

Using GIS analysis and settlement location data from the Coalescent Communities Database (Wilcox et al. 2003), I identify the precipitation level of each settlement. I classify each settlement as receiving low (8" to 14"), moderate (14" to 22"), or high (22" to 36") average annual precipitation based on identifying breaks in a histogram of precipitation values of all settlements identified in central Arizona (Figure 5.7). I repeated this analysis using a histogram of rooms by precipitation levels and the same classification is supported.

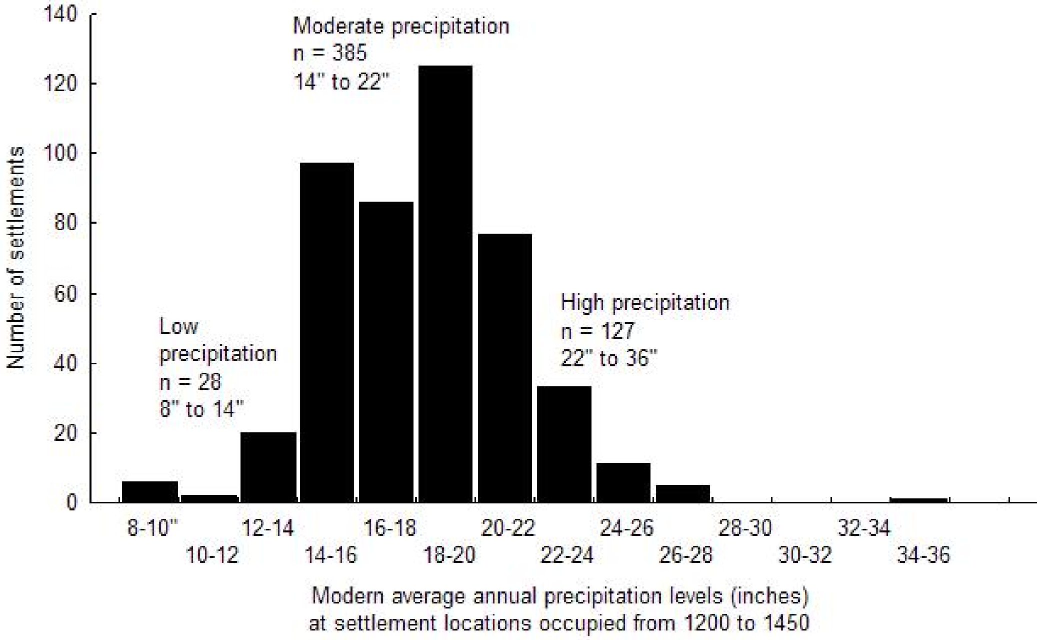


Figure 5.7. Histogram of settlements occupied in central Arizona from 1200 to 1450 by mean annual precipitation of settlement location. The Lower Salt River watershed is excluded from this histogram.

Watershed-Scale Precipitation Levels

To compare precipitation-related resource productivity among watersheds, I calculated the weighted average annual precipitation level of all settlements by watershed (Table 5.2). For each settlement, I multiplied the number of rooms by the average annual precipitation level of the settlement. I summed the products of these calculations and the number of rooms in all settlements. I divided the sum of the products by the sum of the rooms for a weighted annual average precipitation level of settlements in each watershed.

Table 5.4. Weighted Average Annual Precipitation by Watershed.

Watershed	Weighted Average Annual Precipitation of all Settlements Occupied 1200 to 1450
Lower Salt	9.3
Upper Verde	14.7
Agua Fria	16.4
Lower Verde	17.2
Tonto	18.5
Upper Salt	20.3

Dry Periods from 1200 to 1450

The climatic condition examined in this study is very dry conditions, thus, the key climate variables are low precipitation and streamflow. I do not refer to these dry conditions as "droughts". Drought is "a deficiency in precipitation over an extended period, usually a season or more, resulting in a water shortage causing adverse impacts on vegetation, animals, and/or people” (National Weather Service 2006:1). Although more than 150 definitions of drought have been identified (Wilhite and Glantz 1985), it is generally thought of as a condition of “insufficient water to meet needs” (Redmond 2002:1144). These definitions acknowledge the dynamic relationship between water supply and demand with decreases in supply and/or increases in demand contributing to adverse impacts and the occurrence of drought. In contrast, I use the term "dry-period" defined as a multi-year period of relatively low precipitation and streamflow. Dry periods cannot be assumed to be periods of "insufficient water to meet needs" because the climatic event alone does not demonstrate imbalances in water supply and demand. (See Smakhtin and Schipper 2008 for a discussion of problems and issues related to definitions and conceptual understanding of drought).

Climate Proxy Selection

I identify dry periods in the precipitation record of central Arizona using the San Francisco Peaks (SFP) tree-ring reconstruction of annual precipitation (previous October to current July) from A.D. 570 to 1988 (Salzer 2000a; Salzer and Kipfmueller 2005). The reconstruction was developed using both living tree and archaeological chronologies with standard procedures developed at the Laboratory of Tree-Ring Research at the University of Arizona (e.g., Fritts 1976, Rose et al. 1981). Three tree-ring chronologies were used in the San Francisco Peaks precipitation reconstruction: Flagstaff, Navajo Mountain, and Canyon de Chelly (Salzer 2000a:28). These chronologies were originally developed as a part of the Southwest Paleoclimate Project (Dean and Robinson 1978) and are comprised of archaeological and living tree specimens from elevations of approximately 1890 to 2290 meters in northern Arizona and southern Utah (Salzer 2000a:28). Combining chronologies typically strengthens the climate signal by increasing sample sizes and buffering the influence of non-climatic factors at individual sites (Salzer 2000a:28). Furthermore, "spatial networks of tree-ring chronologies usually explain more of the variance in a climate variable than a single chronology can" (Salzer 2000a:28 citing Cook et al. 1994; Meko et al. 1993).

I evaluate the suitability of the SFP reconstruction to represent precipitation conditions in the study area watersheds (except the Lower Salt, discussed below) by examining the strength of the statistical relationship between the reconstruction and modern meteorological stations in the study area. I use modern precipitation levels from previous October to current July (comparable to the SFP reconstruction) for Climate Divisions 3 and 4 to represent conditions in the study area (National Climatic Data Center 2008). Climate division averages are arithmetic means of monthly data from all climate stations within a given division that are thought to reflect the general characteristics of the division (Guttman and Quayle 1996). Precipitation averages are not available at the scale of individual watersheds. Climate Division 3 includes the western portion of the central Arizona study area (Agua Fria, Upper Verde, Big Chino-Williamson watersheds) and Climate Division 4 includes the eastern portion of the central Arizona study area (Lower Verde, Tonto Upper Salt, Carrizo, White watersheds). The correlation between the SFP reconstruction and modern precipitation in Climate Division 3 is r = .75 (Figure 5.8) and r = .72 for Climate Division 4 (Figure 5.9). High precipitation years are less accurately retrodicted by tree-ring proxy data because water is no longer the limiting factor. Low precipitation years (the focus of this study) are well represented by the reconstruction. The strength of these correlations reflects a high degree of spatial homogeneity in climate in the region even though the absolute precipitation values vary largely by elevation.

Differences between the SFP reconstruction and the modern Climate Division 4 data (Figure 5.9) reflect these elevational differences. In sum, the SFP reconstruction effectively represents precipitation conditions in the study area watersheds. These precipitation conditions are also a reasonable indicator of changes in streamflow discharge levels because the streams and rivers of these watersheds are all contained within Climate Divisions 3 and 4 and the study area watersheds.

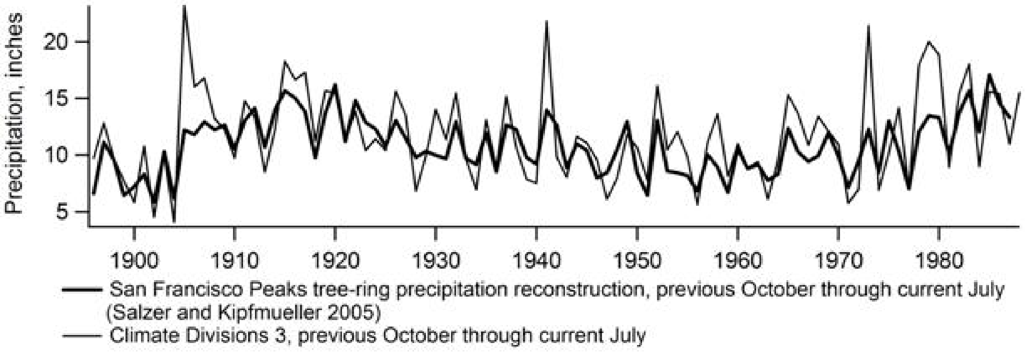


Figure 5.8. Comparison of SFP tree-ring precipitation reconstruction to modern Climate Division 3 precipitation.

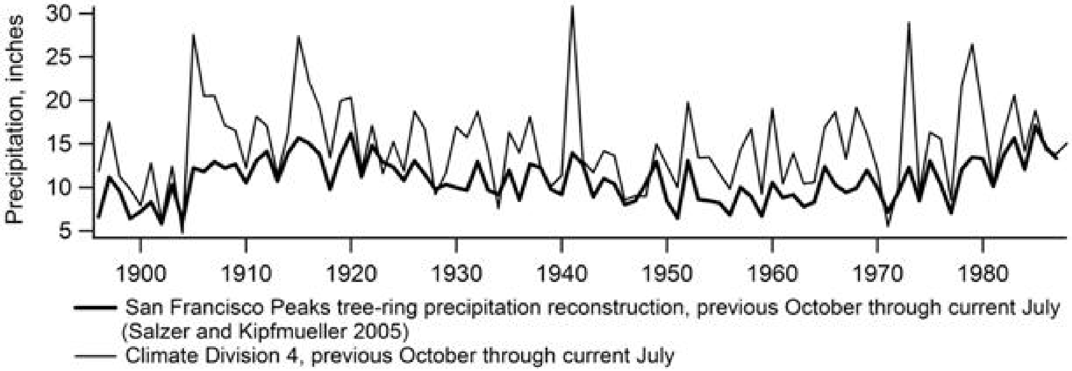


Figure 5.9. Comparison of SFP tree-ring precipitation reconstruction to modern Climate Division 4 precipitation.

A single precipitation reconstruction, especially with combined tree-ring chronologies, can reliably identify climatic conditions throughout the study area because of the highly synchronous spatial and temporal climate patterns in the study area (McPhee et al. 2004:5; Sheppard et al. 2002). That is, “Even though Arizona precipitation is characterized by different annual precipitation totals across the state, year-to-year precipitation variations are quite similar across the state” (McPhee et al. 2004:12). Climate patterns are synchronous because climate is controlled by large-scale atmospheric circulation patterns. The similarly of precipitation in the study area is demonstrated by a 100-year record of average annual precipitation in Climate Divisions 3 and 4 (which include the study area watersheds, excluding the Lower Salt) (Figure 5.10). The annual precipitation levels are strongly correlated (r =.93) (see McPhee et al. 2004 for similar results).

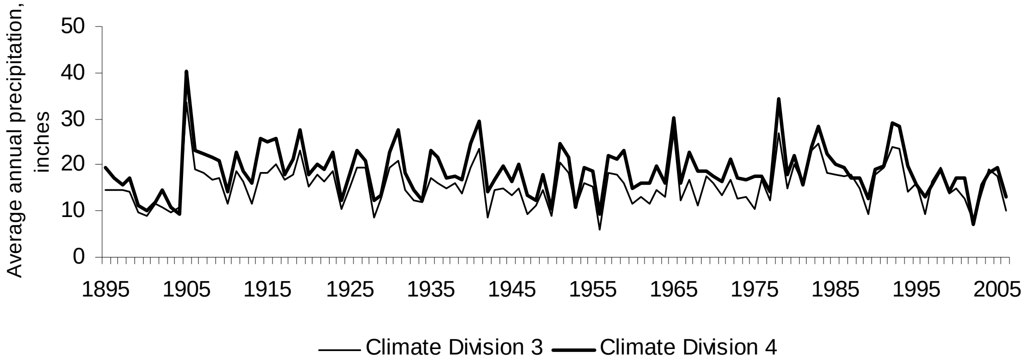


Figure 5.10. Climate Division 3 and 4 average annual precipitation levels (produced using data from the National Climate Data Center 2008).

I use the Lower Salt River (LSR) streamflow reconstruction (Graybill 1989; Graybill et al. 2006) to identify dry periods in the Lower Salt watershed. I use streamflow levels rather than precipitation levels in the Lower Salt watershed to identify dry periods because resource productivity was primarily linked to extensive irrigated agriculture from the Lower Salt River (see Chapter Four). Lower Salt River discharge is comprised of annual discharges from the Salt, Tonto, and Verde Rivers. The watersheds of these rivers extend into eastern and northern Arizona and western New Mexico. Thus, precipitation in the Lower Salt watershed is not a strong indicator of changes in discharge levels or productivity. Streamflow is retrodicted in million acre-feet per year and is reported for water years, October to September. Verification statistics indicate a strong relationship ($r^2 = .72$) between modern streamflow gauge data and the final reconstructed streamflow discharge (Graybill et al. 2006:77). This relationship is shown below during the modern period of overlap (Figure 5.11).

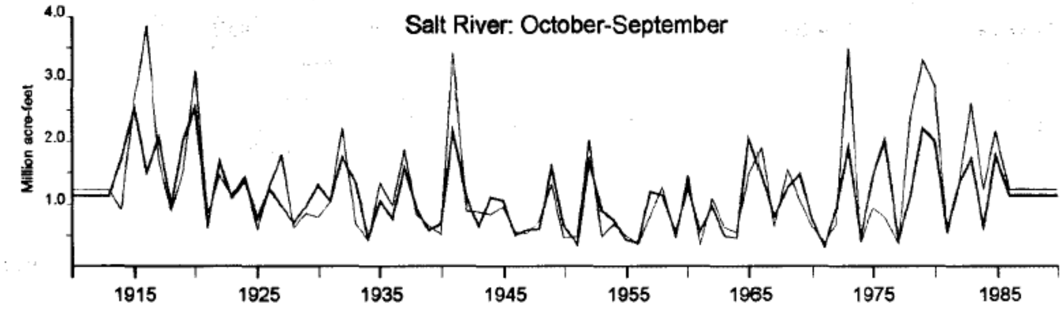


Figure 5.11. Retrodicted and modern discharge levels of the Lower Salt River (after Graybill et al. 2006:78). Lighter line is the actual flow; darker line is the reconstructed flow.

Identifying Dry Periods and Characterizing Severity

Dry periods are identified by smoothing year-to-year precipitation and streamflow variation and selecting threshold values. A centered nine-interval moving average is used to smooth this variation. These interval averages accommodate but do not ignore anomalous years within a dry period that likely do not end the dry period. For example, a single wet year during a dry period would not end the dry period or necessarily replenish stored food reserves or soil moisture. A nine-year interval duration was selected as a compromise between shorter durations, which would not as faithfully represent trends in the proxy climate data, and longer durations, which would obscure climate variation that would have been potentially meaningful for human behavior. The concept of moving averages has been used in a number of paleoclimate studies to identify multi-year dry and wet periods (e.g., Benson et al. 2007; Cordell et al. 2007; Ni et al. 2002; Parks et al. 2006; Van West and Grissino-Mayer 2006; Woodhouse 2001). A nine-year interval duration is supported by numerous climate studies that have documented persistence (year to year similarity) 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). Eight to 20-year overlapping and non-overlapping intervals have been employed to examine relationships between climate and human behavior (Dean 1988; Larson et al. 1996; Parks et al. 2006; Reid et al. 2006; Rose et al. 1981). During data exploration, I compared dry periods identified with different interval lengths (i.e., 5 years, 15 years) and found that interval durations identified dry periods similarly well but resulted in some differences in the start and end dates of individual dry periods.

Threshold values identify dry periods within the distribution of nine-year interval moving averages across the precipitation and streamflow reconstructions (A.D. 572 to 1988). Dry periods are defined as those 9-year intervals in the first quartile of the distribution of interval averages of each reconstruction. 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., Hirschboeck and Meko 2005, Steinemann et al. 2005, Smakhtin 2001). A first quartile threshold value is arbitrary but assumed to represent values and periods with sufficient rarity to have substantially influenced resource productivity or perceptions of productivity relative to typical conditions. During data exploration, I also identified dry periods using a decile threshold. Only nineteen years within the 250-year study period were identified as a dry years using this threshold--too rare for an evaluation of dry-period influences on human behavior and for the temporal resolution of the archaeological data. The percentile value is assigned to the center (middle) of each moving nine-year interval (year 5). When four or fewer years of separation exist between the middle years of two identified dry periods, the intervals are merged into a single extreme event because the nine-year intervals substantially overlap. I use the entire length of the precipitation reconstruction (570 to 1988) to calculate the percentiles. The length of the precipitation reconstruction has little impact on the identification of extreme periods based on my evaluation of dry periods identified using portions (500, 1000, and 1500 years) of the total reconstruction.

To allow comparison of the dry periods to residential abandonment, I identify differences in the severity of dry periods in each 50-year interval from 1200 to 1450. As I stated earlier, documenting demographic changes and residential abandonment at 50-year intervals is currently the best chronological resolution possible in the study area. Thus, the temporal resolution of the climate data must be matched to the resolution of data representing residential abandonment. I identify differences in dry-period severity by summing the number of years identified as a dry period within each 50-year interval and dividing this sum by the 50-year interval duration. The results of these calculations are the percent of each 50-year interval identified as a dry period. I use this percent to represent differences in dry-period severity among the five 50-year intervals. Intervals can then be compared on the basis of this severity value. I emphasize the duration of dry periods as an indicator of severity because as dry periods persist, the effectiveness of strategies to manage shortfalls risks diminishes. For example, food storage is an effective strategy to manage intra or inter-annual variation in productivity and to prevent shortfalls. If productivity remains low for an extended period, stored reserves including seed stores can be depleted and the risk of shortfall increases.

Assessing dry-period severity and making relative comparisons between intervals is a reasonable approach because it is consistent with the strengths of tree-ring reconstructed precipitation data. These data are the strongest and most reliable when they are used to represent relative changes in climate conditions rather than absolute (year-to-year) changes (Fritts 1976; Meko et al. 1995). The statistical correlation between tree growth and climate is always less than perfect;

therefore, an emphasis on individual retrodicted years gives a false sense of precision to an analysis. In sum, analyses and explanations based on year-to-year change in retrodicted precipitation values are not as reliable and well grounded in the data as investigations of multi-year dry periods which can be reasonably compared over time using differences in dry-period severity among 50-year intervals.

Dry Periods, 1200 to 1450

Based on the methods discussed above, dry periods identified in the precipitation and streamflow reconstructions are presented in Tables 5.5 and 5.6 and displayed in Figures 5.12 and 5.13. These dry periods are then used to identify differences in dry-period severity among the intervals (last column) for comparison to variation in the extent of room and settlement abandonment during the period of study. A dry-period that overlaps interval boundaries is counted in the interval containing the majority of the dry-period's years, when human responses are most expected.

Table 5.5. Precipitation Dry Periods in Central Arizona from 1200 to 1450 (San Francisco Peaks [SFP] Precipitation Reconstruction).

Intervals	Dry Periods	Dry-Period Duration	Total Number Of Dry-Period Years in Interval	Percent of Interval Identified as a Dry Period
1200 - 1249	1214 - 1220	7	7	14
1250 - 1299	1248 - 1254	7		
	1282 - 1282	1		
	1294 - 1299	6	14	28
1300 - 1349	1339 - 1351	13	13	26
1350 - 1399	1359 - 1365	7		
	1391 - 1402	12	19	38
1400 - 1449	1412 - 1414	3		
	1438 - 1462[1]	25	28	44

[1] To accommodate this dry period, the number of dry period years in the 1400 to 1449 interval is divided by a 63-year interval duration (i.e., 1400 to 1462). I use the end date of 1462 because it is a reasonable guess at the termination date of this interval in central Arizona prehistory, which is not well known (see for example, Dean 1991).

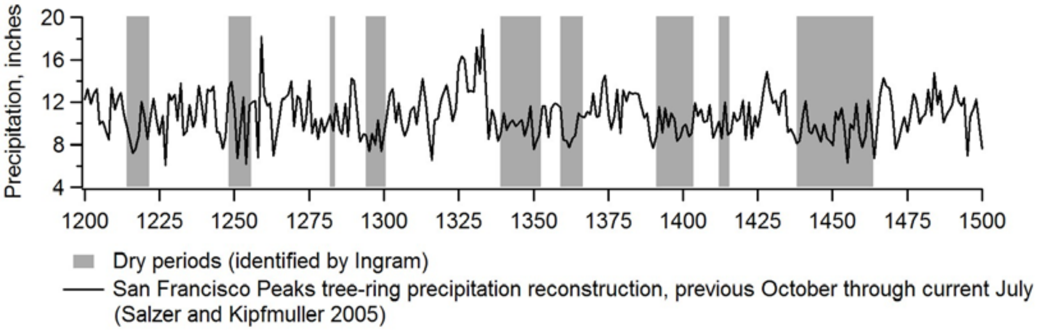


Figure 5.12. Dry periods in central Arizona from 1200 to 1450.

Table 5.6. Streamflow Dry Periods in Central Arizona from 1200 to 1450 (Salt, Tonto, Verde River [LSR] Reconstruction).

Intervals	Dry Periods	Dry-Period Duration	Total Number of Dry-Period Years in Interval	Percent of Interval Identified as a Dry-Period
1200 - 1249	1214 - 1224	11	11	22
1250 - 1299	1250 - 1255	6		
	1280 - 1292	13	19	38
1300 - 1349	1338 - 1352	15	15	30
1350 - 1399	1389 - 1393	5	5	10
1400 - 1449	1408 - 1414	7		
	1436 - 1452	17	24	46

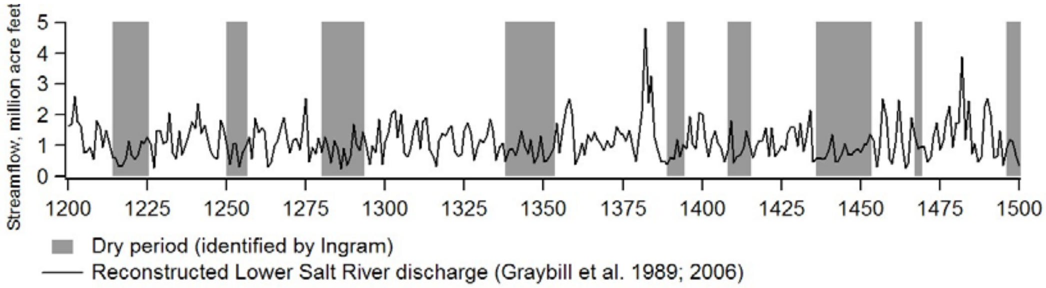


Figure 5.13. Lower Salt River streamflow dry periods.

Residential Abandonment

I identify residential abandonment through reductions in the numbers of occupied rooms at settlements and by reduction in the number of settlements in a watershed. For this study, 535 settlements including 32,082 rooms located in nine watersheds in central Arizona are considered. The number of identified rooms occupied, abandoned, and the percent of rooms abandoned during each 50-year interval from 1200 to 1450 are presented in Table 5.3. I calculated these numbers using the settlement founding and abandonment dates and the number of rooms identified at each settlement, as recorded in the Coalescent Communities Database (previously discussed). For example, a settlement occupied from 1250 to 1349 with 100 identified rooms would be included in the watershed rooms occupied count during the 1250 to 1299 and 1300 to 1349 intervals and be included in the watershed rooms abandoned count during the 1300 to 1349 interval. The total number of rooms abandoned during an interval includes all rooms in settlements with abandonment dates during that interval. I used geographic information systems software (ArcMap 9.2) to assign each settlement and the associated rooms to a watershed.

The general index of residential abandonment I use for each 50-year interval from 1200 to 1450 is: total number of rooms abandoned divided by the total number of rooms occupied; thus, the percent of rooms abandoned during each interval. For example, in the central Arizona study area as a whole during the 1250 to 1299 interval, 10,163 rooms were occupied and 4,699 were abandoned (Table 5.7). The index of residential abandonment, then, is: 4,699 divided by 10,163 = 46% (the percent of rooms abandoned). I do not consider absolute changes in the total number of rooms abandoned during each interval as absolute changes will vary as total population varies. Using the percent of rooms abandoned controls for changes in population size.

Table 5.7. Total Number of Rooms Occupied and the Percent of These Rooms Abandoned During Each Interval by Watershed.

Watershed Rooms	1200 to 1249		1250 to 1299		1300 to 1349		1350 to 1399		1400 to 1449	
	n	%	n	%	n	%	n	%	n	%
Central Arizona[1]										
occupied	7,012		10,163		14,643		12,660		1,620	
abandoned	1,487	21	4,699	46	2,927	20	11,040	87	1,620	100
Agua Fria										
occupied	787		427		1,937		1,917		860	
abandoned	598	76	176	41	20	1	1,057	55	860	100
Big Chino-Williamson										
occupied	102									
abandoned	102	100								
Carrizo										
occupied	165		505		555		185			
abandoned	45	27	120	24	370	67	185	100		
Lower Verde										
occupied	1,162		1,764		3,318		2,750		244	
abandoned	153	13	603	34	568	17	2,506	91	244	100
Lower Salt										
occupied	6,317		7,121		8,126		6,888		486	
abandoned	196	3	796	11	2,351	29	6,480	94	486	100
Tonto										
occupied	1,601		2,221		1,444		1,294			
abandoned	114	7	1277	57	206	14	1,294	100		

Watershed Rooms	1200 to 1249		1250 to 1299		1300 to 1349		1350 to 1399		1400 to 1449	
	n	%	n	%	n	%	n	%	n	%
Upper Salt										
occupied	2,081		3,701		4,922		4,207		361	
abandoned	197	9	2078	56	1,603	33	3,846	91	361	100
Upper Verde										
occupied	869		1,115		1,667		1,507		155	
abandoned	213	25	15	1	160	10	1,352	90	155	100
White										
occupied	245		430		800		800			
abandoned	65	27	430	100	0	0	800	100		

[1] Central Arizona includes all rooms/settlements in the Agua Fria, Big Chino-Williamson Valley, Carrizo, Lower Verde, Tonto, Upper Verde, and Upper Salt, and White watersheds. Big Chino-Williamson Valley, Carrizo, and White watersheds are excluded from the watershed-scale analysis due to low settlement and or room numbers and the limited duration of occupation in these watersheds.

I identify the extent of residential abandonment among settlements and watersheds by each demographic and environmental classification. The specific indices of residential abandonment by demographic conditions (settlement population levels and watershed population density) are in Table 5.8 and the indices of residential abandonment by environmental conditions (proximity to perennial rivers and settlement area precipitation levels) are in Table 5.9. I compare variation in residential abandonment for each of these classifications to variation in dry-period severity to identify the influence of specific demographic and environmental conditions on residential abandonment and vulnerability to dry periods. Data tables for each of these classifications are presented with the results in Chapters Six through Nine.

Table 5.8. Indices of Residential Abandonment by Demographic Conditions.

Demographic Conditions	Residential Abandonment Indices
Low settlement population levels (<=30 rooms)	number of settlements abandoned with low population levels during a 50-year interval divided by the total number of low population settlements occupied during that interval
Moderate settlement population levels (31 to 100 rooms)	number of settlements abandoned with moderate population levels during a 50-year interval divided by the total number of settlements with moderate population levels occupied during that interval
High settlement population levels (>100 rooms)	number of settlements abandoned with high population levels during a 50-year interval divided by the total number of settlements with high population levels occupied during that interval
Low density watershed (<.20 rooms per square kilometer)	number of rooms located in a low density watersheds during a 50-year interval divided by the total number of rooms occupied in a low density watershed during that interval
High density watershed (>.36 rooms per square kilometer)	number of rooms located in a high density watershed during a 50-year interval divided by the total number of rooms occupied in a high density watershed during that interval

Note: Demographic conditions calculated at the watershed and “Central Arizona” scale.

Table 5.9. Indices of Residential Abandonment by Environmental Conditions.

Environmental Conditions of Settlements/Rooms	Residential Abandonment Indices
Near a perennial river (located less than 2 km from a perennial river)	number of rooms abandoned near perennial rivers during a 50-year interval divided by the total number of rooms occupied near perennial rivers during that interval
Far from a perennial river (located more than 2 km from a perennial river)	number of rooms abandoned far from perennial rivers during a 50-year interval divided by the total number of rooms occupied far from perennial river during that interval
Low precipitation (9” to 14” annually)	number of rooms abandoned in areas of low precipitation during a 50-year interval divided by the total number of rooms occupied in areas with low precipitation during that interval
Moderate precipitation (15” to 22” annually)	number of rooms abandoned in areas of moderate precipitation during a 50-year interval divided by the total number of rooms occupied in areas with moderate precipitation during that interval
High precipitation (23” to 35” annually)	number of rooms abandoned in areas of high precipitation during a 50-year interval divided by the total number of rooms occupied in areas with high precipitation

Note: Environmental conditions identified using modern environmental/climatic data assumed to represent conditions during the period of study. Proximity to perennial rivers calculated at the watershed and Central Arizona scale. Precipitation levels calculated only at the Central Arizona scale.

Evaluating Models of Vulnerability by Evaluating Relationships

The previous sections of this chapter have identified how I identified dry periods and classified each room, settlement, and watershed by their demographic and environmental conditions. These conditions are identified in the conceptual models as influencing human vulnerability to dry periods. By examining the relationship between dry-period severity and residential abandonment under each of these conditions, I evaluate the extent to which the models are supported over a 250-year period in central Arizona. If differences in the relationships are detected when conditions are varied (e.g., high vs. low watershed population density, settlements near vs. far from perennial rivers), I attribute these differences to the influence of these conditions on vulnerability to dry periods. Little or no difference in the relationships among classifications will indicate a particular condition did not affect residential abandonment and by implication vulnerability to dry periods. As the number of observations allows, I examine these relationships at the settlement-scale, watershed-scale, and at the scale of the entire study area to provide multiple tests of each model and identify any differences in the spatial distribution of the relationship. The remainder of this chapter identifies the statistics and methods I employ to identify and compare relationships. I also provide a sample analysis.

I assess the relationship between dry-period severity and residential abandonment (in all places and under each condition) by examining the slope and intercept of a best-fit straight line through a scatterplot of data values representing dry-period severity (x) and residential abandonment (y) during each 50-year interval from 1200 to 1450. I also calculate a Pearson's r correlation coefficient and associated p-levels and visually inspect the scatterplot of each relationship.

I use linear regression to identify a best-fit straight line through each scatterplot of data values. A best-fit straight line calculated with linear regression minimizes the sum of the squares of the vertical distances of each data value from the line. I use the regression equation and line to identify the best-fit values of the slope and intercept. The slope identifies the direction of the relationship (positive or negative) and quantifies the steepness of the line. The slope in this analysis equals the percent change in residential abandonment (y) for each one percent change in dry-period severity (x). I use the slope to evaluate the extent of sensitivity to dry-period severity in different places and under different demographic and environmental conditions. For example, if people living in settlements near perennial rivers were less sensitive (or responsive with residential abandonment) to dry-period severity than people living far from perennial rivers, then I expect the slope of the line representing the relationship between dry-period severity and residential abandonment among settlements near perennial rivers will be shallower (less steep) than the slope of the line representing the relationship between dry-period severity and residential abandonment among settlements far from perennial rivers. I also statistically compare slopes to determine if and how sensitivity to dry-period severity was different in one watershed or among settlements with particular characteristics (discussed further below). The y-intercept identifies the elevation of the line and is the expected mean value of y when x = 0; or, the extent of residential abandonment when the index of dry-period severity is 0. It suggests a starting value or constant rate of residential abandonment unaffected by dry periods.

A Pearson's r correlation coefficient is a measure of the degree of linear (or proportional) relationship between the variables: dry-period severity and residential abandonment. The correlation coefficient tells us how good the fit the regression line is to the data values; thus, it is understood as a measure of the strength of the linear relationship between two variables (Drennan 1996:216; Shennan 1997:139). The strength of the relationship is identified on a scale from zero for no linear relationship to one for a strong or "perfect" linear relationship. The sign of the coefficient (+ or -) identifies the direction of the relationship (as does the slope). A positive correlation coefficient indicates that as dry-period severity increased, residential abandonment increased. A negative correlation indicates that as dry-period severity increased, residential abandonment decreased. High r values indicate a good fit with much of the variance in the relationship between dry-period severity and residential abandonment “explained” by changes in dry-period severity. [Quotes are appropriate for “explained” (and “explains” and “unexplained”) because the correlation (or regression) does not “explain” the relationship in an ordinary sense. Quotation marks are hereafter omitted, as is common practice]. Low r values indicate a poor fit and substantial unexplained variance in the relationship between dry-period severity and residential abandonment. The squared value of r (r^2), known as the coefficient of determination, also provides an assessment of the strength of the relationship. It is interpreted as a measure of the proportion of the total variance in y (residential abandonment) explained by the regression. For example, an r value of .90 and the associated r^2 value of .81 means that 81% of the variance in y (residential abandonment) is explained by x (dry-period severity).

A p-level identifies the statistical significance, or reliability, of the correlation coefficient and is interpreted as the probability a correlation we observe in our sample between dry-period severity and the extent of residential abandonment reflects nothing more than the vagaries of sampling. That is, the probability that $r = 0$. It answers the question, “How likely is it that a sample this size with a correlation this strong could be selected from a population where there is no correlation?” The higher the p-level, the less we can believe that the observed relation between variables in the sample is a reliable indicator of the relation between the variables in the population.

I also visually inspect each scatterplot of data values to identify outliers. Outliers have a profound influence on the slope of a regression line and the value of correlation coefficients when there are few data points (as in this study). I evaluate the influence of outliers and the effectiveness of the correlation coefficient and regression lines to represent the relationship between the variables. In some analyses I exclude a relationship or a data value from calculations because it obscures the primary relationship between the variables.

I do not set specific numerical thresholds for the slopes, correlation coefficients, or p-levels to accept or reject the existence of a relationship between the variables, mainly because there is no basis to establish such a level. Rather, I consider all measures of the relationship to characterize and interpret the influence of dry-period severity on residential abandonment under different conditions.

I examine linear relationships between dry-period severity and residential abandonment under different demographic and environmental conditions for both practical and theoretical reasons, noted below.

First, a consistent method of identifying and comparing relationships between the variables is necessary. Linear relationships are easily identified and when found, are reasonably convincing evidence of a relationship between variables. Data exploration also identified linear relationships at multiple spatial scales in most (81%) of the scatterplots of dry-period severity and residential abandonment [Most of the scatterplots that do not suggest a linear relationship are isolated to the Verde watersheds]. In reality, non-linear relationships and thresholds in the relationship between dry-period severity and residential abandonment might also be found and expected. Given the scope of this study and the difficulty of comparing different types of relationships (e.g., linear to quadratic), I choose to investigate a single type of relationship. Investigating only one type of relationship lessens the threat of having expected the type of relationship found and the challenge of predicting and explaining why different types of relationships might be found within the study area. There is also no a priori method of expecting one type of relationship in one place or circumstance and another type of relationship elsewhere. A weakness of focusing exclusively on linear relationships is that I will miss other types of relationships in the data. The weakness is not that I will identify relationships that did not exist.

Furthermore, the purpose of this study is not to identify the specific conditions contributing to vulnerability in each watershed or differences in the contribution of each condition among watersheds. The purpose of this study is to evaluate existing vulnerability models using a spatially extensive study area so that the results identified might have broad applicability.

Second, this dissertation's focus on linear relationships also reflects the relationships expected in the models evaluated. These models do not specify how vulnerability might change over time, or reach a threshold beyond which responses are inevitable, or be influenced by particular social, political, or geographic circumstances. Thresholds in the relationship between dry periods, the risk of shortfalls, and residential abandonment should be expected if people were able to accommodate a range of dry-period related declines in productivity with existing buffering strategies. If beyond this range a threshold is reached and buffering strategies are no longer effective, responses should increase substantially. Such expectations are reasonable and are likely better evaluated with non-linear relationships or an emphasis on detecting thresholds of human response. Identifying and comparing linear and non-linear relationships, including potential thresholds in these relationships, is beyond the scope of this study, given the number of analytical units and variables considered. Furthermore, I do not use a multivariate statistical approach in this study because the conceptual models I evaluate do not assert differences in the contribution of each variable or combine variables to explain vulnerability.

Third, expectations of the relationship between dry-period severity, the risk of food shortfalls, and the extent of human response are often conceptualized as linear. These expectations have their origin in studies of environmental risk wherein the magnitude of a risk is expected to be related to the magnitude of the human response (Halstead and O'Shea 1989 ed.). The risk of food shortfalls is understood to increase as dry-period severity increases. This is because as dry periods persist over time, water-related resource productivity declines, stored food reserves are used, and other buffering strategies begin to fail. An emphasis on dry periods and associated risk severity is pervasive in Southwestern archaeological studies of dry-period influences on regional-scale abandonments. The characteristics of the coincident dry-period are investigated in terms of its severity (duration and/or magnitude) and contrasted with previous dry periods with or without human responses (e.g., Benson et al. 2007; 2009; Van West and Grissino-Mayer 2006; Van West and Dean 2000). These comparisons are sometimes used to question the influence of the late 1200s dry period in the northern U.S. Southwest on the depopulation of that region because the late 1200s dry period was less severe than a previous dry period (mid-1100s) that did not result in depopulation. This study’s evaluation of linear relationships investigates the potential for linear responses although in reality non-linear relationships should also be expected.

Example Analysis

Figures 5.14 a. and b. represent the relationship between dry-period severity and residential abandonment under two different (hypothetical) environmental conditions. I separate the data by differences in the conditions identified in the conceptual models. These conditions are identified as influencing human vulnerability to dry periods. Separating the data into groups clearly identifies the influence of dry-period severity on residential abandonment in each group so that the relationships can be evaluated, contrasted, and compared with model expectations. The data points in each scatterplot are the percent of each 50-year interval identified as a dry-period (the index of dry-period severity) and the percent of rooms abandoned during that interval (the indicator of residential abandonment). Thus, in Figure 5.8a, the data point labeled “1250-1299” identifies that 56% of the rooms occupied during this interval were abandoned during this interval and 28% of the years during this interval are classified as a dry-period.

In Figure 5.14 a., the best-fit value of the slope (m) of the regression line is 1.4 (Table 5.10), indicating that for every one percent increase in the number of years identified as a dry-period, there was a 1.4 percent increase in the percent of rooms abandoned. The intercept (b) is -5% rooms abandoned (Table 5.10). A negative percent of rooms abandoned suggests that when a 50-year interval did not contain years identified as a dry-period ($x = 0$), residential abandonment under these conditions was very low or non-existent. A negative intercept may also suggest an attraction to an area such that people stayed in these locations even as dry-period severity increased. And, it might indicate a threshold below which abandonment was not strongly influenced by dry periods and above which abandonment was more strongly influenced.

There is a positive but relatively weak linear relationship between the variables, indicated by the correlation coefficient $r = .42$ and the poor fit (or distance) of the data points to the regression line. The relatively low coefficient and poor fit ($r^2 = 18\%$) indicates that much of the variance in residential abandonment among people living in settlements located in Environmental Condition 1 is not explained by changes in dry-period severity--other factors besides changes in dry-period severity are influencing changes in residential abandonment. Finally, there is a 49% probability ($p = .49$) that this correlation represents nothing more than the vagaries of sampling; thus, we cannot be confident that the observed relationship between the variables in the sample is a reliable indicator of the relationship between the variables in the population.

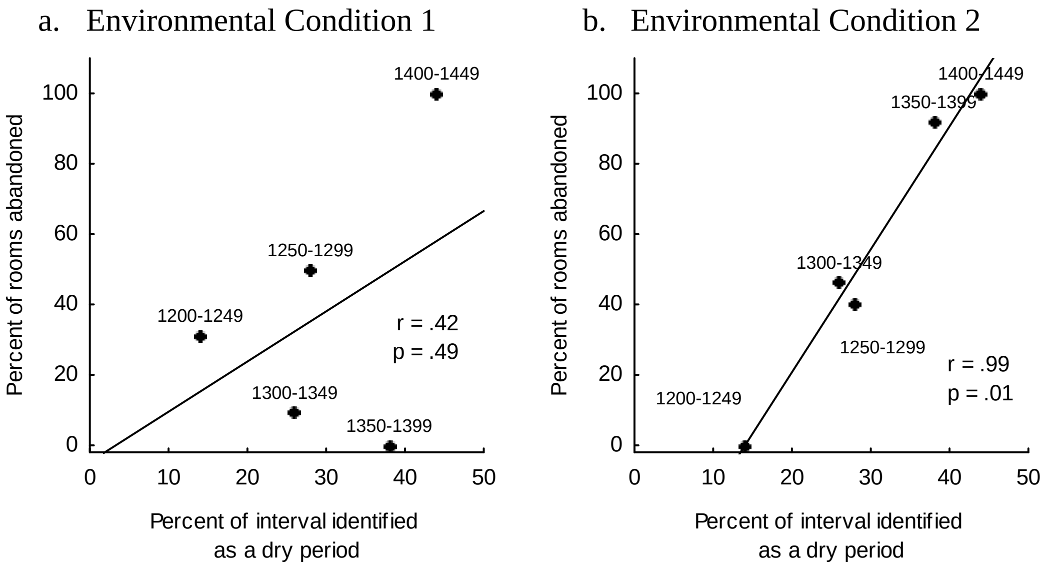


Figure 5.14. Sample scatterplots of relationship between dry-period severity and residential abandonment under different environmental conditions.

Table 5.10. Slopes, Intercepts, Correlation Coefficients, and Their Probability of Equality.

Central Arizona Settlements	Slopes		Intercepts		Correlation Coefficients	
	slope	probability of equality	intercept	probability of equality	r	probability of equality
Environmental Condition 1	1.4	30%	-5	40%	.42	3%
Environmental Condition 2	3.5		-49		.99	

Figure 5.14 b. represents the relationship between dry-period severity and residential abandonment under Environmental Condition 2. The slope of the line is 3.5 indicating that for every one percent increase in the number of years

identified as a dry-period, there was a 3.5% increase in the percent of rooms abandoned (Table 5.10). Thus, residential abandonment under Environmental Condition 2 is much more sensitive to changes in dry-period severity than under Environmental Condition 1. The intercept is -49% of rooms abandoned--not a meaningful measure of residential abandonment. It suggests, though, that when there were no dry-period years, there was no residential abandonment. There is a strong positive linear relationship between the variables, indicated by the correlation coefficient r = .99 and the good fit (or closeness) of the data points to the regression line. The r^2 value indicates that 98% of the variance in residential abandonment in Environmental Condition 2 is explained by variation in dry-period severity. There is only a 1% probability (p = .01) that the correlation represents nothing more than the vagaries of sampling; thus, we can be reasonably confident that the observed relationship in this sample is a reliable indicator of the relationship between the variables in the population.

To evaluate whether differences between relationships are substantial enough to conclude a particular demographic or environmental condition (identified in the conceptual models) affected the extent of residential abandonment and thus vulnerability to dry periods, I statistically compare the best-fit slopes, intercepts, and correlation coefficients to identify their “probability of equality.” For the slopes, I report a p-value (two-tailed) that answers the question, “If the slopes really were identical, what is the chance that randomly selected data points would have slopes as different (or more different) than those observed?” (Zar 1984; www.graphpad.com). The p-value is the probability that the null hypothesis is correct--that the slopes are identical (the lines are parallel) and sensitivity to dry periods under both conditions was similar. For the intercepts (also called “elevations”), I also report a p-value for each comparison that answers the question, “If the overall elevations were identical, what is the chance of randomly choosing data points with elevations this different (or more different) than those observed?” [From GraphPad Prism 5 software; www.graphpad.com]. For the correlation coefficients, I use an interactive on-line calculator (http://people.ku.edu/~preacher/corrtest/corrtest.htm; Preacher 2002) where I input the r values of each correlation to be compared and the n values for each correlation. The n values represent the number of 50-year intervals in which there is evidence of settlement occupation under the specific conditions considered. Each correlation coefficient is converted into a z-score using Fisher's r-to-z transformation. Then, making use of the sample size employed to obtain each coefficient, these z-scores are compared using formula 2.8.5 from Cohen and Cohen (1983:54). The calculator yields the result of a test of the hypothesis that two correlation coefficients obtained from independent samples are equal. I use and report the p-values associated with a 2-tailed test because there is no reason to expect that one correlation coefficient should be greater than the other.

The lower the probability of equality of the slopes, intercepts, and correlation coefficients, the greater the probability that differences between them are statistically significant. I do not establish a specific probability level for concluding equality or difference between slopes, intercepts, and coefficients. Rather, I use a general interpretation such as if the probability of equality of two slopes is below 50%, then correlations are more likely to be different than not different.

The probability of equality of the slopes, intercepts, and correlation coefficients in the previous example are presented in Table 5.10. If the slopes were identical, there is a 30% chance of randomly choosing data points with slopes this different. Thus, the probability of equality of the slopes is relatively low indicating that the slopes are more likely to be different than the same. If the overall elevations (intercepts) were identical, there is a 40% chance of randomly choosing data points with elevations this different. Thus, the probability of equality of the intercepts is somewhat low indicating that the intercepts are more likely to be different than the same. The probability of equality of the correlation coefficients is 3%, thus, it is very likely the coefficients are different. In sum, a comparison of the relationship between dry-period severity and residential abandonment under Environmental Condition 1 and 2 consistently supports an interpretation that the relationships were different. People living in Environmental Condition 2 were more sensitive to dry-period severity, or more responsive through residential abandonment, than people living in Environmental Condition 1. Thus, a conceptual model asserting the influence of Environmental Condition 2 on vulnerability to dry periods is supported by the evidence considered in this example. A conceptual model asserting the influence of Environmental Condition 1 on vulnerability to dry periods is less strongly supported.

Summary

This chapter describes the data and methods for classifying all settlements and rooms within the study area by the demographic and environmental conditions emphasized in the models of vulnerability to dry periods. Methods of identifying dry periods in central Arizona are also presented. Classifying all settlements by differences in demographic and environmental conditions allows an examination of differences in the sensitivity and strength of the relationships between dry-period severity and residential abandonment among settlements with different characteristics. I use these differences to infer differences in vulnerability to dry periods. Evaluating the vulnerability models involves examining the extent to which each model's expectations are supported by the residential abandonments that occurred from 1200 to 1450 in central Arizona.

In the next four chapters I evaluate models of vulnerability to dry periods used by archaeologists and other scholars to understand temporal and spatial variation in vulnerability to dry periods. In Chapter Six, I evaluate an aridity model that emphasizes resource marginality and widespread vulnerability across all demographic and environmental conditions. Evaluating this model also identifies the spatial distribution of vulnerability to dry periods allowing the assumption of resource marginality to be evaluated in the study area. In Chapter Seven, I evaluate models that emphasize the influence of demographic conditions on vulnerability to dry periods. In Chapter Eight, I evaluate models that emphasize the influence of environmental conditions. In Chapter Nine, I evaluate models that combine both demographic and environmental conditions to understand the influence of population-resource imbalances on vulnerability. Following the presentation of the empirical results in each chapter, I interpret and discuss the implications of the findings.

CHAPTER 6:

THE INFLUENCE OF ARIDITY ON VULNERABILITY TO DRY PERIODS

The analyses in this chapter evaluate an 'aridity' model of vulnerability to dry periods by testing the expectation that dry-period declines in resource productivity, regardless of other environmental, social, and demographic variables, created widespread vulnerability to the risk of shortfall. This expectation is implied by the assumption of resource marginality, which treats vulnerability to dry periods as a biophysical or landscape condition rather than a product of demographic and environmental conditions that affect the extent of resource supplies and demand. In biophysical models of vulnerability to natural hazards, vulnerability is understood as a function of the frequency and severity of the hazard (Brooks 2003:4). It is important to evaluate this model because it has been widely applied throughout the U.S. Southwest and other dry climates, especially to explain regional-scale depopulations coincident with severe dry periods. Evaluating this model also identifies the extent and spatial distribution of vulnerability to dry periods allowing the assumption of resource marginality to be evaluated in the study area.

To assess the utility of an aridity model for explaining vulnerability to dry periods, I examine the relationship between dry-period severity and residential abandonment within six watersheds in central Arizona from 1200 to 1450. I use the relationship between dry-period severity and residential abandonment as an indicator of the extent of vulnerability within each watershed. By geographically disaggregating the study area into watersheds, I test the assumption of vulnerability as a regional-scale, biophysical condition. The aridity model and the assumption of regional-scale resource marginality will be supported if I find strong and sensitive relationships between dry-period severity and residential abandonment in all watersheds.

Results identify substantial variation in the slopes, intercepts, and strength of the correlation coefficients representing the relationship between dry-period severity and residential abandonment among the study area watersheds (Table 6.1 and 6.2, Figures 6.1, 6.2, 6.3). Variation in the slopes, from m = -.03 to m = 3.9, demonstrates a range of sensitivity to dry-period severity. Variation in the intercepts, b = -59 to b = 48, suggests that during intervals with no dry-period years, residential abandonment was minimal in some watersheds (those with negative intercepts) and extensive in others (those with positive intercepts). Correlation coefficients range from r = -.01 to r = .98 (r^2 = 0 to .96) demonstrating substantial differences in fit of the data values to the regression line and in the extent of unexplained variance in the relationship between dry-period severity and residential abandonment among watersheds.

A comparison of specific differences in the relationship between dry-period severity and residential abandonment among all watersheds suggests the six watersheds can be sorted into two groups: those watersheds where changes in residential abandonment <u>were strongly related</u> to changes in dry-period severity and those watersheds where changes in residential abandonment <u>were not strongly related</u> to changes in dry-period severity.

Changes in residential abandonment were strongly related to changes in dry-period severity in the Upper Salt, Lower Verde, and Tonto watersheds (Figure 6.1). Slopes are relatively steep (Upper Salt m = 3.2; Lower Verde m = 3.3; Tonto m = 3.9) indicating that residential abandonment was very sensitive to changes in dry-period severity. For every one percent change in dry-period severity, residential abandonment increased between 3.2 and 3.9%. Correlation coefficients identify good fits with the regression line indicating that much of the changes over time in residential abandonment in these watersheds can be explained by changes in dry-period severity (Upper Salt r = .98; Lower Verde r = .93; Tonto r = .90). The negative intercepts identified in the regression equations suggest residential abandonment may have been very low in the absence of dry-period years (Upper Salt b = -40; Lower Verde b = -49; Tonto b = -59). The Upper Salt, Lower Verde, and Tonto watersheds include 46 percent of the identified rooms occupied sometime during the 1200 and 1450 study period and comprise 41 percent of the central Arizona study area (Table 6.3).

Changes in residential abandonment were not strongly related to changes in dry-period severity in the Lower Salt, Agua Fria, and Upper Verde watersheds (Figure 6.2). Slopes of the regression lines are shallower in the Lower Salt (m = -.03), Agua Fria (m = 1.0), and the Upper Verde (m = 3.1) indicating that residential abandonment was less sensitive to changes in dry-period severity than elsewhere in the study area. For every one percent change in dry-period severity, residential abandonment decreased slightly in the Lower Salt, increased one percent in the Agua Fria, and increased 3.1% in the Upper Verde. Correlation coefficients and inspection of the scatterplots also identify relatively poor fits in the Lower Salt (r = -.01), Agua Fria (r = .31), and Upper Verde (r = .78). Poor fits indicate that much of the change in residential abandonment in these watersheds cannot be explained by changes in dry-period severity. Other factors besides dry-period severity are influencing changes in residential abandonment. The intercepts of the regression lines in the Lower Salt (b = 48) and Agua Fria (b = 24) scatterplots also suggests a base level of residential abandonment unrelated to dry periods. In the Upper Verde (b = -49) the intercepts suggest low levels of abandonment in the absence of dry period years. The Lower Salt, Agua Fria, and Upper Verde watersheds include 47 percent of the identified rooms occupied sometime during the 1200 to 1450 study period and 35 percent of the study area (Table 6.3). (The remaining 7% of rooms occupied were located in Carrizo, Big Chino, and White watersheds which are not included in the watershed-scale analysis due to limited room numbers and short settlement histories. These watersheds comprise 24% of the central Arizona study area.)

The test for statistical similarity and difference between the slopes and correlation coefficients generally supports the identification of differences between the two groups of watersheds (Table 6.2). The slopes of the regression lines that describe the linear relationship between dry-period severity and residential abandonment in the Lower Salt and Agua Fria watersheds compared to the slopes of the regression lines that describe the relationship in the Upper Salt, Lower Verde, and Tonto watersheds are all more likely to be different than the same. That is, the probabilities of equality of the slopes of the Lower Salt and

Agua Fria regression lines compared with the slopes of the regression lines from other watersheds are all less than 40%. Similarly, the test for the probability of equality of the correlation coefficients finds the correlations between dry-period severity and residential abandonment in the Lower Salt and Agua Fria compared to the other watersheds more likely to be different than the same (p < 47%).

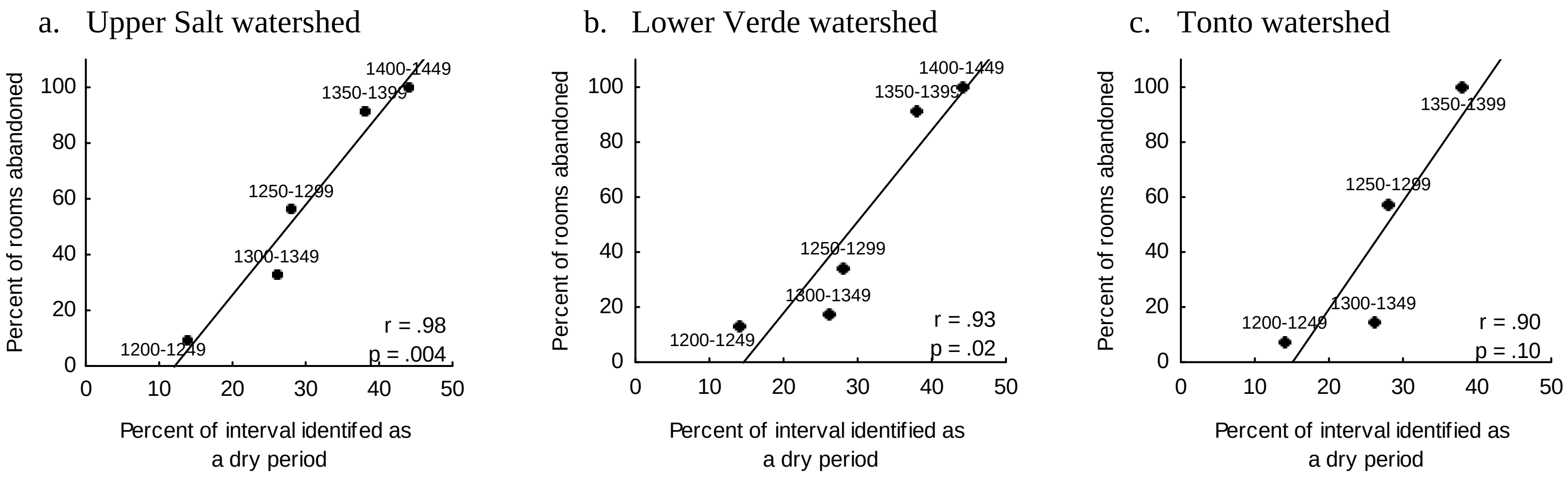
The Upper Verde watershed represents a borderline case. The slope of the regression line identified in the Upper Verde scatterplot is more likely to be similar to than different from the slopes of the lines in the Lower Verde, Tonto, and Upper Salt scatterplots (p >73%). As noted above, however, inspection of the Upper Verde scatterplot suggests a relatively poor linear fit and weaker relationship between dry-period severity and residential abandonment in this watershed. Watershed-scale analyses considered later in this study (see Chapter Eight, Figures 8.10 b. and 8.11) demonstrate that results from the Upper Verde are most strongly related to (or “group” with) the Agua Fria and Lower Salt rather than with the Lower Verde, Tonto, and Upper Salt. These results combined with the poor linear fit suggest conditions in the Upper Verde were most similar to the watersheds where changes in dry-period severity were not strongly related to changes in residential abandonment.

Inter-watershed differences in the relationships between dry-period severity and residential abandonment suggest that conditions other than regional-scale aridity must be considered to more fully understand variation in vulnerability to dry periods. That is, why were people living in some watersheds more vulnerable to dry periods, or at least more responsive to dry periods through abandonment, than people living in other watersheds? The extent to which the demographic and environmental conditions within each watershed contributed to differences in inter-watershed vulnerability is examined with the remaining three vulnerability models. The ability of the models to explain these differences is used as a crucial part of the evaluation of each model. If additional paleoclimatic reconstructions in central Arizona are developed in the future, watershed-scale differences in precipitation and streamflow conditions during the period of study should also be considered as a possible explanation of watershed-scale variation in vulnerability to dry periods. Differences in residential abandonment and vulnerability caused by differences in the watershed-scale representativeness of the climate reconstruction seems unlikely, however, because current evidence from modern and paleoclimate studies demonstrates substantial homogeneity in climate conditions at multiple spatial and temporal scales (as discussed in Chapter Five).

Table 6.1. Rooms Occupied and Abandoned by 50-year Interval and Correlation with Percent of Rooms Abandoned.

Watershed Rooms	1200 to 1249		1250 to 1299		1300 to 1349		1350 to 1399		1400 to 1449		Correl.: Dry-Period Severity and Percent Rooms Abandoned
	n	%	n	%	n	%	n	%	n	%	
Agua Fria											
occupied	787		427		1,937		1,917		860		
abandoned	598	76	176	41	20	1	1,057	55	860	100	.31 (p = .61)
Lower Salt[1]											
occupied	6,317		7,121		8,126		6,888		486		
abandoned	196	3	796	11	2,351	29	6,480	94	486	100	-.01 (p = .99)
Lower Verde											
occupied	1,162		1,764		3,318		2,750		244		
abandoned	153	13	603	34	568	17	2,506	91	244	100	.93 (p = .02)
Tonto											
occupied	1,601		2,221		1,444		1,294				
abandoned	114	7	1277	57	206	14	1,294	100			.90 (p = .10)
Upper Salt											
occupied	2,081		3,701		4,922		4,207		361		
abandoned	197	9	2,078	56	1,603	33	3,846	91	361	100	.98 (p = .01)
Upper Verde											
occupied	869		1,115		1,667		1,507		155		
abandoned	213	25	15	1	160	10	1,352	90	155	100	.78 (p = .12)
Dry-period severity, all watersheds except Lower Salt[1]		14		28		26		38		44	
Dry-period severity for Lower Salt[2]		22		38		30		10		46	

[1] Dry-period severity identified with San Francisco Peaks (SFP) precipitation reconstruction; see Chapter 5, Table 5.5.
[2] Dry-period severity identified using Lower Salt River (LSR) streamflow reconstruction; see Chapter 5, Table 5.6.



a. Upper Salt watershed

b. Lower Verde watershed

c. Tonto watershed

Figure 6.1. Watersheds where changes in abandonment were strongly related to changes in dry-period severity.

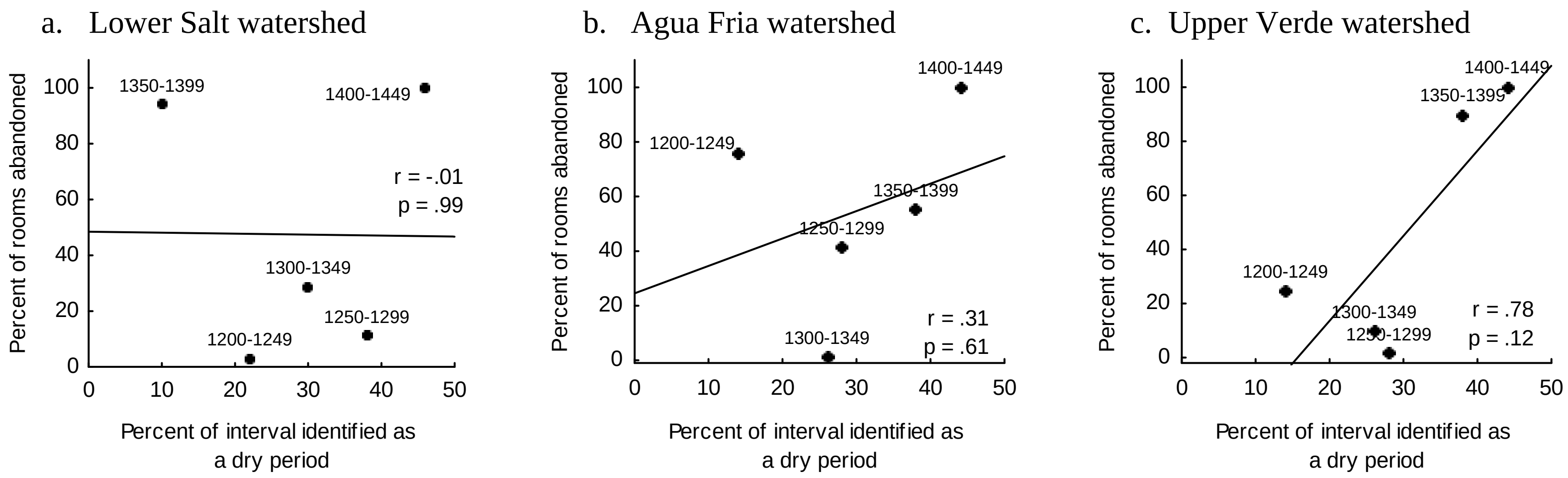


Figure 6.2. Watersheds where changes in abandonment were not strongly related to changes in dry-period severity.

Table 6.2. Slopes, Intercepts, Correlations and the Pairwise Probability of Their Equality, by Watershed.

Watershed Slopes, Intercepts, and Correlations			Pairwise Probability of Equality of Slopes, Intercepts, and Correlations (Percent)					
			Upper Salt	Lower Verde	Tonto	Lower Salt	Agua Fria	Upper Verde
Upper Salt	slope:	3.2		93	60	18	26	94
	intercept:	-40	n/a	44	92	73	87	41
	correlation	.98		52	50	2	5	21
Lower Verde	slope:	3.3	93		70	18	27	90
	intercept:	-49	44	n/a	66	92	87	73
	correlation:	.93	52		88	10	18	54
Tonto	slope:	3.9	60	70		25	30	73
	intercept:	-59	92	66	n/a	100	91	57
	correlation:	.90	50	88		23	34	73
Lower Salt	slope:	-.03	18	18	25		71	25
	intercept:	48	73	92	100	n/a	81	92
	correlation	-.01	2	10	23		74	29
Agua Fria	slope:	1.0	26	27	30	71		39
	intercept:	24	87	87	91	81	n/a	70
	correlation:	.31	5	18	34	74		47
Upper Verde	slope:	3.1	94	90	73	25	39	
	intercept:	-49	41	73	57	92	70	n/a
	correlation:	.78	21	54	73	29	47	

Note: Watersheds where changes in residential abandonment were strongly related to changes in dry-period severity are identified with shading.

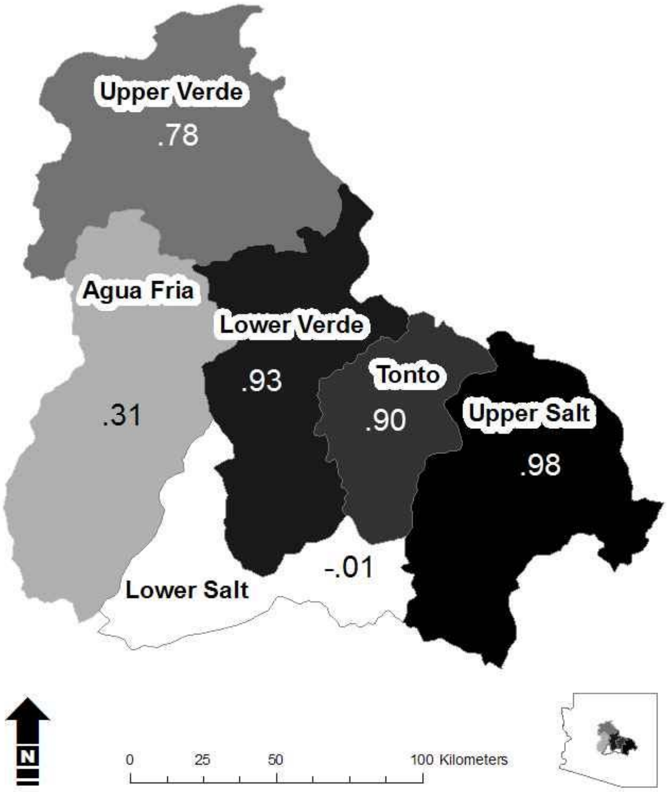


Figure 6.3. Watersheds by correlation between dry-period severity and residential abandonment, A.D. 1200 to 1450.

Table 6.3. Number of Rooms Occupied in Central Arizona from 1200 to 1450 and Proportions of Rooms by Watershed, Area, and Percent of the Total Study Area.

Watersheds	Number of Identified Rooms	Percent of Total Rooms Identified	Area, Square Kilometers	Percent of Total Study Area
Lower Salt	10,397	32	3,442	9
Upper Salt	8,085	25	5,612	15
Lower Verde	4,074	13	5,019	13
Tonto	2,891	9	2,694	7
Agua Fria	2,711	8	6,355	16
Other[a]	2,117	7	9,129	24
Upper Verde	1,895	6	6,372	16
Total	32,170	100	38,623	100

[a] Rooms located in Carrizo (n = 720), Big Chino (n = 102), and White (n = 1,295) watersheds which are not included in the watershed scale analysis due to limited rooms numbers and short settlement histories.

Summary and Implications

The aridity model of vulnerability to dry periods is supported in three of the six watersheds examined in central Arizona. The evidence supporting this conclusion is the strong and sensitive relationships between dry-period severity and residential abandonment in three watersheds. However, weaknesses in this relationship in three other watersheds demonstrate vulnerability to dry periods varied across the study area and can be conceptualized as having an identifiable spatial distribution. Thus, vulnerability to dry periods was not an inherent regional-scale biophysical or landscape condition nor a necessary consequence of living in a dry climate. These conclusions rely, in part, on the strong ability of the precipitation reconstruction to detect dry periods and accurately reflect precipitation conditions in each watershed (as discussed and demonstrated in

Chapter Five). Conclusions also rely on the assumption that dry period risks of food shortfalls throughout the study area were manageable with residential abandonment and population movement during the period of study.

Identifying this spatial distribution of vulnerability to dry periods challenges the assumption that resource marginality due to inherently low and variable precipitation conditions created widespread vulnerability to dry periods. Challenges to the marginality assumption challenge approaches to climate-human behavior studies in U.S. Southwest and in other arid and semi-arid regions. Marginality provides the critical linking argument between climate and human behavior by making variation in climate-related resource productivity meaningful to people because of its affect on the risk of shortfalls. If resources cannot be demonstrated to be marginal or vulnerability to dry periods widespread, then this link between climate and human behavior is weakened. More refined linking arguments will need to be investigated and tested.

Challenges to the marginality assumption also bring into question other models of vulnerability to dry periods that share a reliance on a marginality assumption. For example, increases in interannual variability in precipitation and streamflow levels have been argued to increase the risk of shortfalls especially in dry climates (Cashdan 1990; Dean 1988; Graybill et al. 2006; Halstead and O'Shea 1989b; Nials et al. 1989). Where resources are considered marginal, this variability can challenge successful food provisioning and increase the real or perceived risk of shortfall by increasing the frequency of low productivity, shortfalls, and uncertainty in agricultural planning. Where resources are not considered marginal, however, these oscillations in productivity due to interannual precipitation variability might have challenged food provisioning by creating uncertainty in agricultural planning, but they would likely not have increased the risk of shortfalls.

Aridity models and the assumption of resource marginality have been used to link dry periods to regional-scale abandonments in the U.S. Southwest (as discussed in Chapter Four). Widespread vulnerability and associated increases in shortfall risk are necessary to explain why a demographically, environmentally, and social diverse region would be depopulated during a dry period. In the absence of widespread vulnerability, we should expect variation in responses, including no response, to a dry period because the conditions that affect people's vulnerability to dry periods are not regionally homogeneous.

This study's challenge to an aridity model of vulnerability to dry periods is consistent with a growing body of evidence in the U.S. Southwest that demonstrates that precipitation conditions alone cannot explain regional abandonments or substantial settlement reorganizations. Van West (1994, 1996) has shown through detailed reconstructions of summer droughts and agricultural potential that a significant number of people could have remained in the Mesa Verde region of the northern Southwest during a severe dry period coincident with the late 13th century regional depopulation. According to Van West (1994, 1996), people could have remained because there were places on the landscape with sufficient potential productivity to support populations through the dry period. Similarly, Schollmeyer (2009) has recently examined the role of resource stress in the 12th century settlement reorganization in the Mimbres area of southwest New Mexico. Using a combination of archaeological evidence, mathematical modeling, and GIS to assess the magnitude and timing of periods of resource stress from a combination of reduced precipitation and prolonged hunting and farming activities she found that environmental explanations focused on long-term population resource imbalances have been over emphasized. Specifically, precipitation-related changes in the extent of productive arable land do not explain the extent of the 12th century settlement reorganization.

The results of this chapter also have implications for studies of settlement abandonment and population movement in central Arizona, the U.S. Southwest, and likely other dry climates. Results have revealed both very strong and very weak long-term relationships between dry-period severity and settlement abandonment and associated population movement. This variation suggests that the validity of a linkage between dry periods and abandonments and population movements is locationally dependent. That is, the linkage is valid in some places and invalid in others. Consequently, we must consider both possibilities and, if feasible, identify the prevailing pattern in an area and compare specific results, such as a particular settlement's abandonment, to the broader and longer-term pattern.

The strong long-term relationships between dry-period severity and residential abandonment and associated population movement identified in some watersheds in this study contradict previous results identified in the Black Mesa area of northeastern Arizona (Gumerman 1988). The models and findings of the

Black Mesa project are one of if not the most widely cited study of prehistoric human-environmental interactions in the U.S. Southwest. In this study, Plog et al. (1988:259) argue that precipitation variation was "likely to be too episodic to stimulate any but the most localized of abandonments." They (Plog et al. 1988:259) further argued that "Falling alluvial water tables, widespread floodplain erosion, and low effective moisture are the only environmental factors general enough and severe enough to cause habitat deterioration on a scale sufficient to precipitate abandonment." Their results generally supported these expectations. In contrast, I have identified in about one-half of the central Arizona study area strong long-term relationships between precipitation variation and settlement abandonment. Differences in results between studies may suggest cultural differences in strategies of response to precipitation variation between the Black Mesa residents and the peoples of central Arizona.

In sum, the results of this chapter identify a spatial distribution of vulnerability to dry periods that provides location-specific support for an aridity model. This spatial distribution of vulnerability to dry periods provides no support for regional-scale resource marginality and widespread vulnerability to dry periods throughout the study area. In the next chapter, I consider the influence of demographic conditions on vulnerability to dry periods.

CHAPTER 7:

THE INFLUENCE OF DEMOGRAPHIC CONDITIONS ON VULNERABILITY TO DRY PERIODS

The analyses in this chapter evaluate 'demand' models of vulnerability to dry periods by testing the expectation that demographic conditions associated with greater resource demands resulted in greater vulnerability to dry periods. The demographic conditions I consider are settlement population levels and watershed population density. I use these conditions as indicators of differences in resource demands, the rate of consumption of resources, and the extent of labor available to invest in strategies to manage shortfalls.

In each analysis in this chapter, I compare the relationships between dry-period severity and residential abandonment in areas of greater resource demands (watersheds with high population density, settlements with moderate or high population levels) to the relationships between dry-period severity and residential abandonment in areas of lesser resource demands (watersheds with low population density, settlements with low population levels). If these demographic conditions influenced vulnerability to dry periods, then the sensitivity and strength of the relationships between dry-period severity and residential abandonment will increase as watershed population density and settlement population levels increased.

It is important to assess demand models and the scale at which they might apply so that we have a basis to evaluate arguments that rely on differences and changes in demographic conditions to explain intra-regional differences in impacts and responses to dry periods. As previously discussed (Chapter Three), plausible arguments have been made that relatively high areal population density and settlement population levels could increase <u>or</u> decrease vulnerability to dry periods. Increases in shortfall risks and associated vulnerability are expected to occur during dry periods because resource supplies are assumed to be inherently limited by low precipitation in dry climates and resource demands are assumed to always be close to a threshold above which there is insufficient food to meet needs. Decreases in shortfall risks and vulnerability to dry periods are expected to occur when higher settlement population levels are assumed to provide the labor necessary for increasing productive capacity or higher areal population density offers a diversity of opportunities for acquiring food from others when needed. This analysis clarifies the influence of these demographic conditions on vulnerability to dry periods within central Arizona.

Based on the results presented below, the primary argument of this chapter is that models of vulnerability that emphasize the influence of watershed-scale population density on vulnerability to dry periods are supported while models that emphasize the influence of settlement population levels are not supported. People living in watersheds with high population density were more vulnerable to dry periods, or more responsive to dry periods through residential abandonment and movement, than people living in areas of low population density. And, people living in settlements with low to high population levels were all similarly vulnerable to dry periods, or similarly responsive to dry periods through movement. Thus, the scale at which resource demands are assessed is a critical aspect of demand models of vulnerability to dry periods. I present the results first by the influence of watershed population density then by the influence of settlement population levels on vulnerability to dry periods.

Resource Demands Assessed with Watershed Population Density

To assess the influence of watershed population density on vulnerability to dry periods, I examine the relationship between dry-period severity and residential abandonment in two ways: (1) by comparing the relationship between dry-period severity and residential abandonment among all rooms located in low density watersheds to the relationship in high density watersheds; and (2) by examining the extent to which differences in population density explain inter-watershed differences in the relationship between dry-period severity and residential abandonment identified in Chapter 6. Watershed population-density calculations are presented in Chapter Five, Table 5.2 and average density is listed again below in Table 7.2.

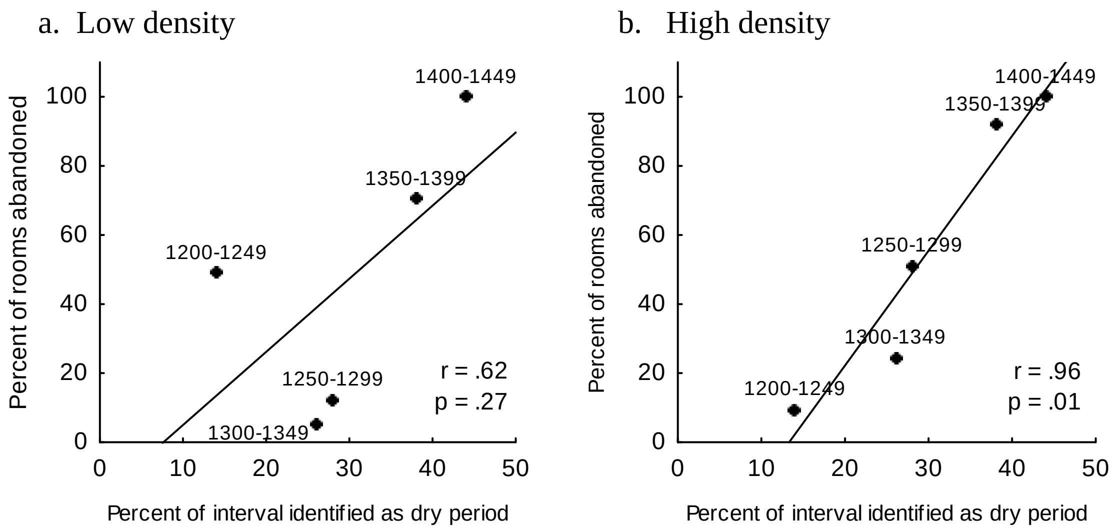
Dry Periods and Residential Abandonment in Low and High Density Watersheds

I compare the relationship between dry-period severity and residential abandonment among rooms located in low density watersheds to the relationship in high density watersheds. Rooms located in the Agua Fria and Upper Verde watersheds comprise the low density room group because density in these watersheds was consistently the lowest in the study area during the 1200 to 1450 period (Table 5.3). Rooms located in the Lower Verde, Upper Salt, and Tonto watersheds comprise the high density room group because density in these watersheds was consistently the highest in the study area throughout the period of study. I exclude the Lower Salt from this first analysis (but include it in all others below) because inclusion of the high number of rooms located in the Lower Salt would dominate the results of the high density room group. I calculate the percent of rooms abandoned by 50-year interval for both low and high density groups then identify the slopes, intercepts, and correlation coefficients that describe the relationship between dry-period severity and residential abandonment in each group (Table 7.1, 7.2; scatterplots in Figure 7.1).

Results suggest a stronger, more sensitive relationship between dry-period severity and residential abandonment in high density watersheds than in low density watersheds. The slope of the regression line in the high density watershed scatterplot (m = 3.3) is steeper than the slope in the low density watershed scatterplot (m = 2). For every one percent change in dry-period severity, residential abandonment increased 3.3% in high density watersheds and 2% in low density watersheds. Thus, residential abandonment in high density watersheds was more sensitive to changes in dry-period severity than in low density watersheds. The slopes cannot, however, be demonstrated statistically different (50% probability of equality), suggesting some necessary caution in our interpretations of difference. The intercept values from the regression equations (low density -16%; high density -44%) are also more likely to be the same than different (p = 65%). The intercept values are not meaningful as negative percents of residential abandonment, but they suggest that in the absence of dry-period years, residential abandonment was minimal. Correlation coefficients and inspection of the scatterplots indicate that the data values from high density watersheds better fit the regression line (r = .96) than the data values from the low density watersheds (r = .62). The r^2 values indicate that 92% of the variance in the relationship between dry-period severity and residential abandonment in high density watersheds is explained by changes in dry-period severity. Only 38% of the variance in the relationship between dry-period severity and residential abandonment is explained in low density watersheds. Factors other than dry-period severity influenced much of the changes in residential abandonment in low density watersheds.

Table 7.1 Number of Rooms Occupied, Abandoned, and Percent Abandoned in Central Arizona.

Watershed Density	Number Rooms Occupied and Abandoned and Percent of Rooms Abandoned										Correlation Between Dry-Period Severity and the Percent of Rooms Abandoned
	1200 to 1249		1250 to 1299		1300 to 1349		1350 to 1399		1400 to 1449		
	n	%	n	%	n	%	n	%	n	%	
Low density											
occupied	1,656		1,542		3,604		3,424		1,015		
abandoned	811	49	191	12	180	5	2,409	70	1,015	100	.62 (p = .27)
High density											
occupied	4,844		7,686		9,684		8,251		605		
abandoned	464	10	3,933	51	2,377	25	7,586	92	605	100	.96 (p = .01)
Dry-period severity indices (SFP precipitation)		14		28		26		38		44	


a. Low density

b. High density

Figure 7.1. Scatterplots of dry-period severity and residential abandonment by rooms in low and high density watersheds.

Table 7.2. Central Arizona: Slopes, Intercepts, Correlation Coefficients, and Their Probability of Equality.

Central Arizona Rooms	Slopes		Intercepts		Correlation Coefficients	
	slope	probability of equality	intercept	probability of equality	r	probability of equality
low density	2	50%	-16	63%	.62	22%
high density	3.3		-44		.96	

Population Density and Watershed-Scale Vulnerability

These results are consistent with a watershed-scale comparison of differences in the slopes of the regression lines that describe the relationship between dry-period severity and residential abandonment in each watershed (Chapter Six, Table 6.2). I use the slopes as an indicator of differences in vulnerability to dry periods. I also compare the correlations to identify the fit of the data values to the lines and the extent of explained and unexplained variance in the relationship between dry-period severity and abandonment in each watershed. Where watershed population density was lowest, the slope of the regression lines are shallower and the correlations lower (Upper Verde m = 3.1, r = .78; Agua Fria m = 1.0, r = .31) than where population density was highest (Lower Verde m = 3.3, r = .93; Upper Salt m = 3.2, r = .98; Tonto m = 3.9, r = .90) (Table 7.3; Figure 7.2). The Lower Salt is an obvious outlier, as discussed below. I demonstrated in Chapter 6, Table 6.2 that the slope of the regression line and the correlations for the Agua Fria watershed were statistically more likely to be different than similar to the slopes and correlations in the other watersheds. Similar statistical differences cannot be demonstrated for the Upper Verde.

Table 7.3. Watershed Population Density, Slopes, and Correlations Between Dry-period Severity and Residential Abandonment.

Watershed	Average Population Density 1200 to 1450 (Rooms per Square Kilometer[a])	Slopes[b]	Correlation[b] Between Dry-Period Severity and Room Abandonment	
		m	r	r^2
Upper Verde	.17 (low)	3.1	.78	.61
Agua Fria	.19 (low)	1.0	.31	.10
Lower Verde	.37 (high)	3.3	.93	.86
Upper Salt	.54 (high)	3.2	.98	.96
Tonto	.61 (high)	3.9	.90	.80
Lower Salt	1.68 (very high)	-.03	-.02	.0004

[a] density calculations in Chapter Five, Table 5.2
[b] slopes and correlations presented in Chapter Six, Table 6.2.

Inter-watershed differences in population density explain about half of the variance ($r^2 = .45$) in the steepness of the slopes (and inferred vulnerability to dry periods) identified in Chapter Six, Table 6.2. Specifically, there is a moderately strong linear relationship ($r = .67$, $p = .21$) between population density and the slope of the line describing the relationship between dry-period severity and abandonment in each watershed (Figure 7.2 a.). If the steepness of the slopes are used to rank vulnerability to dry periods in each watershed and watershed population density is also ranked, the relationship between density and vulnerability is also clearly demonstrated (Figure 7.2 b.).

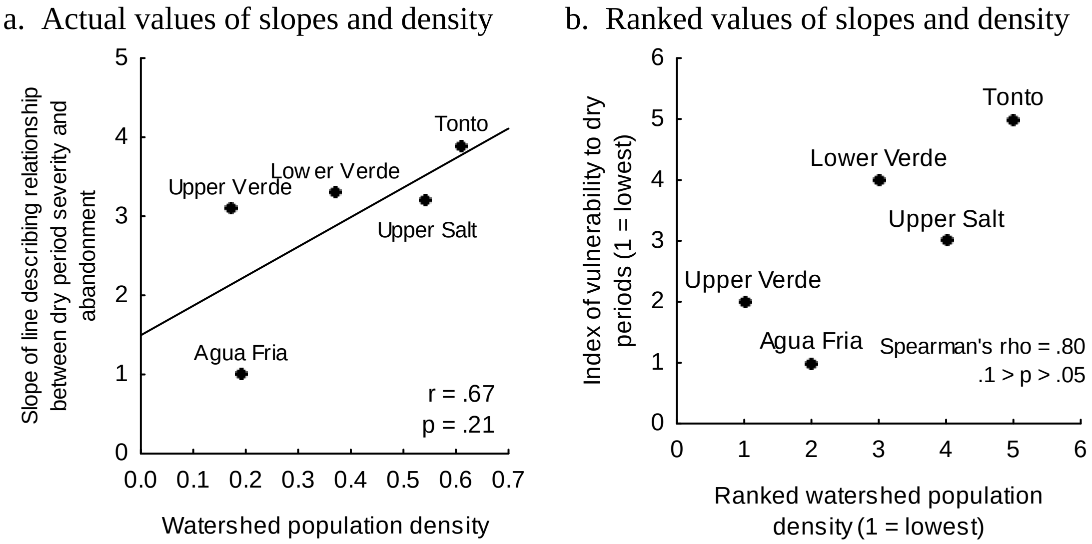


Figure 7.2. Relationship between watershed population density and the slopes of the lines describing the relationship between dry-period severity and abandonment.

Differences in density also explain about half of the variance (r^2 = .46) in the fit of the data values to these lines and the associated percent of explained variance in the relationship between dry-period severity and abandonment in each watershed (Figures 7.3. a., b.). As watershed population density increased, the amount of explained variance in the relationship between dry-period severity and abandonment increased. That is, most of the differences in residential abandonment among people living in settlements located in high density watersheds are explained by variation in dry-period severity. In contrast, other factors besides changes in dry period severity are influencing changes in residential abandonment in low density watersheds.

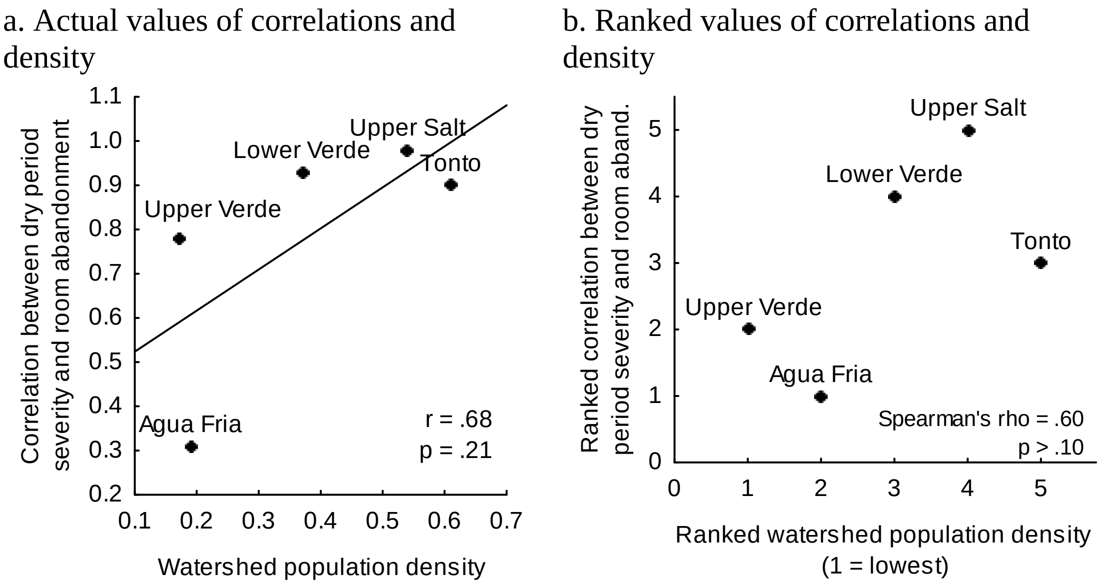


Figure 7.3. Relationship between watershed population density and correlation between dry-period severity and abandonment in each watershed.

Lower Salt

Unlike other watersheds in the study area, high population density in the Lower Salt watershed was not associated with a strong or sensitive relationship between dry-period severity and residential abandonment (r = -.01, m = -.03, b = 48; Figure 7.4 [same as Figure 6.1 b.]). For people living along the perennial Lower Salt River, extensive riverine agriculture and riparian resources created substantially different conditions from elsewhere in central Arizona. In addition to these resources, vulnerability to dry periods may have been attenuated by some combination of substantial available labor for water management, perennial streamflow for crops, and/or intra-watershed population shifting to obtain more access to water when needed (upstream/downstream, up-canal/down-canal).

Residential abandonment might have been discouraged by the lack of better watered locations (or refuges during dry periods) outside of the Lower Salt watershed. And, the relatively large numbers of people along the Lower Salt also could not have been easily accommodated elsewhere. It is also possible that dry-period reductions in potential productivity rarely resulted in meaningful increases in the risk of shortfalls. Perhaps most importantly, settlement abandonment along the Lower Salt may not have been considered a viable strategy in response to dry periods or other circumstances. Settlement along the Lower Salt has been documented for at least a thousand years prior to the study period. Such occupational durations and associated cultural history undoubtedly contributed to strong attachments to this area.

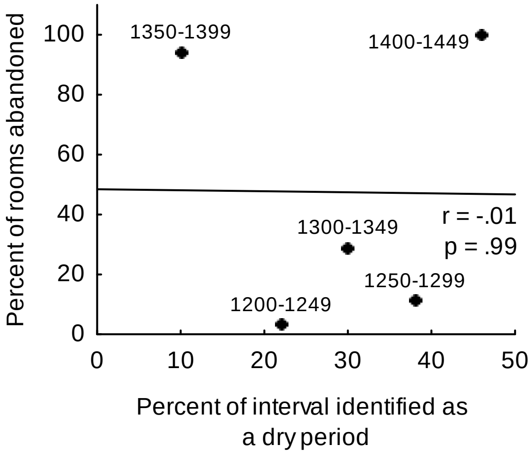


Figure 7.4. Relationship between dry-period severity and residential abandonment in the Lower Salt watershed (from Chapter Six).

In sum, the results suggest the relationship between dry-period severity and abandonment was different in low and high density watersheds. People living in low density watersheds were somewhat less vulnerable to dry periods, or less responsive through movement, than those living in high density watersheds. The Lower Salt River watershed is a notable exception to this finding.

Resource Demands Assessed with Settlement Population Levels

To assess the influence of settlement population levels on vulnerability to dry periods, I compare the relationship between dry-period severity and residential abandonment among settlements with low, moderate, and high population levels. I examine these relationships at the scale of the total study area ("Central Arizona") and within individual watersheds. Table 7.4 presents the number of rooms occupied, the number of rooms abandoned, and the percent of rooms abandoned by settlement population levels in each watershed and in the total study area. Methods of classifying settlements by low, moderate, and high population levels are presented in Chapter Five.

Table 7.4. Settlements Occupied and Abandoned by 50-year Interval, by Watershed, and the Correlation Between Dry-Period Severity and the Percent of These Settlements Abandoned During Each Interval.

Watershed – Settlement Population Levels[a]	1200 to 1249		1250 to 1299		1300 to 1349		1350 to 1399		1400 to 1449		Correlation Between Dry-Period Severity and Percent of Settlements Abandoned
	n	%	n	%	n	%	n	%	n	%	
Central Arizona[b]											
occupied – low	148		155		122		89		20		
abandoned – low	34	23	112	72	34	28	69	78	20	100	.90 (p = .04)
occupied – moderate	57		71		108		92		12		
abandoned – moderate	15	26	31	44	20	19	80	87	12	100	90 (p = .04)
occupied – high	6		16		28		27		5		
abandoned – high	0	0	5	31	4	14	22	81	5	100	.96 (p = .01)
Agua Fria											
occupied – low	18		5		13		12		9		
abandoned – low	14	78	3	60	1	8	3	25	9	100	.12 (p = .85)
occupied – moderate	8		4		15		15		8		
abandoned – moderate	5	63	3	75	0	0	7	47	8	100	.36 (p = .55)
occupied – high	0		1		6		6		2		
abandoned – high	0		0	0	0	0	4	67	2	100	.99 (p = .01)

Watershed – Settlement Population Levels[a]	1200 to 1249		1250 to 1299		1300 to 1349		1350 to 1399		1400 to 1449		Correlation Between Dry-Period Severity and Percent of Settlements Abandoned
	n	%	n	%	n	%	n	%	n	%	
Lower Salt[c]											
occupied – low	22		21		19		20		22		
abandoned – low	1	5	3	14	0	0	4	20	22	100	.60 (p = .28)
occupied – moderate	10		9		11		12		1		
abandoned – moderate	1	10	1	11	0	0	11	92	1	100	-.02 (p = .97)
occupied – high	10		11		12		11				
abandoned – high	0	0	1	9	3	25	11	100			-.77 (p = .23)
Lower Verde											
occupied – low	34		33		39		34		9		
abandoned – low	6	18	19	58	5	13	25	74	9	100	.90 (p = .04)
occupied – moderate	10		13		31		28		2		
abandoned – moderate	1	10	4	31	3	10	26	93	2	100	.91 (p = .03)
occupied – high	1		3		4		3				
abandoned – high	0	0	1	33	1	25	3	100			.94 (p = .06)

Watershed – Settlement Population Levels[a]	1200 to 1249		1250 to 1299		1300 to 1349		1350 to 1399		1400 to 1449		Correlation Between Dry-Period Severity and Percent of Settlements Abandoned
	n	%	n	%	n	%	n	%	n	%	
Tonto											
occupied – low	35		43		15		9				
abandoned – low	3	9	34	79	7	47	9	100			.97 (p = .04)
occupied – moderate	16		20		14		14				
abandoned – moderate	1	6	11	55	1	7	14	100			.87 (p = .13)
occupied – high	0		1		1		1				
abandoned – high	0		0	0	0	0	1	100			.99 p = .10)
Upper Salt											
occupied – low	47		63		38		19		1		
abandoned – low	3	6	53	84	19	50	18	95	1	100	.93 (p = .02)
occupied – moderate	10		12		32		22		2		
abandoned – moderate	2	20	9	39	13	41	20	91	2	100	.96 (p = .01)
occupied – high	3		6		12		13		2		
abandoned – high	0	0	3	50	2	17	11	85	2	100	.97 (p = .01)

Watershed – Settlement Population Levels[a]	1200 to 1249		1250 to 1299		1300 to 1349		1350 to 1399		1400 to 1449		Correlation Between Dry-Period Severity and Percent of Settlements Abandoned
	n	%	n	%	n	%	n	%	n	%	
Upper Verde											
occupied – low	7		7		15		14		1		
abandoned – low	3	43	1	14	1	7	13	93	1	100	.70 (p = .19)
occupied – moderate	6		6		12		10				
abandoned – moderate	3	50	0	0	2	17	10	100			.40 (p = .60)
occupied – high	2		3		3		3		1		
abandoned – high	0	0	0	0	0	0	2	67	1	100	.89 (p = .05)
Dry-period severity indices (SFP) for all watersheds except Lower Salt	14		28		26		38		44		
Dry-period severity indices (LSR) for Lower Salt	22		38		30		10		46		

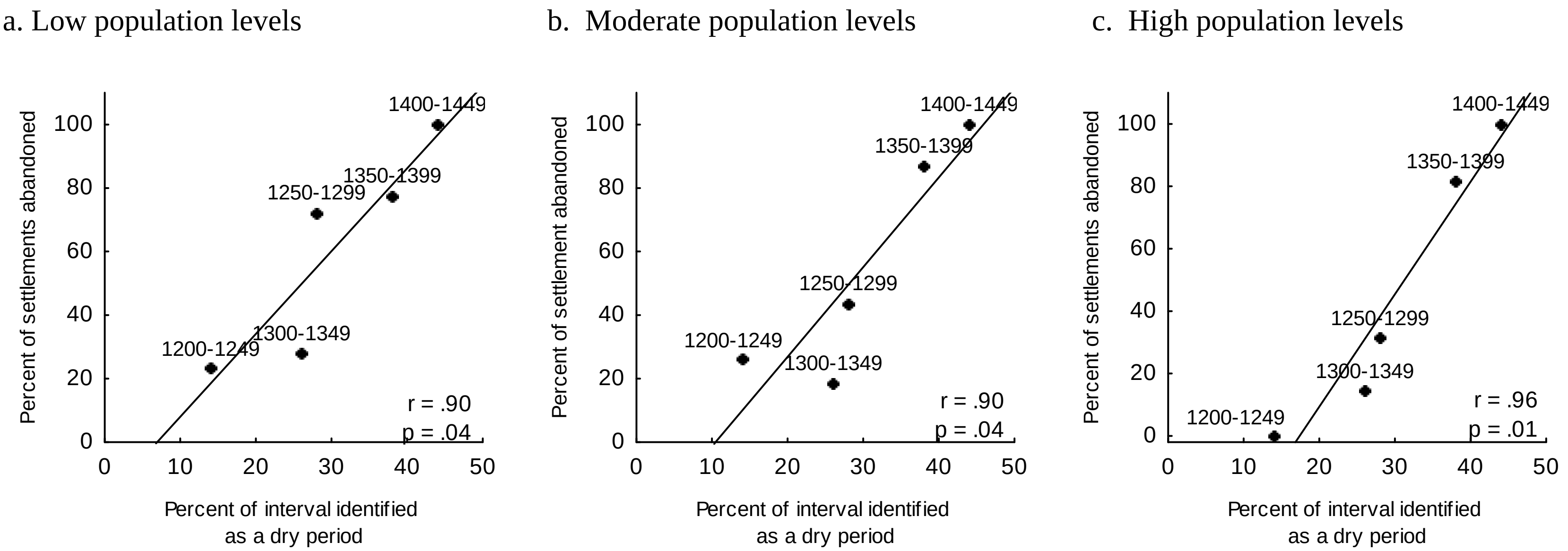
[a] Low population levels = 13 to 30 rooms, moderate population levels = 31 to 100 rooms, high population levels = 100+ rooms (size classes created by inspection of a histogram, Figure 5.1, of all settlements occupied in the study area, as discussed in Chapter Five).

[b] Central Arizona” includes all rooms/settlements in the Agua Fria, Big Chino-Williamson Valley, Carrizo, Lower Verde, Tonto, Upper Verde, and Upper Salt, and White watersheds. Big Chino-Williamson Valley, Carrizo, and White watersheds are excluded from the watershed-scale analysis due to low settlement and/or room numbers and the limited duration of occupation in these watersheds.

[c] Different settlement size classes are used for the Lower Salt; see Chapter Five, Figure 5.2.

Results indicate that the sensitivity and strength of the relationship between dry-period severity and residential abandonment at the Central Arizona scale (total study area) did not substantially vary with settlement population levels (Table 7.4; scatterplots in Figure 7.5. a., b., c.). The slopes of the regression lines in the low (m = 2.6), moderate (m = 2.8), and high population (m = 3.6) level scatterplots indicate sensitivity to dry-period severity at all settlement population levels (Table 7.5). For every one percent change in dry-period severity, residential abandonment increased 2.6 to 3.6%. The probability of equality of all slopes is 60%--more likely to be the same than different. The pairwise comparison indicates that the probability of equality of slopes for settlements with low and moderate population levels is also high--85%. The comparison of slopes for moderate and high (p = 46%) and low and high (p = 32%) population levels indicates, however, that these slopes are more likely different than the same. Visual inspection of the slopes plotted on a single scatterplot, however, is not sufficiently persuasive to conclude differences in vulnerability, despite the statistical differences (Figure 7.6). The intercept values for low (b = -18), moderate (b = -30) and high (b = -63) settlement population levels are more likely different than the same (p = 34%). The pairwise comparison indicates that the probability of equality of intercepts for settlements with low and high (p = 16%) and moderate and high population levels (p = 35%) is also low. The comparison of settlements with low and moderate population levels is more likely the same than different (p = 64%). The negative values suggest residential abandonment in the absence of dry-period years may have been less among settlements with high population levels than low population levels. And, that the level of dry period severity that finally induced residential abandonment was higher in high-population settlements than in low-population settlements. Correlation coefficients (low population levels, r = .90; moderate population levels, r = .90; high population levels, r = .96) and the scatterplots indicate strong fits of the data to each line. Changes in dry-period severity explain changes in residential abandonment among each population level about equally well.

Note that during data exploration, I examined relationships between dry-period severity and residential abandonment using different settlement size class thresholds (e.g., low population settlements with less than 31, 21, and 14 rooms and high population settlements with more than 30 and 50 rooms) at the Central Arizona scale. Differences in relationships were minimal and could not be attributed to more than chance. Thus, the interpretations presented in this section do not strongly depend on my classification of settlement population levels.



a. Low population levels

b. Moderate population levels

c. High population levels

Figure 7.5. Central Arizona: relationship between dry-period severity and residential abandonment by settlement population levels.

Table 7.5. Central Arizona: Slopes, Intercepts, Correlation Coefficients, and Their Probability of Equality.

Central Arizona Settlements	Slopes		Intercepts		Correlation Coefficients	
	slope	probability of equality	intercept	probability of equality	r	probability of equality
low population levels	2.6	low and high: 32%	-18	low and high: 16%	.90	low and high: 64%
moderate population levels	2.8	mod. and high: 46%	-30	mod. and high: 35%	.90	mod. and high: 64%
high population levels	3.6	low and mod.: 85% all: 60%	-63	low and mod.: 64% all: 34%	.96	low and mod.: 100%

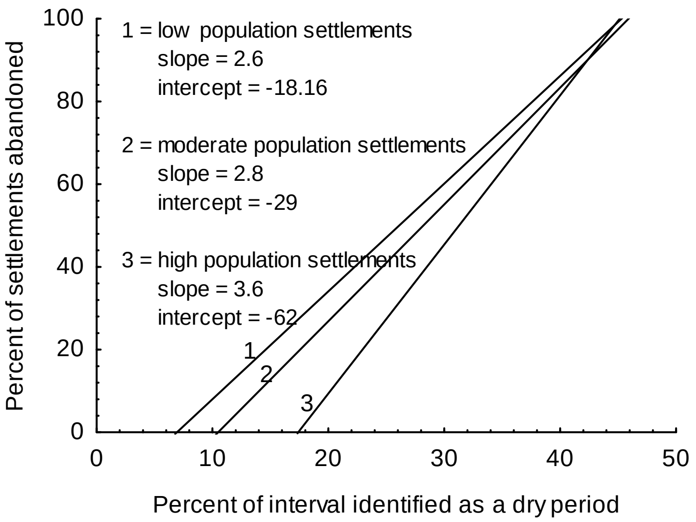


Figure 7.6. Comparison of slopes of regression lines for settlements with low, moderate, and high population levels.

Results within individual watersheds also support the conclusion that settlement population levels did not influence vulnerability or the extent of movement in response to dry periods. I present these results by watershed in the paragraphs below.

In the Agua Fria watershed, the relationship between dry-period severity and residential abandonment did not substantially vary with settlement population levels (Figure 7.7; Table 7.6). I exclude settlements with high population levels from this analysis because of low numbers of high population settlements (Table 7.4). The slopes of the regressions lines for settlements with low (m = .4) and moderate (m = 1.2) population levels indicate slightly greater sensitivity to changes in dry-period severity among settlements with moderate population levels. That is, for every one percent change in dry-period severity, residential abandonment increased .4% in settlements with low population levels and to 1.2% in settlements with moderate population levels. The slopes, however, are statistically more likely the same than different (77% probability of equality), suggesting no statistical basis to argue differences in sensitivity. The intercept values for settlements with low (b = 43) and moderate (b = 22) population levels are also more likely the same than different (probability = 91%). The high intercept values suggest residential abandonment may have been high in both groups even in the absence of dry-period years. Correlation coefficients (low r = .12; moderate r = .36) and the scatterplots indicate very weak fits of the data to the lines. Changes in dry-period severity poorly explain the changes in residential abandonment at both settlement population levels and the correlations are statistically more likely the same than different (p = 79%).

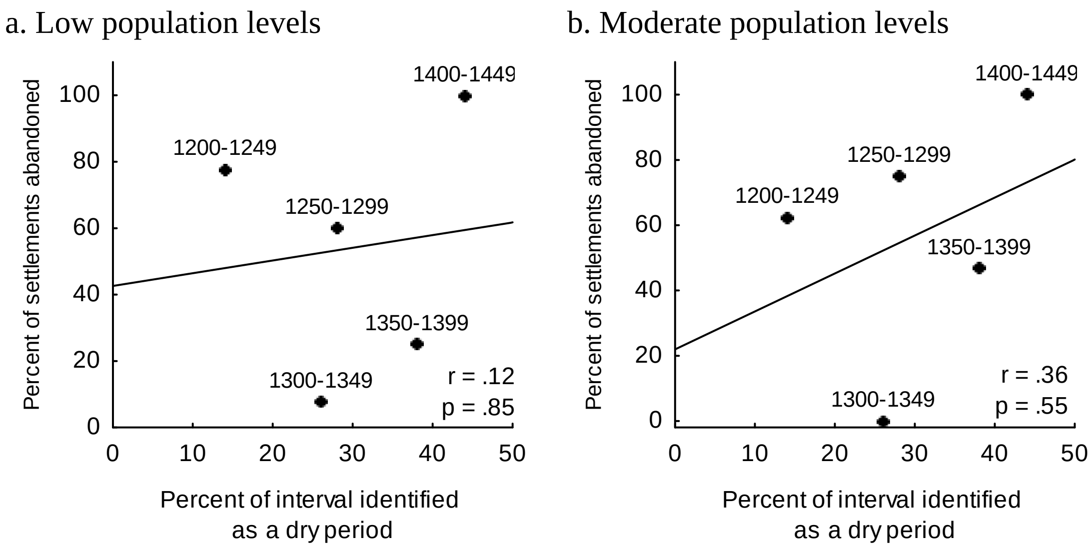


Figure 7.7. Agua Fria: relationship between dry-period severity and residential abandonment by settlement population levels.

Table 7.6. Agua Fria: Slopes, Intercepts, Correlation Coefficients, and Their Probability of Equality.

Agua Fria Watershed Settlements	Slopes		Intercepts		Correlation Coefficients	
	slope	probability of equality	intercept	probability of equality	r	probability of equality
low population levels	.4	77%	43	91%	.12	low and moderate: 79%
moderate population levels	1.2		22		.36	
high population levels	Relationship excluded due to few settlements with high population levels. See Table 7.4.					

In the Lower Salt watershed, interpretation of the influence of settlement population levels on residential abandonment is compromised for several reasons (Figure 7.8; Table 7.7). First, inspection of the scatterplots reveals the strong influence of outliers on the slopes of the regression lines describing the linear relationship between dry-period severity and residential abandonment among settlements with low and high population levels. Omitting the outliers would change the slope and direction of both relationships. Second, data on differences in settlement population levels in the Lower Salt are likely the least reliable because of challenges to systematic survey and excavation in the urban area (Phoenix) containing most watershed settlements (see Chapter Five). Note also that there are no identified settlements occupied with high population levels during the 1400 to 1449 interval (Table 7.4). Third, inspection of the low and moderate population level scatterplots suggests a quadratic (rather than a linear) relationship between dry-period severity and residential abandonment. Dry-period severity in the middle and minimum range are associated with the least residential abandonment. Explaining this relationship is beyond the scope of the models considered and this study. For these reasons, I do not rely on the results identified for this watershed to evaluate the vulnerability models.

I present the results for the Lower Salt, however, because they demonstrate the unique circumstances and suggest the need for further efforts to understand the influence of settlement population levels on residential abandonment in this watershed. The slopes of the regression lines for settlements with low (m = 1.8), moderate (m = -.08), and high (m = -2.9) population levels indicate relatively low and decreasing sensitivity to changes in dry-period severity. For every one percent change in dry-period severity, residential abandonment increased 1.8% among settlements with low population levels or decreased to -.08% to -2.9% in settlements with moderate and high population levels. The probability of equality of the slopes is 28% (and 9%, 38%, and 48% for the pairwise comparisons)--all more likely to be different than the same. The intercept values for settlements with low (b = -24), moderate (b = 45), and high population levels (b = 107) are, however, more likely the same than different (p > 63% for all pairwise comparisons). Correlation coefficients (low r = .60, moderate r = -.02, high r = -.77) and the scatterplots indicate very poor linear fits of the data to each regression line. Changes in dry-period severity do not effectively explain changes in residential abandonment at any settlement population level. The correlations are statistically more likely to be different than the same (p < 48%).

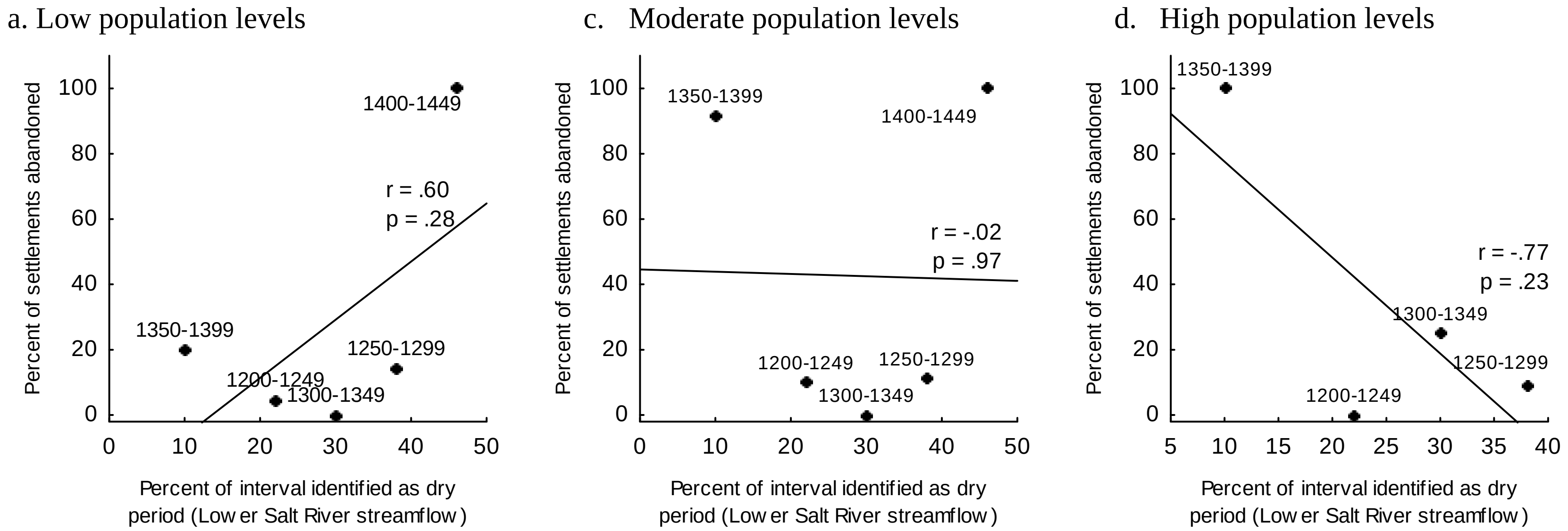


Figure 7.8. Lower Salt: relationship between dry-period severity and abandonment by settlement population levels.

Table 7.7. Lower Salt: Slopes, Intercepts, Correlation Coefficients, and Their Probability of Equality.

Lower Salt Watershed Settlements	Slopes		Intercepts		Correlation Coefficients	
	slope	probability of equality	intercept	probability of equality	r	probability of equality
low population levels	1.8	low and high: 9%	-24	low and high: 85%	.60	low and high: 16%
moderate population levels	-.08	mod. and high: 38%	45	mod. and high: 70%	-.02	mod. and high: 41%
high population levels	-2.9	low and mod.: 48% all: 28%	107	low and mod.: 63% all: 89%	-.77	low and mod.: 48%

In the Lower Verde watershed, the relationship between dry-period severity and residential abandonment did not vary with settlement population levels (Figure 7.9; Table 7.8). Note that relatively few high population settlements suggest caution in interpreting the relationship between dry-period severity and residential abandonment among settlements with high population levels (Table 7.4). The slopes of the regressions lines for settlements with low (m = 2.9), moderate (m = 3.5), and high (m = 4.1) population levels indicate relatively strong and increasing sensitivity to changes in dry-period severity. For every one percent change in dry-period severity, residential abandonment increased 3 to 4 percent. The slopes, however, are statistically more likely the same than different, suggesting no statistical basis to argue differences in sensitivity (69% probability of equality of all slopes; at least 41% probability of equality for the pairwise comparisons). The intercept values for settlements with low (b = -33), moderate (b = -57), and high population levels (b = -.69) are also more likely the same than different (all pairwise comparisons, p > 76%). The negative intercepts suggest residential abandonment may have been very low in the absence of dry-period years. Correlation coefficients (low r = .90; moderate r = .91, high r = 94) and the scatterplots indicate good fits of the data to the lines. Changes in dry-period severity effectively explain much of the variance in residential abandonment at all settlement population levels. The correlations are statistically more likely the same than different (p >83%).

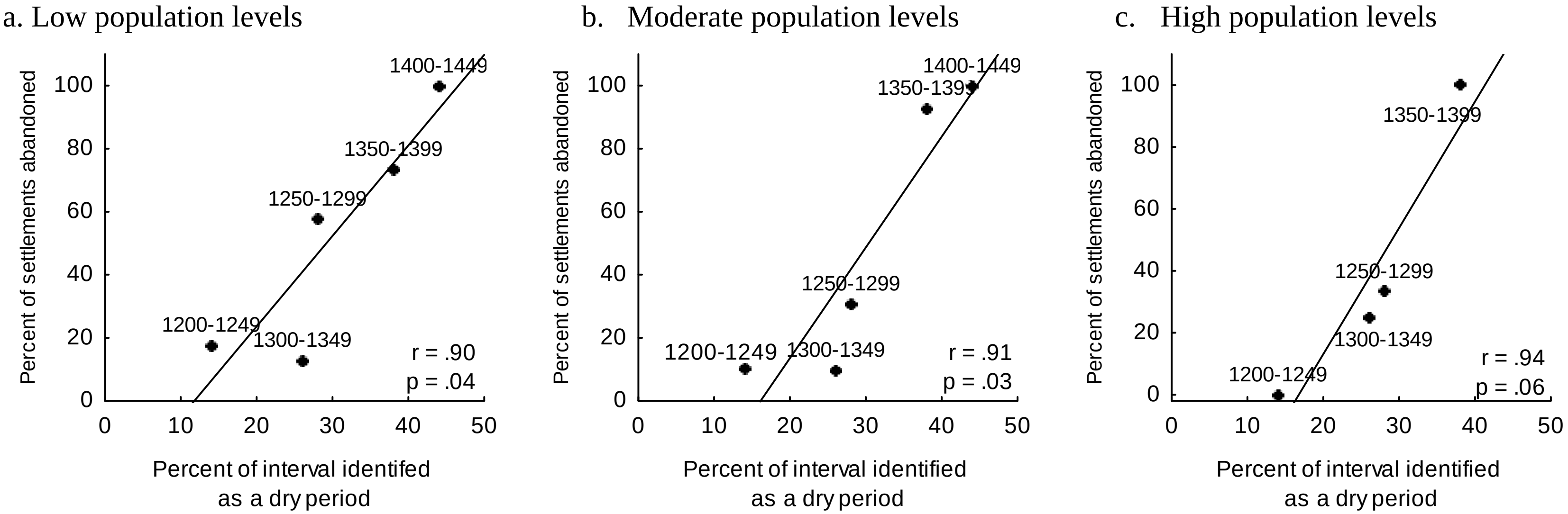


Figure 7.9. Lower Verde: relationship between dry-period severity and abandonment by settlement population levels.

Table 7.8. Lower Verde: Slopes, Intercepts, Correlation Coefficients, and Their Probability of Equality.

Lower Verde Watershed Settlements	Slopes		Intercepts		Correlation Coefficients	
	slope	probability of equality	intercept	probability of equality	r	probability of equality
low population levels	2.9	low and high: 41%	-33	low and high: 90%	.90	low and high: 83%
moderate population levels	3.5	mod. and high: 70%	-57	mod. and high: 78%	.91	mod. and high: 86%
high population levels	4.1	low and mod.: 61% all: 69%	-69	low and mod.:76% all: 95%	.94	low and mod.: 95%

In the Tonto watershed, the relationships between dry-period severity and residential abandonment did not substantially vary with settlement population levels (Figure 7.10; Table 7.9). I exclude settlements with high population levels because of low numbers of high population settlements (see Table 7.4). The slopes of the regressions lines for settlements with low (m = 3.9) and moderate (m = 4) population levels indicate relatively high sensitivity to changes in dry-period severity. For every one percent change in dry-period severity, residential abandonment increased about 4 percent. The probability of the equality of the slopes is 97%--more likely to be the same than different. The intercept values for settlements with low (b = -44) and moderate (b = -63) population levels are more likely different than the same (p = 27%). The negative intercepts suggest residential abandonment may have been very low in the absence of dry-period years and possibly lowest in the moderate precipitation group. Correlation coefficients (low r = .97; moderate r = .87) and the scatterplots indicate good fits of the data to the lines. The r^2 values indicate that 94% of the variance in the relationship between dry period severity and residential abandonment in settlements with low population levels and 76% of the variance in abandonment of settlements with moderate population levels is explained by changes in dry-period severity. The correlations are, however, statistically more likely to be the same than different (p = 59%).

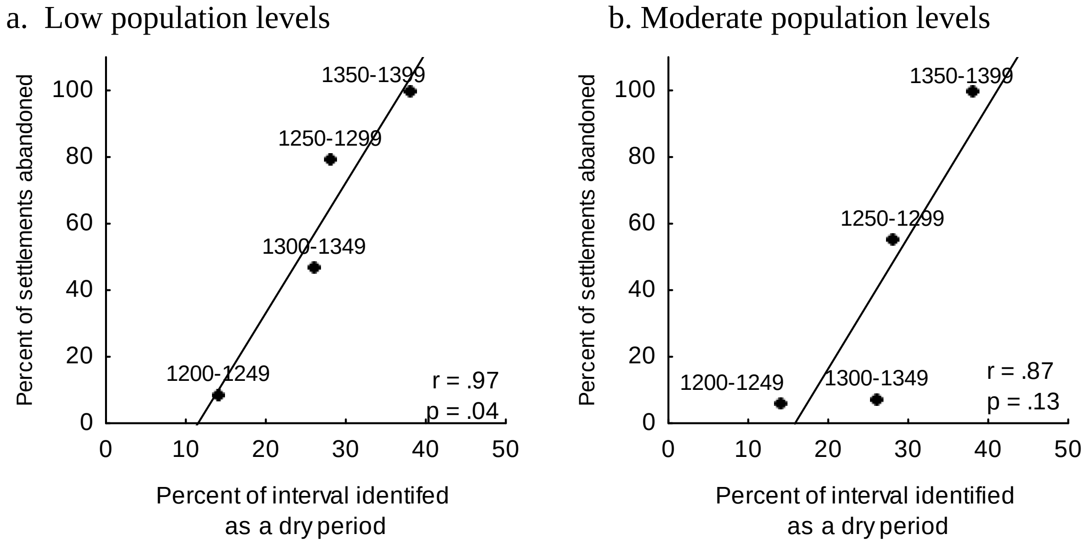
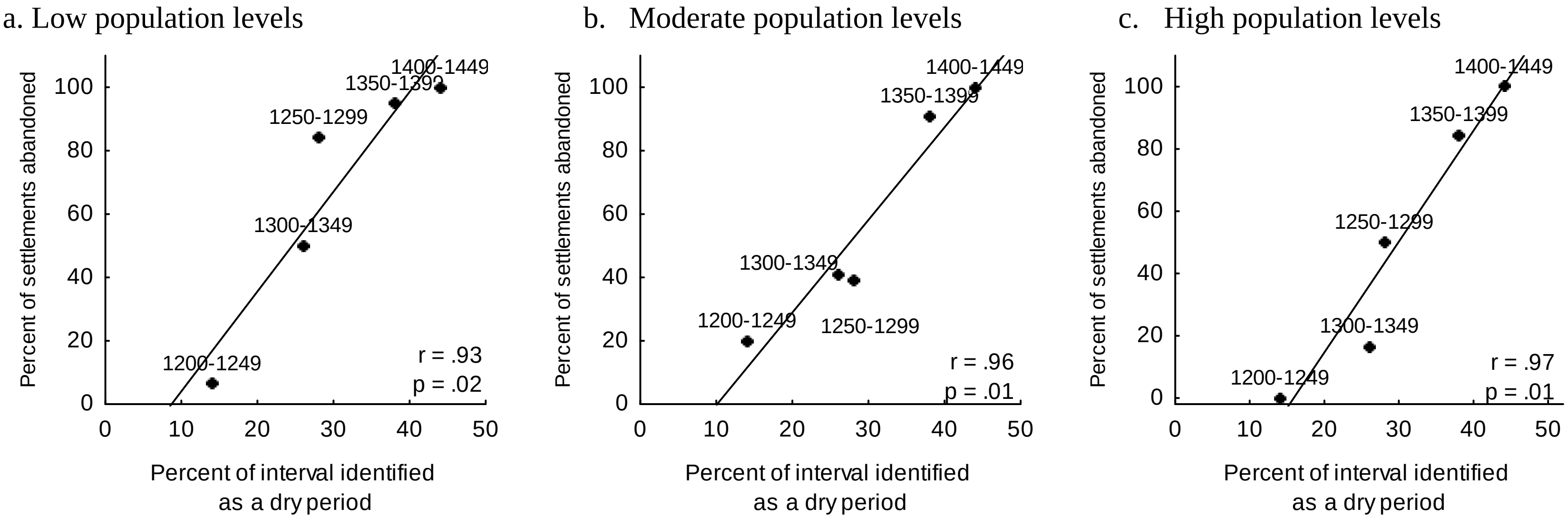


Figure 7.10. Tonto: relationship between dry-period severity and residential abandonment by settlement population levels.

Table 7.9. Tonto: Slopes, Intercepts, Correlation Coefficients, and Their Probability of Equality.

Tonto Watershed Settlements	Slopes		Intercepts		Correlation Coefficients	
	slope	probability of equality	intercept	probability of equality	r	probability of equality
low population levels	3.9		-44		.97	
		97%		27%		59%
moderate population levels	4		-63		.87	
high population levels	Relationship excluded due to few settlements with high population levels. See Table 7.4.					

In the Upper Salt watershed, the relationship between dry-period severity and residential abandonment did not substantially vary with settlement population levels (Figure 7.11; Table 7.10). The slopes of the regressions lines for settlements with low (m = 3.2), moderate (m = 2.9), and high (m = 3.6) population levels indicate relatively strong sensitivity to changes in dry-period severity at each population level. For every one percent change in dry-period severity, residential abandonment increased 2.9 to 3.6 percent. The probability of equality of the slopes is 74% (and at least 41% for all pairwise comparisons)--mostly more likely to be the same than different. The intercept values for settlements with low (b = -28), moderate (b = -29), and high population levels (b = -.57) are more likely different than the same (p < 33%). The negative intercepts suggest residential abandonment may have been very low in the absence of dry-period years and lowest among settlements with the highest population levels. Correlation coefficients (low r = .93; moderate r = .96, high r = .97) and the scatterplots indicate very good fits of the data to the lines. Thus, changes in dry-period severity effectively explain most of the changes in residential abandonment at all settlement population levels.



a. Low population levels

b. Moderate population levels

c. High population levels

Figure 7.11. Upper Salt: relationship between dry-period severity and abandonment by settlement population levels.

Table 7.10. Upper Salt: Slopes, Intercepts, Correlation Coefficients, and Their Probability of Equality.

Upper Salt Watershed Settlements	Slopes		Intercepts		Correlation Coefficients	
	slope	probability of equality	intercept	probability of equality	r	probability of equality
low population levels	3.2	low and high: 67%	-28	low and high: 10%	.93	low and high: 67%
moderate population levels	2.9	mod. and high: 41%	-29	mod. and high: 33%	.96	mod. and high:88%
high population levels	3.6	low and mod.: 79%	-57	low and mod.: 32%	.97	low and mod.: 77%
		all: 74%		all: 17%		

In the Upper Verde watershed, the relationship between dry-period severity and residential abandonment did not substantially vary with settlement population levels (Figure 7.12; Table 7.11). Note that relatively few high population settlements suggest caution in interpreting the relationship between dry-period severity and residential abandonment among settlements with high population levels (Table 7.4). The slopes of the regressions lines for settlements with low (m = 2.6), moderate (m = 1.8), and high (m = 3.6) population levels indicate relatively high sensitivity to changes in dry-period severity. For every one percent change in dry-period severity, residential abandonment increased 1.8 to 3.6 percent. The slopes, however, are statistically more likely the same than different, suggesting no statistical basis to argue differences in sensitivity (78% probability of equality of all slopes; at least 52% probability of equality for the pairwise comparisons). The intercept values for settlements with low (b = -27), moderate (b = -5), and high population levels (b = -.75) are, when considered together, more likely the same than different (p = 64%). The pairwise comparisons, however, show that the intercepts for settlements with low and moderate population levels compared to the high population intercept are more likely different than the same (low and high: p = 37%; moderate and high: p = 47%). The negative intercepts suggest residential abandonment may have been very low in the absence of dry-period years and that the level of dry period severity that finally induced residential abandonment was higher in high-population settlements than in low-population settlements. Correlation coefficients (low r = .70; moderate r = .40, high r = .89) and the scatterplots indicate poor to moderate fits of the data to the lines. Thus, changes in dry-period severity explain some of the variance in the relationship between dry-period severity and residential abandonment at low (r^2 = .49) and high settlement population levels (r^2 = .78) but little at the moderate population level (r^2 = .16).

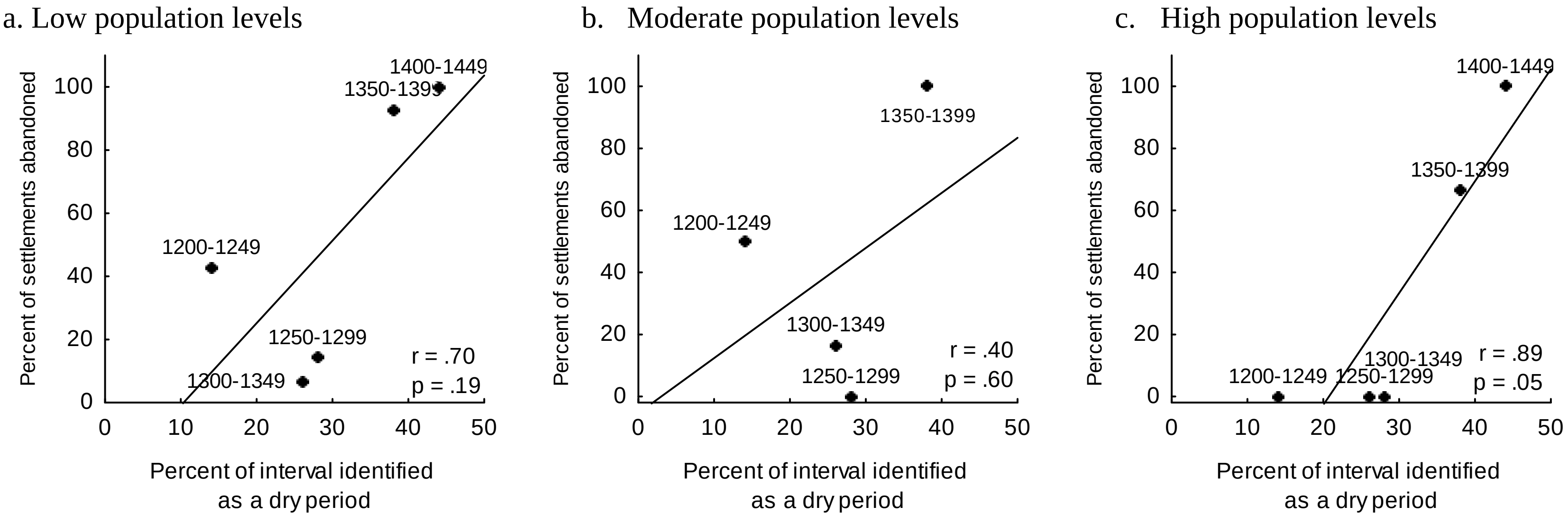


Figure 7.12. Upper Verde: relationship between dry-period severity and abandonment by settlement population levels.

Table 7.11. Upper Verde: Slopes, Intercepts, Correlation Coefficients, and Their Probability of Equality.

Upper Verde Watershed Settlements	Slopes		Intercepts		Correlation Coefficients	
	slope	probability of equality	intercept	probability of equality	r	probability of equality
low population levels	2.6	low and high: 62%	-27	low and high: 37%	.70	low and high: 65%
moderate population levels	1.8	mod. and high:52%	-5	mod. and high: 47%	.40	mod. and high:48%
high population levels	3.6	low and mod.: 79% all: 78%	-75	low and mod.: 96% all: 64%	.89	low and mod.: 72%

Summary and Implications

Watershed Population Density

Models of vulnerability to dry periods that emphasize differences in watershed population density to explain differences in vulnerability are supported by this study. Evidence supporting this conclusion includes: (1) less sensitive and weaker relationships between dry-period severity and residential abandonment among those living in areas of low population density than among those living in areas of high population density, (2) inter-watershed differences in population density explain about half of the variance in the steepness of the slopes (and inferred vulnerability to dry periods) among watersheds, and (3) differences in density also explain about half of the variance in the fit of the data values (correlations) and explained variance in the relationship between dry-period severity and abandonment in each watershed. In the evaluation of combined demand and supply models (Chapter Nine) I find that high watershed population density is usually associated with greater vulnerability to dry periods regardless of the potential productivity of settlement locations. Thus, people living in watersheds with the highest population density were more vulnerable to the risk of shortfalls during dry periods, or at least more responsive to dry-period vulnerabilities through residential abandonment and movement, than those living in watersheds with the lowest population density. This relationship is not evident in the very high density Lower Salt watershed where dry-period severity was not correlated with changes in the extent of residential abandonment. As discussed above, conditions in the Lower Salt were demographically and productively unique which suggests relationships identified elsewhere in central Arizona might not be evident in this watershed.

The influence of watershed population density implies that decisions to move into, encourage, and maintain (or not prevent) densely populated areas likely increased vulnerability to dry periods, or at least influenced residential abandonment during dry periods. Results also imply that moving into less densely populated areas would have been a viable strategy for managing vulnerability to dry periods. Increasing population density might increase vulnerability to dry periods by increasing the rate of consumption of resources within a given area, restricting movements to acquire resources, and/or increasing settlement and cultivation in areas of marginal productivity.

The influence of watershed population density on vulnerability to dry periods suggests the influence of exogenous events such as immigration on vulnerability to dry periods. Increasing population density due to an influx of immigrants into a watershed would have increased vulnerability for all watershed residents. In contrast with settlement-scale events and processes that can increase vulnerability and may be amenable to management, increases in watershed population density involved many people and places that could not be easily controlled. Limiting immigration throughout a watershed would likely have required violence or the threat of violence. Thus, settlement-scale strategies to manage dry-period related shortfall risks may have been necessary but not sufficient to reduce vulnerability to dry periods.

The strong and sensitive relationship between dry-period severity and residential abandonment in high density watersheds contradicts arguments that link increases in areal population density to decreases in residential mobility (Cordell 2000:183; Dean 1994:85; Minnis 1996; Powell 1988). High population density could limit residential mobility if settlement locations were already claimed, occupied, or hostilities restricted movement. Evidence from this study, however, shows that the percent of rooms abandoned in high density watersheds during the five, 50-year intervals from 1200 to 1450 are not systematically lower than the percent of rooms abandoned in low density watersheds (See Table 7.1 for the central Arizona scale and Table 6.1 for the watershed scale data. Table 7.3 identifies watersheds by high and low density). Thus, the idea that high areal population density (watershed or region) is associated with lesser residential mobility and low areal population density is associated with greater residential mobility is not supported in the central Arizona study area. Decoupling high population density from decreases in mobility questions arguments that have used this linkage. For example, Varien et al. (1996) have argued that increased population density due to settlement aggregation in the northern Southwest contributed to a socially constrained landscape and increasingly immobile organizational entities. Results identified here find no such linkage between high population density and decreased mobility, except in results for the Lower Salt watershed (as discussed above in this chapter.)

Settlement Population Levels

Models of vulnerability to dry periods that emphasize differences in settlement population levels to explain variation in human responses to dry periods are not supported. The evidence that supports this conclusion is the similarity of the sensitivity and strength of the relationships between dry-period severity and residential abandonment among those living in settlements with low, moderate, and high population levels throughout the study area. Thus, people living in settlements with high population levels and concomitantly high resource demands were about as vulnerable to dry periods as those living in settlements with low population levels and low resource demands. Differences in the influence of watershed population density and settlement population levels on vulnerability to dry periods suggests the scale at which resource demands are assessed is a critical aspect of vulnerability to dry periods.

These results do not resolve the currently contradictory views regarding the influence of settlement population levels on vulnerability to dry periods (Boserup 1965; Malthus 2001 [1798]; Meyer et al. 1998: 241). One view holds that more people place added stress on the environment thereby increasing vulnerability to dry periods. The other view holds that more people reduce vulnerability because a more populous society has greater resources with which to cope. Because vulnerability to dry periods among settlements with both low and high population levels was similar and relatively high, both or neither view may be correct. Yet, it is significant that settlements with the highest population levels were not substantially more vulnerable to dry periods. This implies that people living in settlements with high population levels did not have any apparent demographic-related advantage in managing shortfalls risks compared to people living in smaller settlements with fewer labor resources. In other words, any labor advantage was offset by a demand disadvantage. This result provides no support for arguments that emphasize differences in settlements population levels to explain differences in vulnerability to dry periods.

The finding of consistency in vulnerability between settlements with low and high population levels has implications for arguments regarding the causes of the pattern of settlement aggregation that began in the U.S. Southwest around 1100. Aggregation refers to "the processes that produce spatial clustering of households, communities, or archaeological habitation sites" and it appears in the archaeological record of the U.S. Southwest sometime after A.D. 1000 (Cordell et al. 1994:109). Subsistence stress has been argued to be among the causal factors of settlement aggregation (Haury 1962; Hill et al. 1970; Longacre 1966). However, because there is no evidence that settlements with relatively high population levels were less vulnerable to dry periods than settlements with low population levels, aggregation cannot be considered a 'solution' to subsistence stress. Thus, there is no evidence that population aggregation increased the effective organization of labor and more efficient food distribution to manage increasing risks of shortfall. Or, if there were subsistence benefits to aggregation, these benefits were short lived and did not result in increased settlement longevity or decreased frequency of residential abandonment.

In sum, results demonstrate that the veracity of demand models of vulnerability to dry periods depend on the spatial scale at which these demands are assessed. This directs attention to the importance of potential thresholds in areal population density rather than toward identifying specific settlement population levels in understanding vulnerability to dry periods. Future efforts to evaluate the influence of population levels on vulnerability to dry periods should identify and “hold constant” differences in the potential productivity of settlement locations and watersheds. In Chapter Nine, I consider a few demand/supply combinations but the focus of this chapter and study is the evaluation of existing vulnerability models. A thorough evaluation of the influence of settlement population levels on vulnerability to dry periods under a variety of productivity conditions is beyond the scope of this study. In the next chapter, I consider the influence of settlement and watershed-scale environmental conditions on vulnerability to dry periods.

CHAPTER 8:

THE INFLUENCE OF ENVIRONMENTAL CONDITIONS ON VULNERABILITY TO DRY PERIODS

The analyses in this chapter evaluate 'supply' models of vulnerability to dry periods by testing the expectation that environmental conditions associated with relatively greater resource productivity (supply) resulted in lesser vulnerability to dry periods. The environmental conditions I consider are each settlement's location relative to the nearest perennial river and the average annual precipitation level of settlement locations. At the watershed scale, I consider precipitation and streamflow discharge levels. I use these environmental conditions, which each identify differences in access to or availability of water, as indicators of differences in potential resource productivity and resource supplies among settlements and watersheds.

In each analysis in this chapter, I compare the relationships between dry-period severity and residential abandonment among those located in areas of greater potential productivity (near perennial rivers and in areas of high average annual precipitation and streamflow levels) to the relationships between dry-period severity and residential abandonment among those located in areas of lesser potential productivity (far from perennial rivers and in areas of low average annual precipitation and streamflow). If the environmental conditions considered in this chapter influenced vulnerability to dry periods, then the relationships between dry-period severity and residential abandonment will be less sensitive and weaker where productivity is assumed to have been higher and more sensitive and stronger where productivity is assumed to have been lower.

It is important to assess supply models of vulnerability to dry periods and the scale at which they might apply so that we have a basis to evaluate arguments that rely on intra-regional or inter-settlement productivity differences to explain differences in vulnerability to dry periods. These differences are often used to explain settlement location shifting motivated by dry-period increases in shortfall risks or why some settlements are abandoned during dry periods and others are not.

Based on the results presented below, the primary argument of this chapter is that models of vulnerability that link environmental conditions associated with greater potential resource productivity to lesser vulnerability to dry periods are not supported. People living where potential resource productivity was the highest were not less vulnerable to dry periods. Instead, those in areas with the highest potential productivity were often most vulnerable to dry periods. I present the results first by differences in environmental conditions among settlements then by differences in conditions among watersheds.

Settlement Proximity to Perennial Rivers

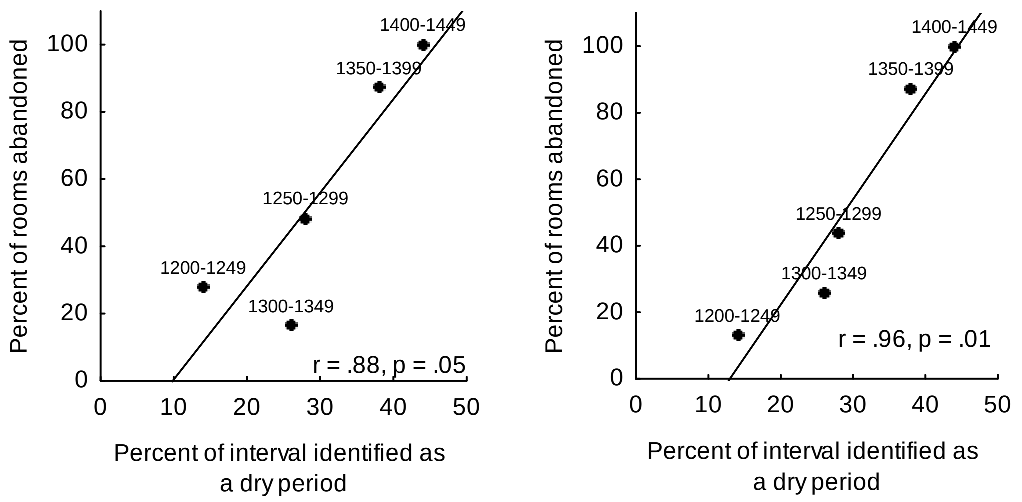
To assess the influence of a settlement's location relative to the nearest perennial river on vulnerability to dry periods, I compare the relationships between dry-period severity and residential abandonment among rooms located near and far from perennial rivers. Table 8.1 presents the number of rooms occupied, the number of rooms abandoned, the percent of rooms abandoned by riverine proximity in each watershed and in the total study area, and the associated correlation coefficients and p-levels. I exclude the Lower Salt watershed from this analysis because few settlements are located distant from the perennial Lower Salt River and we have already found that people living there were either relatively invulnerable to dry periods or if vulnerable, residential abandonment was not a response to this vulnerability. Methods of classifying settlements by locations near and far from perennial rivers are presented in Chapter Five.

At the scale of the total study area ("Central Arizona"), results indicate that the relationship between dry-period severity and residential abandonment was not influenced by a settlement's location relative to perennial rivers (Figure 8.1; Table 8.2). The slope of the regression line in the scatterplot of data values representing residential abandonment among rooms far from perennial rivers (m = 2.8) is similar to the slope of the line representing residential abandonment among rooms distant from perennial rivers (m = 3.2). For every one percent change in dry-period severity, residential abandonment increased 2.8 to 3.2 percent indicating sensitivity to dry periods in both riverine and non-riverine locations. The slopes are statistically more likely the same than different (71% probability of equality), suggesting no statistical basis to argue differences in sensitivity. The intercept values for settlements far from rivers (b = -27) and near rivers (b = -41) are also more likely the same than different (p = 86%). Correlation coefficients (far from rivers r = .88; near rivers r = .96) and the scatterplots indicate a slightly better fit and more explained variance in the near riverine room group but the correlations are statistically more likely the same than different (p = 57%). Thus, people living in settlements near perennial rivers were not less vulnerable to dry periods than people living far from perennial rivers, as predicted by a resource supply model of vulnerability to dry periods.

Table 8.1. Number and Percent of Rooms Occupied and Abandoned by Proximity to Perennial Rivers, by Watershed.

Watershed Room Locations By Riverine Proximity (Far From or Near To)	Number and Percent of Rooms Abandoned and Occupied										Correlation Between Dry-Period Severity and Percent of Rooms Abandoned
	1200 to 1249		1250 to 1299		1300 to 1349		1350 to 1399		1400 to 1449		
	n	%	n	%	n	%	n	%	n	%	
Central Arizona											
occupied – far	3,889		5,401		9,014		8,280		1,061		
abandoned – far	1,081	28	2,615	48	1,475	16	7,219	87	1,061	100	.88 (p = .05)
occupied – near	3,123		4,762		5,629		4,380		559		
abandoned– near	406	13	2,084	44	1,452	26	3,821	87	559	100	.96 (p = .01)
Agua Fria											
occupied – far	755		427		1,570		1,550		700		
abandoned - far	566	75	176	41	20	1	850	5	700	100	.32 (p = .60)
occupied - near	32		0		367		367		160		
abandoned– near	32	100	0		0	0	207	56	160	100	.07 (p = .93)
Lower Verde											
occupied – far	551		546		1,086		1,011		13		
abandoned - far	80	15	288	53	75	7	998	99	13	100	.89 (p = .04)
occupied - near	611		1,218		2,232		1,739		231		
abandoned– near	73	12	315	26	493	22	1,508	87	231	100	.93 (p = .02)

Watershed Room Locations By Riverine Proximity (Far From or Near To)	Number and Percent of Rooms Abandoned and Occupied										Correlation Between Dry-Period Severity and Percent of Rooms Abandoned
	1200 to 1249		1250 to 1299		1300 to 1349		1350 to 1399		1400 to 1449		
	n	%	n	%	n	%	n	%	n	%	
Tonto											
occupied – far	1,189		1,535		1,004		934				
abandoned - far	98	8	906	59	126	13	934	100			.88 (p = .12)
occupied - near	412		686		440		360				
abandoned– near	16	4	371	54	80	18	360	100			.93 (p = .07)
Upper Salt											
occupied – far	878		2,072		3,883		3,684		348		
abandoned - far	42	5	905	44	884	23	3,336	91	348	100	.97 (p = .01)
occupied - near	1,203		1,629		1,039		523		13		
abandoned– near	155	13	1,173	72	719	69	510	98	13	100	.96 (p = .01)
Upper Verde											
occupied – far	259		131		196		176				
abandoned - far	128	49	0	0	20	10	176	100			.39 (p = .61)
occupied - near	610		984		1,471		1,331		155		
abandoned– near	85	14	15	2	140	10	1,176	88	155	100	.84 (p = .08)
Dry-period severity indices (SFP precipitation)	14		28		26		38		44		



a. Central Arizona rooms abandoned located far from perennial rivers

b. Central Arizona rooms abandoned near perennial rivers

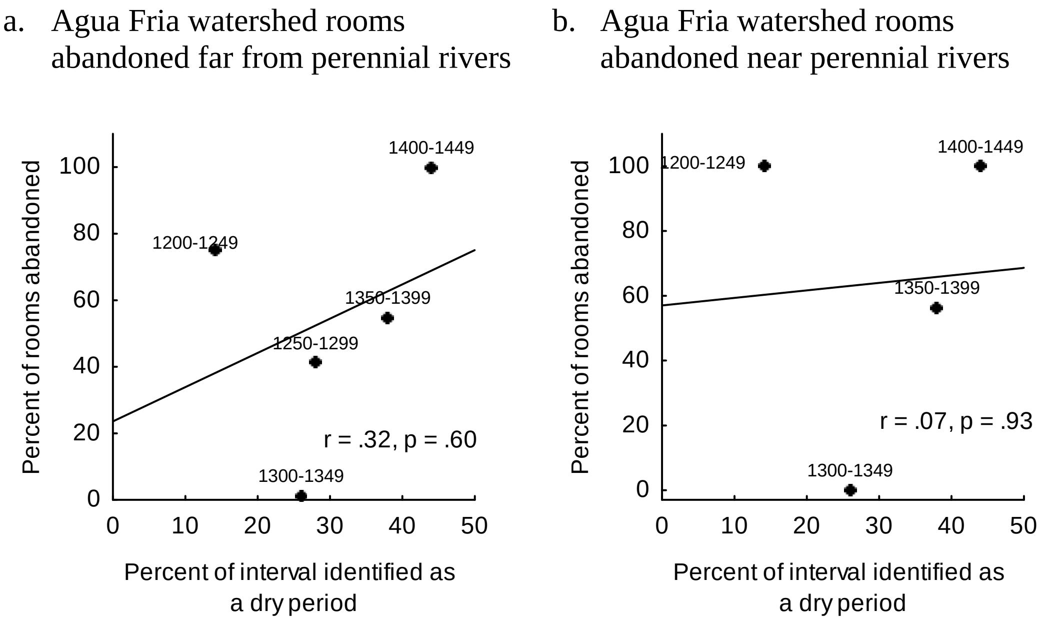
Figure 8.1. Central Arizona: rooms abandoned by riverine proximity.

Table 8.2. Central Arizona: Slopes, Intercepts, Correlation Coefficients, and Their Probability of Equality.

Central Arizona Settlements	Slopes		Intercepts		Correlation Coefficients	
	slope	probability of equality	intercept	probability of equality	r	probability of equality
far from a perennial river	2.8	71%	-27	86%	.88	57%
near a perennial river	3.2		-41		.96	

The results for the total study area are consistent with those for individual watersheds (except the Upper Salt discussed below). The slopes of the regression lines that describe the linear relationship between dry-period severity and residential abandonment, correlation coefficients, and the scatterplots indicate relatively similar relationships between dry-period severity and residential abandonment among rooms near and far from perennial riverine resources (Figures 8.2 through 8.6). Strong statistical evidence that the pairs of correlation coefficients in each watershed are different is also lacking as the probabilities of equality of the slopes, intercepts, and correlations are all relatively high (Tables 8.3 through 8.7). This similarity suggests resource productivity as affected by proximity to perennial rivers, did not influence vulnerability to dry periods, or at least decisions to abandon existing settlements.

The only exception to the broad-scale study area pattern is in the Upper Salt where results identify somewhat greater sensitivity to dry periods among those living far from perennial rivers (Figure 8.5; Table 8.6). The slope of the line (m = 3.5) representing the relationship between dry-period severity and residential abandonment far from perennial rivers is somewhat steeper that the line representing the relationship near perennial rivers (m = 2.9). For every one percent change in dry-period severity, residential abandonment increased 3.5% far from perennial rivers and 2.9% near perennial rivers. The slopes and intercepts are both more likely different than the same (slopes p = 45%; intercepts p = 5%). The data values fit the regression lines equally well (r = .97 and .96, probability of equality: 88%) indicating changes in dry-period severity explain residential abandonment equally well among both groups. Given the relatively small difference in sensitivity (about one-half a percent in residential abandonment between groups), this exception does not threaten the broad-scale pattern. Therefore, models of vulnerability to dry periods that emphasize differences in riverine proximity to explain variation in vulnerability to dry periods are not supported. [Because of the consistency of the other findings and the focus of this analysis on evaluating models of vulnerability (not explaining residential abandonment in each watershed), I do not describe the results for each watershed. The details are presented in the associated figures and tables].



a. Agua Fria watershed rooms abandoned far from perennial rivers

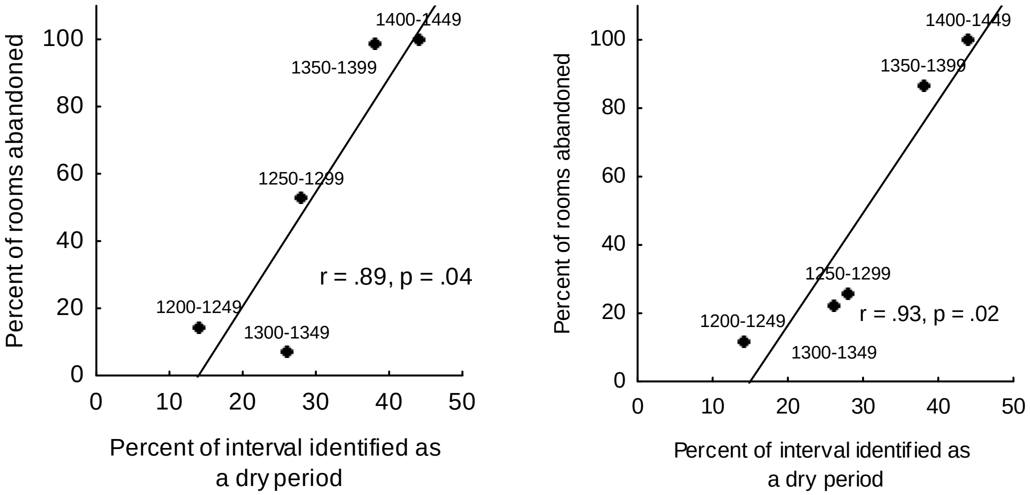
b. Agua Fria watershed rooms abandoned near perennial rivers

Figure 8.2. Agua Fria: rooms abandoned by riverine proximity.

Table 8.3. Agua Fria. Slopes, Intercepts, Correlation Coefficients,

and Their Probability of Equality.

Agua Fria Watershed Settlements	Slopes		Intercepts		Correlation Coefficients	
	slope	probability of equality	intercept	probability of equality	r	probability of equality
Far from a perennial river	.29	99%	36	57%	.32	83%
Near a perennial river	.23		57		.07	



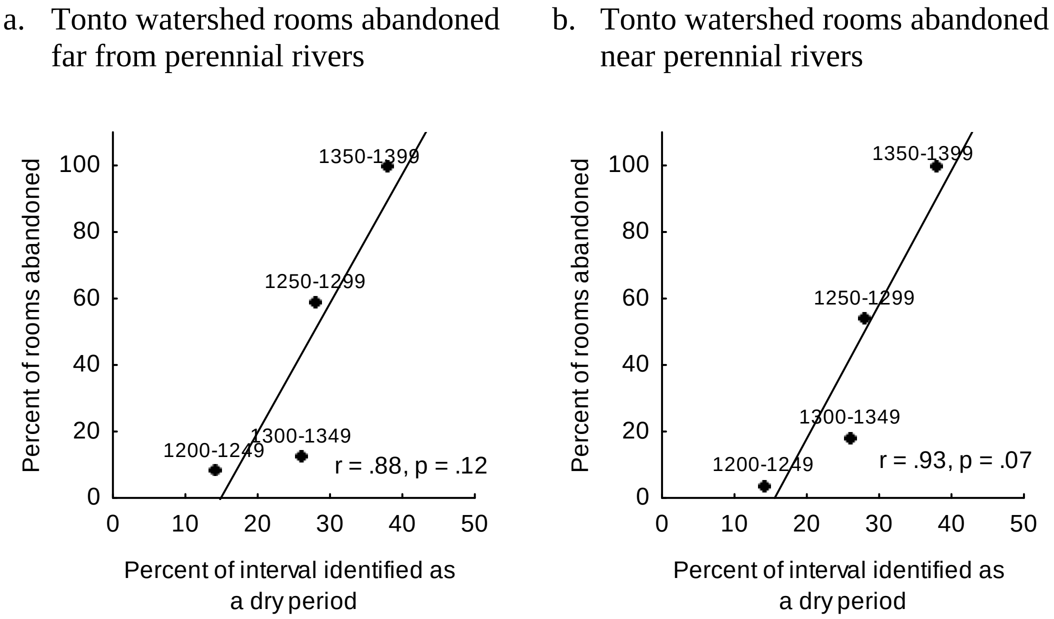
a. Lower Verde watershed rooms abandoned far from perennial rivers

b. Lower Verde watershed rooms abandoned near perennial rivers

Figure 8.3. Lower Verde: rooms abandoned by riverine proximity.

Table 8.4. Lower Verde: Slopes, Intercepts, Correlation Coefficients, and Their Probability of Equality.

Lower Verde Settlements	Slopes		Intercepts		Correlation Coefficients	
	slope	probability of equality	intercept	probability of equality	r	probability of equality
Far from a perennial river	3.4	94%	-47	67%	.89	81%
Near a perennial river	3.3		-49		.93	



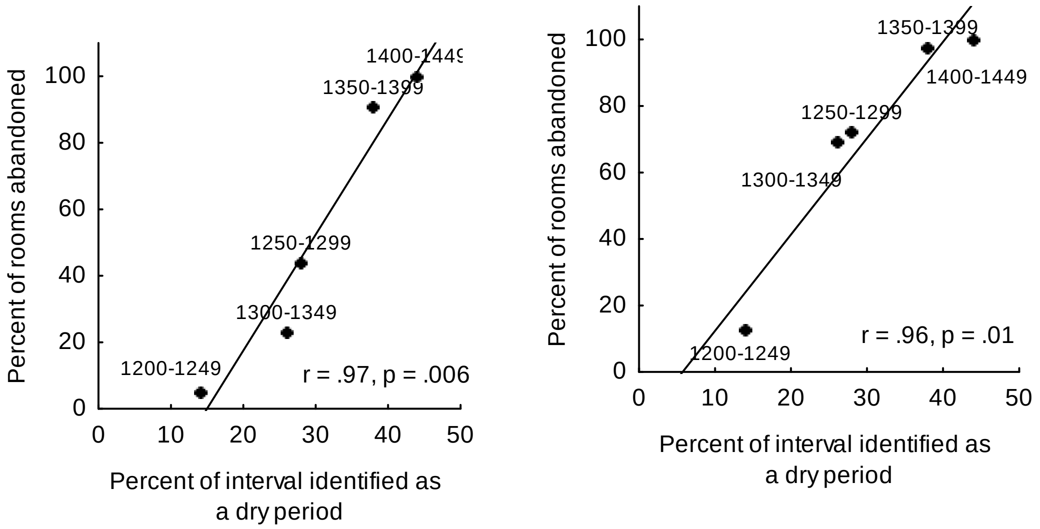
a. Tonto watershed rooms abandoned far from perennial rivers

b. Tonto watershed rooms abandoned near perennial rivers

Figure 8.4. Tonto: rooms abandoned by riverine proximity.

Table 8.5. Tonto: Slopes, Intercepts, Correlation Coefficients, and Their Probability of Equality.

Tonto Watershed Settlements	Slopes		Intercepts		Correlation Coefficients	
	slope	probability of equality	intercept	probability of equality	r	probability of equality
Far from a perennial river	3.9	94%	-58	95%	.88	84%
Near a perennial river	4		-63		.93	



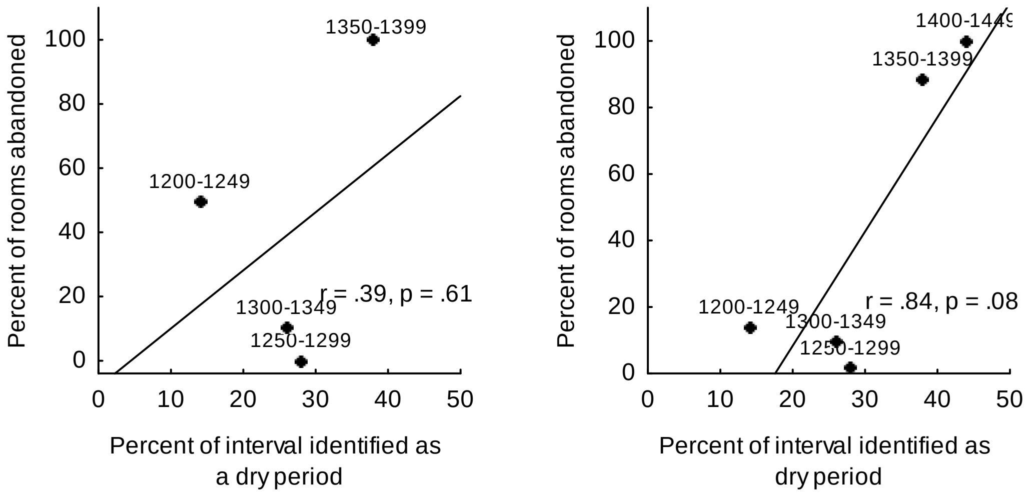
a. Upper Salt watershed rooms abandoned far from perennial rivers

b. Upper Salt watershed rooms abandoned near perennial rivers

Figure 8.5. Upper Salt: rooms abandoned by riverine proximity.

Table 8.6. Upper Salt: Slopes, Intercepts, Correlation Coefficients, and Their Probability of Equality.

Upper Salt Watershed Settlements	Slopes		Intercepts		Correlation Coefficients	
	slope	probability of equality	intercept	probability of equality	r	probability of equality
Far from a perennial river	3.5	45%	-52	5%	.97	88%
Near a perennial river	2.9		-17		.96	



a. Upper Verde watershed rooms abandoned far from perennial rivers

b. Upper Verde watershed rooms abandoned near perennial rivers

Figure 8.6. Upper Verde: rooms abandoned by riverine proximity.

Table 8.7. Upper Verde: Slopes, Intercepts, Correlation Coefficients, and Their Probability of Equality.

Upper Verde Watershed Settlements	Slopes		Intercepts		Correlation Coefficients	
	slope	probability of equality	intercept	probability of equality	r	probability of equality
Far from a perennial river	1.8	60%	-8.7	79%	.39	50%
Near a perennial river	3.4		-60		.84	

Settlement Area Precipitation Levels

To assess the influence of the average annual precipitation level of a settlement's location on dry-period related residential abandonment, I compare the relationship between dry-period severity and residential abandonment among rooms located in areas receiving low, moderate, and high precipitation. I examine these relationships only at the scale of the total study area. The range of settlement precipitation values is limited at the watershed scale. For example, there are no settlements located in areas of low precipitation in the Upper Salt and no settlements located in areas of high precipitation in the Agua Fria. Methods of classifying settlements by low, moderate, and high precipitation levels are presented in Chapter Five.

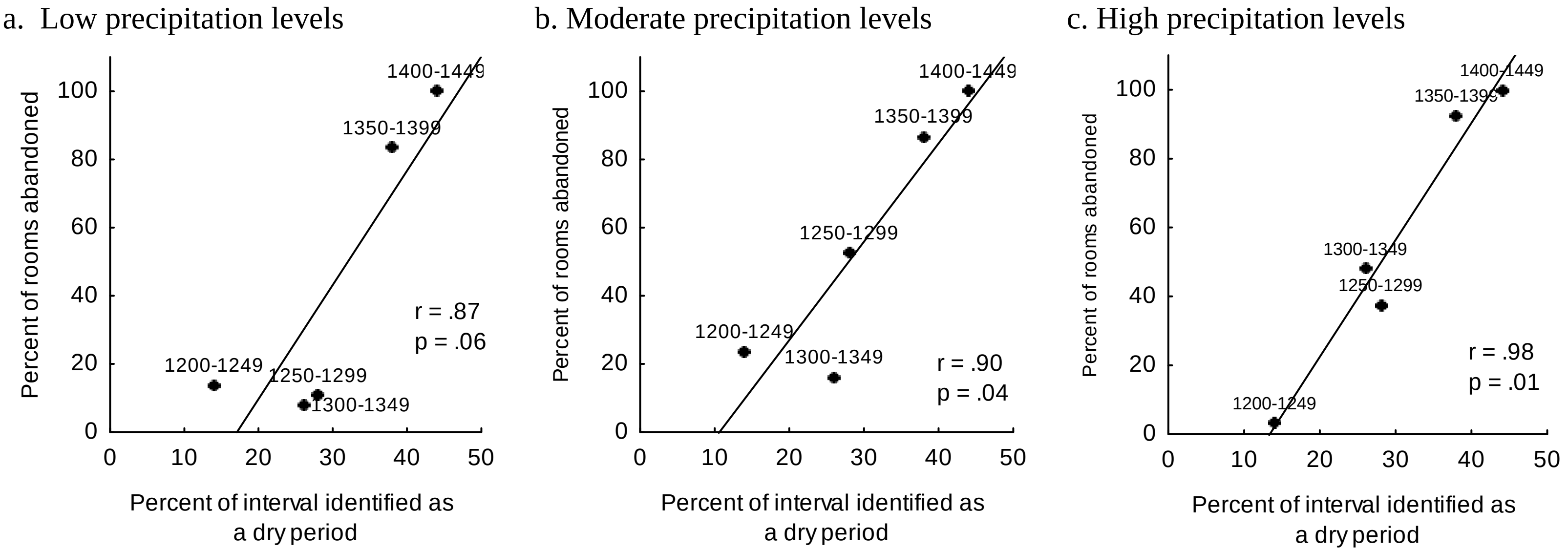
Results do not demonstrate strong differences in the relationship between dry-period severity and residential abandonment by differences in precipitation levels (Table 8.8, 8.9; Figure 8.7). People living in settlement areas with the highest precipitation levels were not the least vulnerable to dry periods, contrary to model expectations. The slopes of the regression lines in the low (m = 3.3), moderate (m = 2.9), and high precipitation (m = 3.4) level scatterplots identify sensitivity to dry-period severity at all settlement population levels. For every one percent change in dry-period severity, residential abandonment increased 2.9 to 3.6%. The probability of equality of the slopes is 89% (and 58% to 95% for each pair comparison)--more likely to be the same than different. The intercept values for low (b = -57), moderate (b = -30) and high (b = -46) precipitation levels are more likely different than the same (p = 43%; and lower for particular pairs).

Negative residential abandonment percents are not quantitatively meaningful but they suggest residential abandonment in the absence of dry-period years may have been the least among settlements with low precipitation. In sum, there is not a strong basis to argue differences in sensitivity or vulnerability to dry periods due to settlement-scale average annual precipitation conditions.

There is, however, some evidence suggesting the possibility of differences in the relationship between dry-period severity and residential abandonment at different precipitation levels. The strongest evidence is the difference in the fit of the data values to the regression lines in each scatterplot. As indicated by the correlation coefficients (low r = .87; moderate r = .90; high r = .98) and visual inspection of the scatterplots, the fit improves as settlement area precipitation levels increase. The correlations are more likely to be different than the same in two of the three pair comparisons: low and high, p = 34%, moderate and high, p = 41%, low and moderate, p = 89%. Differences in the fit of the data values to the line demonstrate that changes in dry-period severity explain more of the variance in the relationship between dry-period severity and residential abandonment as precipitation levels increase. The r^2 values indicate that 76% of the variance in the relationship between dry-period severity and residential abandonment in areas with low precipitation, 81% of the variance in areas with moderate precipitation, and 96% of the variance in areas of high precipitation is explained by differences in dry-period severity. Differences in sensitivity to dry periods cannot be argued because of the similarity of the slopes. Differences in explained variance and especially the patterned increase with precipitation levels, however, might indirectly signal differences in vulnerability to dry periods. I continue to investigate these differences in the next section.

Table 8.8. Central Arizona: Number and Percent of Rooms Occupied and Abandoned by Settlement Area Precipitation Level.

Room Locations by Precipitation Levels	Number and Percent of Rooms										Correlation Between Dry-Period Severity and Percent of Rooms Abandoned
	1200 to 1249		1250 to 1299		1300 to 1349		1350 to 1399		1400 to 1449		
	n	%	n	%	n	%	n	%	n	%	
Central Arizona											
occupied – low (8-14”)	755		1,096		1,248		1,148		190		
abandoned – low	104	14	117	11	100	8	958	83	190	100	.87, p = .06
occupied– mod. (14-22”)	5,781		7,778		11,346		9,951		1,315		
abandoned – moderate	1,367	24	4,096	53	1,839	16	8,636	87	1	100	.90, p = .04
occupied – high (22-36”)	476		1,289		2,049		1,561		115		
abandoned – high	16	3	486	38	988	48	1,446	93	115	100	.98, p = .01
Dry-period severity indices (SFP precipitation)	14		28		26		38		44		



a. Low precipitation levels

b. Moderate precipitation levels

c. High precipitation levels

Figure 8.7. Central Arizona: relationship between dry-period severity and rooms abandoned by settlement area precip. levels.

Table 8.9. Slopes, Intercepts, Correlation Coefficients, and Their Probability of Equality.

Central Arizona Settlements	Slopes		Intercepts		Correlation Coefficients	
	slope	probability of equality	intercept	probability of equality	r	probability of equality
Low precip. levels	3.3	low and high: 95%	-57	low and high: 28%	.87	low and high: 34%
Moderate precip. levels	2.9	mod. and high: 58%	-30	mod. and high: 97%	.90	moderate and high: 41%
High precip. levels	3.4	low and mod.: 75%	-46	low and mod.: 37%	.98	low and moderate: 89%
		all: 89%		all: 43%		

Settlement Area Precipitation Levels by Riverine Proximity

To further investigate the influence of settlement area precipitation levels on vulnerability to dry periods, I compare the relationships between dry-period severity and residential abandonment among those living in areas of low, moderate, and high precipitation near and far from perennial rivers. I conduct this analysis at the scale of the entire study area to maximize the number of rooms in each productivity classification. I first create two groups of rooms: those located near perennial rivers and those far from perennial rivers. I then identify within each of these groups those rooms located in areas of low, moderate, and high precipitation levels. After inspecting the room counts in each classification, I exclude two groups of rooms from this analysis due to low numbers of rooms/settlements: rooms far from perennial rivers in areas of low precipitation and rooms near perennial rivers in areas of high precipitation. I examine the relationship between dry-period severity and residential abandonment for each of the remaining groups. Table 8.10 identifies the number of rooms occupied, abandoned, the percent of rooms abandoned in each classification, and the relationship with dry-period severity.

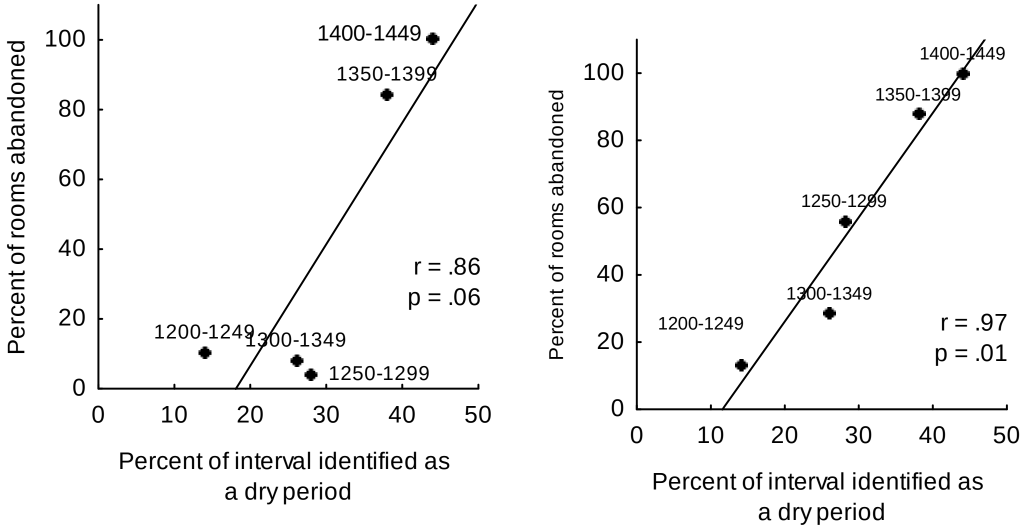
For people living near perennial rivers, results do not demonstrate strong differences in the relationship between dry-period severity and residential abandonment by differences in precipitation levels (Table 8.10, 8.11; Figure 8.8). Note that I exclude the high precipitation, near riverine room group as the number of rooms in the category is limited. The slopes of the regression lines in the low (m = 3.5) and moderate (m = 3.1) precipitation group scatterplots identify sensitivity to dry-period severity at both precipitation levels. For every one percent change in dry-period severity, residential abandonment increased 3.1 to 3.5%. We cannot draw strong conclusions about differences in sensitivity, however, because the statistical probability of equality of the slopes is high (p = 79%).

Consistent with the analysis in the previous section, there is weak evidence that as precipitation levels increased, vulnerability to dry periods increased. The evidence suggesting this possibility is the difference in the fit of the data values to the similarly sloped regression lines in each scatterplot. As indicated by the correlation coefficients (low r = .86; moderate r = .97) and visual inspection of the scatterplots, the fit improves as settlement area precipitation levels increase between the low and moderate precipitation groups. The correlations are more likely to be different than the same (p = 42%). The correlations demonstrate that changes in dry-period severity explain almost all of the variance in residential abandonment in the moderate precipitation group (r^2 = .94) and less in the low precipitation group (r^2 = .74). The low precipitation group intercept (b = -62) and moderate group intercept (b = -36) are also more likely different than the same (p = 24%). Differences in the intercepts suggest that in the absence of dry-period years, residential abandonment might have been the least in the low precipitation group. In sum, this evidence strengthens the finding that people living in settlement areas with higher precipitation levels were not the least vulnerable to dry periods.

Table 8.10. Central Arizona: Number and Percent of Rooms Occupied and Abandoned by Settlement Area Precipitation Level; Includes Only Those Near Perennial Rivers.

Rooms Located Near Perennial Rivers by Precipitation Levels	Number and Percent of Rooms										Correlation Between Dry-Period Severity and Percent of Rooms Abandoned
	1200 to 1249		1250 to 1299		1300 to 1349		1350 to 1399		1400 to 1449		
	n	%	n	%	n	%	n	%	n	%	
Central Arizona											
occupied – low (8-14”)	628		1,007		1,235		1,135		177		
abandoned – low	66	11	41	4	100	8	958	84	177	100	.86, p = .06
occupied – mod. (14-22”)	2,441		3,551		4,078		3,115		382		
abandoned – moderate	324	13	1,992	56	1,166	29	2,733	88	382	100	.97, p = .01
occupied – high (22-36”)	54		204		316		130				
abandoned – high	16	30	51	25	186	59	130	100			n/a[1]
Dry-period severity indices (SFP precipitation)		14		28		26		38		44	

[1] Excluded from analysis due to low number of rooms.



a. Rooms abandoned near perennial rivers and in areas receiving 8-14” of precipitation annually

b. Rooms abandoned near perennial rivers and in areas receiving between 14 and 22” of precipitation annually

Figure 8.8. Scatterplots of relationship between dry-period severity and rooms abandoned among people living near perennial rivers.

Table 8.11. Central Arizona: Slopes, Intercepts, Correlation Coefficients, and Their Probability of Equality.

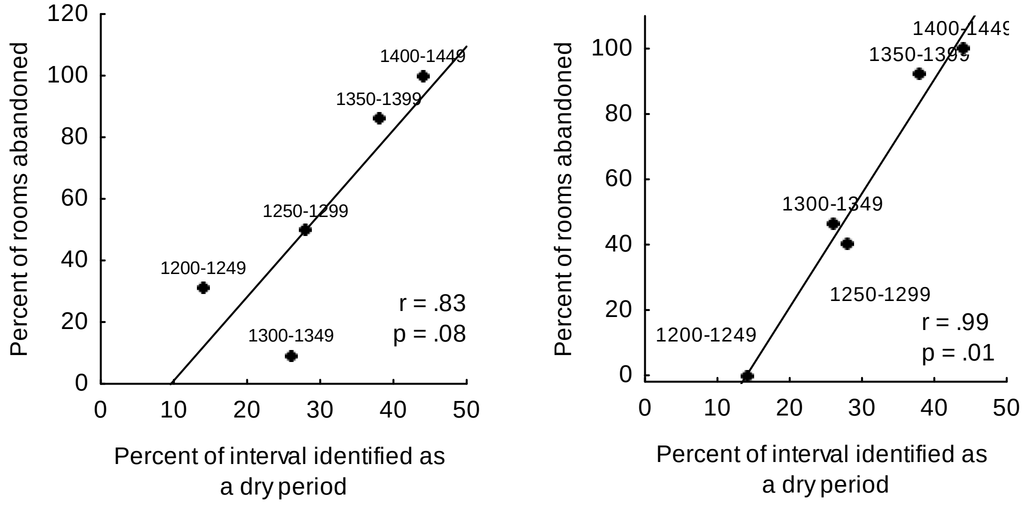
Central Arizona Settlements	Slopes		Intercepts		Correlation Coefficients	
	slope	probability of equality	intercept	probability of equality	r	probability of equality
Near river, low precipitation	3.5	79%	-62	24%	.86	42%
Near a river, moderate precipitation	3.1		-36		.97	

Among people living far from perennial rivers, results demonstrate that those living in settlement areas with the highest precipitation levels were not the least vulnerable to dry periods (Table 8.12, 8.13; Figure 8.9). The slopes of the regression lines in the moderate (m = 2.7) and high (m = 3.5) precipitation level scatterplots identify greater sensitivity to dry-period severity at the high precipitation level. For every one percent change in dry-period severity, residential abandonment increased 2.7% in the moderate precipitation group and 3.5% in the high precipitation group. The probability of equality of the slopes is 50%--as likely to be different as the same. The intercept values for the moderate precipitation group (b = -26) and high precipitation group (b = -49) are more likely the same than different (p = 97%). Correlation coefficients (moderate r = .83; high r = .99) and the scatterplots indicate that the fit of the data to the line improves between the moderate and high precipitation level scatterplots. The probability of equality of these correlations is low, p = 14%. The correlations demonstrate that changes in dry-period severity explain almost all of the variance in residential abandonment in the high precipitation group and less of the variance in the moderate precipitation groups. These results imply (but do not strongly demonstrate) that vulnerability to dry periods may have been greater among those living in areas receiving the highest precipitation levels.

Table 8.12. Central Arizona: Number and Percent of Rooms Occupied and Abandoned by Settlement Area Precipitation Level; Includes Only Those Located Far From Perennial Rivers.

Rooms Located Far From Perennial Rivers by Precipitation Levels	Number and Percent of Rooms										Correlation Between Dry-Period Severity And Percent Of Rooms Abandoned
	1200 to 1249		1250 to 1299		1300 to 1349		1350 to 1399		1400 to 1449		
	n	%	n	%	n	%	n	%	n	%	
Central Arizona											
occupied – low (8-14”)	127		89		13		13		13		n/a[1]
abandoned – low	38	30	76	85	0	0	0	0	13	100	
occupied – mod. (14-22”)	3,340		4,227		7,268		6,836		933		
abandoned – moderate	1,043	31	2,104	50	673	9	5,903	86	933	100	.83, p = .08
occupied – high (22-36”)	422		1,085		1,733		1,431		115		
abandoned – high	0	0	435	40	802	46	1,316	92	115	100	.99, p = .01
Dry-period severity indices (SFP precipitation)	14		28		26		38		44		

[1] Excluded from analysis due to low number of rooms.



a. Far from perennial rivers and in areas receiving between 14 and 22 inches of precipitation annually

b. Far from perennial rivers and in areas receiving between 22 and 36 inches of precipitation annually

Figure 8.9. Scatterplots of relationship between dry-period severity and rooms abandoned among people living far from perennial rivers in areas of moderate and high precipitation.

Table 8.13. Central Arizona: Slopes, Intercepts, Correlation Coefficients, and Their Probability of Equality.

Central Arizona Settlements	Slopes		Intercepts		Correlation Coefficients	
	slope	probability of equality	intercept	probability of equality	r	probability of equality
Far from a river, moderate precipitation	2.7	50%	-26	97%	.83	14%
Far from a river, high precipitation	3.5		-49		.99	

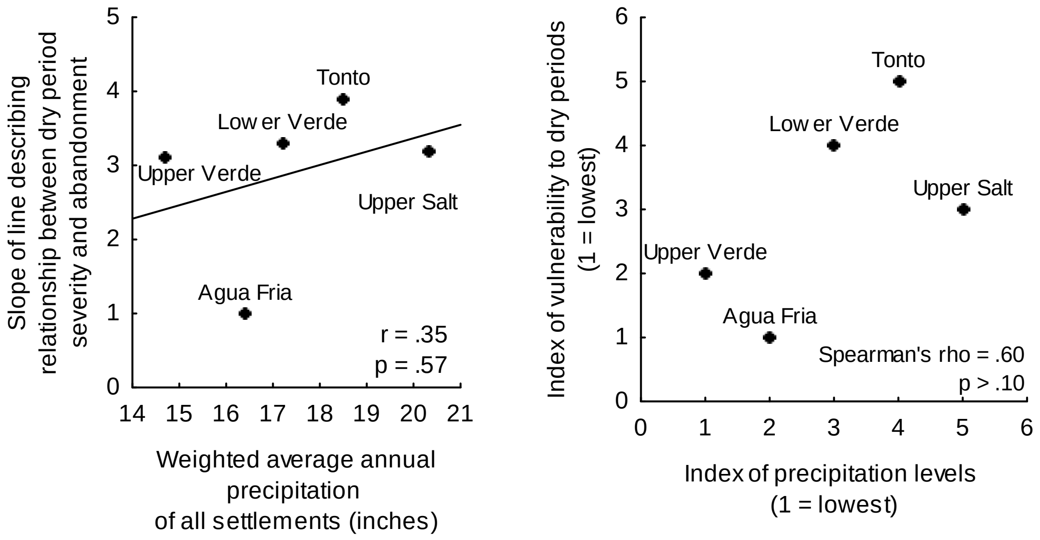
The remainder of this chapter continues this evaluation of supply models of vulnerability to dry periods at the watershed scale. Relationships identified and suggested at the settlement-scale find additional confirmation at the watershed scale.

Watershed Precipitation Levels

Differences in precipitation levels among watersheds explain some of the inter-watershed differences in the relationships between dry-period severity and residential abandonment identified in Chapter Six. To identify inter-watershed differences in precipitation levels, I use the weighted average annual precipitation level of all settlements within each watershed presented in Chapter Five, Table 5.4 (presented again in Table 8.14 below). I use the slopes of the lines describing the relationship between dry-period severity and abandonment in each watershed to identify differences in vulnerability to dry periods (Chapter Six, Table 6.2). I rank the slopes from shallowest (least vulnerable) to steepest (most vulnerable). The scatterplots of actual values (Figure 8.10 a., r = .35, p = .57) and ranked values (Figure 8.10 b., Spearman's rho = .60, p = > .10) demonstrate the relationship between the variables. Watersheds with settlements in areas with the lowest precipitation levels (Agua Fria, Upper Verde) were less vulnerable to dry periods than watersheds with settlements in areas with the highest precipitation levels (Upper Salt, Tonto, Lower Verde). Thus, watershed precipitation levels explain some of the inter-watershed differences in vulnerability to dry periods identified in Chapter Six.

Table 8.14. Influence of Settlement Area Precipitation Levels on Vulnerability.

Watershed	Slope of Regression Lines Describing Relationship Between Dry-Period Severity and Residential Abandonment (see Table 6.2)		Weighted Average Annual Precipitation of All Settlements (see Table 5.4)	
	slope	rank	average	rank
Agua Fria	1	1	16.4	2
Upper Verde	3.1	2	14.7	1
Upper Salt	3.2	3	20.3	5
Lower Verde	3.3	4	17.2	3
Tonto	3.9	5	18.5	4



a. Actual values of correlations and precipitation levels

b. Indices of vulnerability and precipitation levels

Figure 8.10. Scatterplots of relationships between weighted average annual precipitation of all settlements and the correlations between dry-period severity and residential abandonment within each watershed.

Watershed Precipitation Levels Plus Streamflow Discharge Levels

In this final analysis, I consider the combined influence of both precipitation and streamflow discharge levels on vulnerability to dry periods. I create a single index of water-related productivity for each watershed. This index is the sum of each watershed's precipitation and streamflow discharge level rank (as discussed in Chapter Five; see also Table 5.3, 5.4). The index is crude but approximates differences in the availability of water (precipitation and streamflow) in each watershed. I compare this index to the slopes of the regression lines describing the relationship between dry-period severity and residential abandonment in each watershed (Chapter Six, Table 6.2). For consistency, I rank these slopes by steepness (as above).

Results identify a positive relationship between the productivity and vulnerability indices (Figure 8.11; Table 8.15). Specifically, the scatterplot shows two groups of watersheds. In the upper right of the scatterplot are the Tonto, Lower Verde, and Upper Salt. I identified these watersheds in Chapter Six as areas where changes in residential abandonment were strongly related to changes in dry-period severity. These watersheds have the highest water-related productivity indices and the greatest vulnerability to dry periods. In the lower left are the Agua Fria, Upper Verde, and Lower Salt. I identified these watersheds in Chapter Six as areas where changes in residential abandonment were <u>not</u> strongly related to changes in dry-period severity. These watersheds have the lowest water-related productivity indices and the lowest vulnerability. [Of course, the extent of water-related productivity in the Lower Salt is debatable--very high streamflow, very low precipitation.] If people living in areas with the greatest water-related productivity were the least vulnerable to dry periods, I would expect the opposite of what was found. In sum, differences in precipitation and streamflow levels explain some of the inter-watershed differences in vulnerability identified in Chapter Six. Where water-related resource productivity was highest, vulnerability to dry periods was greatest. And, where water-related resource productivity was lowest, vulnerability to dry periods was the least.

Table 8.15. Influence of Water-Related Productivity on Vulnerability.

Watershed	Slope of Regression Lines Describing Relationship Between Dry-Period Severity and Residential Abandonment (See Table 6.2)		Mean Annual Discharge, acre-feet/year (See Table 5.3)		Weighted Average Annual Precipitation of All Settlements (See Table 5.4)		Water-Related Productivity Index (Sum of Precipitation Plus Streamflow Level Ranks)
	slopes	rank	discharge	rank	average	rank	index
Lower Salt	-.01	1	644,942	6	9.3	1	7
Agua Fria	1.0	2	16,327	1	16.4	3	4
Up. Verde	3.1	3	128,062	3	14.7	2	5
Upper Salt	3.2	4	474,817	5	20.3	6	11
Low. Verde	3.3	5	409,875	4	17.2	4	8
Tonto	3.9	6	113,232	2	18.5	5	7

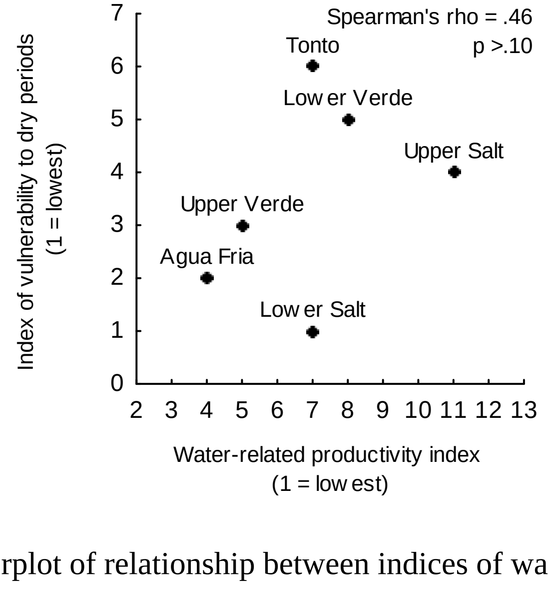


Figure 8.11. Scatterplot of relationship between indices of water-related productivity and vulnerability.

Summary and Implications

Models of vulnerability to dry periods that link environmental conditions associated with greater potential resource productivity to lesser vulnerability to dry periods are not supported. People living where potential productivity is assumed to be highest were not less vulnerable to dry periods than those living where potential productivity is assumed to be the lowest. Differences in potential productivity considered in this analysis were all related to access to water (riverine and precipitation); therefore, results also demonstrate that vulnerability models that link increasing access to water with lesser vulnerability to dry periods are not supported.

Evidence supporting this conclusion at the settlement-scale includes similar relationships between dry-period severity and residential abandonment among riverine and non-riverine settlements and among settlements located in areas of low, moderate, and high average annual precipitation. Similarly, people living in watersheds with settlements located in areas with the highest average precipitation levels were not the least vulnerable to dry periods.

Results also suggest that as potential resource productivity increased, vulnerability to dry periods somewhat increased. The evidence supporting this conclusion includes: (1) watersheds with settlements in areas with the highest precipitation levels had the steepest slopes of the regression lines describing the relationship between dry-period severity and abandonment; and (2) watersheds with settlements in areas with the highest combined precipitation and streamflow indices also had the steepest slopes and greatest inferred vulnerability to dry periods.

Differences in the frequency of food shortfalls between areas of low and high potential resource productivity may explain why people living in areas with the least potential productivity were in some cases less vulnerable to dry periods, or at least less responsive with movement, than people living in areas with the most potential productivity. If shortfalls were more frequent in areas of low productivity, then people living under these conditions may have been more effective at managing these risks than people living in areas of high productivity where shortfalls were likely less frequent. Strategies such as diet and crop diversification, increases in physical food storage, exchanges for food, decreases in food consumption, and the development of water management strategies for a variety of precipitation conditions can all be used to manage shortfall risks (e.g., Braun and Plog 1982; Burns 1983; Dean 2006; Halstead and O’Shea 1989b:3-4; Minnis 1985; Rautman 1993; Slatter 1979:80-84). Most of these strategies, however, require efforts to develop over time and could not be effectively initiated as immediate responses to particular increases in shortfall risk associated with a specific dry period. Thus, in high productivity areas residential abandonment as a response to shortfall risks may have been the most effective response.

Greater investments in water management infrastructure (e.g., check dams, terracing, water diversion structures) in areas of low productivity might also explain why vulnerability as expressed by residential abandonment was less among those living in areas of lower potential productivity. Janssen et al. (2003) use the "sunk-cost effect" (Arkes and Ayton 1999) to link investments in physical structures to delays in adaptive adjustments in response to disturbances, such as dry periods. Using examples from the prehistoric northern Southwest, they argue that this tendency to hold onto previous investments even if these investments are a rationally bad choice explains the delayed demise (relative to hamlets) of Puebloan villages in the face of resource stress. Further research is needed, however, to determine if people living in areas of lower potential productivity made greater investments in physical water management infrastructure. For people living near perennial rivers, results suggest that any investments in irrigation agriculture infrastructure did not substantially decrease mobility, given the strong and sensitive relationship between dry-period severity and residential abandonment among people living near perennial rivers.

Greater vulnerability to dry periods in areas of higher potential productivity may address an important argument used to refute the influence of the "Great Drought" of 1276 to 1299 (Douglass 1929) on the depopulation of the northern U.S. Southwest. Jett (1964:285) has argued "...if drought were the reason for abandonment, why would relatively well-watered areas such as Mesa Verde, Canyon de Chelly, and the Mogollon Mountains be deserted while less-favored areas, such as the Hopi and Little Colorado, grew in population?" Precipitation levels at Hopi and along the Little Colorado were lower than in Mesa Verde, Canyon de Chelly, and the Mogollon Mountains. Although I do not identify areas where population levels increased, the pattern of increases in abandonment during dry periods in areas with the highest productivity identified by Jett (1964) is consistent with the pattern identified in this study.

That living in an area with greater access to or availability of water did not decrease vulnerability to dry periods likely demonstrates the importance of factors that affect resource productivity other than water. These factors include soils, temperature, slopes of land, extent of arable land etc. and they are not necessarily reflected by proximity to perennial rivers or average precipitation levels. Social factors (e.g., the existence of food exchange relationships, territoriality that restricted movements) that affect the risk of shortfalls are also not accounted for when local-scale environmental settlement characteristics are emphasized.

In sum, results do not support simplified notions of the relationship between access to and availability of water and vulnerability to dry periods. In the next chapter, I consider the combined influence of demographic and environmental conditions on vulnerability to dry periods.

CHAPTER 9:

THE COMBINED INFLUENCE OF DEMOGRAPHIC AND ENVIRONMENTALCONDITIONS ON VULNERABILITY TO DRY PERIODS

The analyses in this chapter evaluate 'demand and supply' models of vulnerability to dry periods by testing the expectation that people living where demand was highest (high population settlements, high density watersheds) and potential supply lowest (far from perennial rivers, low precipitation areas) were more vulnerable to dry periods than those living where demand was lowest (low population settlements, low density watersheds) and potential supply highest (near perennial rivers, high precipitation areas). The indicators of demand and supply were employed in Chapters Seven and Eight.

In each analysis in this chapter, I compare the relationships between dry-period severity and residential abandonment where demands were high and supplies low to the relationships where demands were low and supplies high. If the balance between population and available resources influenced vulnerability to dry periods in the region, then the relationship between dry-period severity and residential abandonment will be stronger and more sensitive where imbalances were potentially the greatest and weaker and less sensitive where imbalances were the least likely. We expect differences in vulnerability because when dry periods decrease productivity, the extent of shortfall risk and associated vulnerability is assumed to be related to the differential between resource demands and supplies.

By simulating the extremes of the possible differential--high demand/low supply (population-resource imbalances most likely) and low demand/high supply (population-resource imbalances least likely)--I test the influence of these conditions on the extent of residential abandonment and vulnerability to dry periods.

It is important to assess demand and supply models and the scale at which they might apply so that we have a basis to evaluate arguments that emphasize population-resource imbalances to explain intra-regional differences in impacts and responses to dry periods across time and space. It is reasonable to assume that population-resources imbalances influenced impacts and responses to dry periods. However, were these imbalances always predictive of vulnerability or merely among the many factors operating to influence vulnerability to dry periods? By considering long-term relationships between dry-period severity and residential abandonment among those living where the imbalances were likely the greatest, we identify the role of population-resource balances in vulnerability to dry periods over time.

Based on the results presented below, the primary argument of this chapter is that models of vulnerability that emphasize the influence of <u>watershed-scale</u> population-resource imbalances on vulnerability to dry periods are supported. People living in watersheds with high population density in areas of low potential productivity were more vulnerable to dry periods than people living in watersheds with low population density in areas of high potential productivity. Results also demonstrate that high watershed population density is more often associated with greater vulnerability to dry periods regardless of the potential productivity of settlement locations. Models of vulnerability to dry periods that emphasize the influence of settlement-scale imbalances are, however, not supported. Thus, the scale at which resource demands are assessed is a critical aspect of population-resource models and demand models (Chapter Seven) of vulnerability to dry periods. I present the results by the two indicators of resource demand (watershed population density and settlement population levels) followed by a watershed-scale analysis.

Demand (Watershed Population Density) and Supply

This analysis compares the relationship between dry-period severity and residential abandonment where resource demands were high (rooms located in watersheds with high population density) and potential supplies low (rooms located far from perennial rivers) to the relationships between dry-period severity and residential abandonment where resource demands were low (rooms located in watersheds with low population density) and potential supplies high (rooms located near perennial rivers). I do not use precipitation levels as an indicator of productivity because too few settlements were identified in low density, high precipitation and high density, low precipitation areas for the analysis.

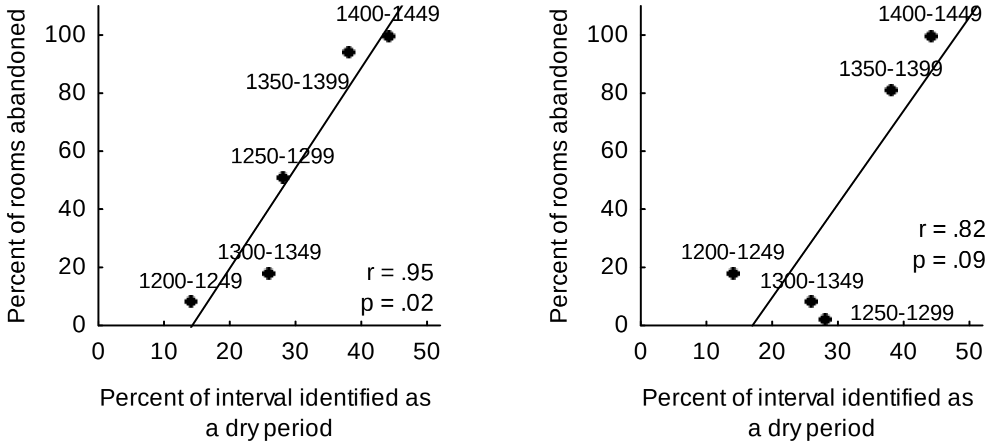
To identify rooms located in these extreme conditions, I classified all rooms in the Agua Fria and Upper Verde as located in a low density area and all rooms in the Lower Verde, Upper Salt, and Tonto as located in a high density area based on density calculations in Chapter Five, Table 5.2 (this method also used in Chapter Seven). Among rooms located in high density watersheds, I identified those far from perennial rivers to identify rooms where demands were high and supplies low (imbalances high). Among rooms located in low density watersheds, I identify those near perennial rivers to identify rooms where demands were low and supplies high (imbalances low). I identified the total number of rooms occupied, abandoned, and the percent of rooms abandoned during each 50-year interval for each of these groups of rooms (Table 9.1). I then calculated the slopes, intercepts, and correlations between dry-period severity and the percent of rooms abandoned for both combinations (Table 9.2). I exclude the Lower Salt watershed because inclusion of the high number of rooms in this watershed--all classified as located in a high density watershed, near a perennial river, and in an area of low precipitation--would dominate the results of these analyses.

Results provide some support for the expectation that vulnerability to the risk of shortfalls was influenced by population-resource imbalances when watershed population density is used as the indicator of resource demands. The slope of the regression line in the high density/far riverine group (imbalances high) is steeper (m = 3.5) than in the low density/near riverine group (m = 3.2) (imbalances low). Steeper slopes indicate greater sensitivity to changes in dry-period severity. The slopes cannot, however, be demonstrated to be statistically different (probability of equality: 88%, Table 9.2). The intercept values for the high density/far riverine group (b = -49) and the low density/near riverine group (b = -55) are more likely different than the same (p = 41%). The negative intercepts suggest residential abandonment may have been very low in the absence of dry-period years in both groups. The strongest support for concluding differences between the relationships is the fit of the data values to the regression lines and the associated correlation coefficients. The fit of the data values is clearly much better in the high density/far riverine group (r = .95; Figure 9.1 a.) than in the low density/near riverine group (r = .82; Figure 9.1 b.). Differences in the fits and correlations demonstrate that changes in dry-period severity explain 90% of the variance in residential abandonment in the high density/distant riverine group and only 67% of the variance in the low density/near riverine group. Statistical support for the observed difference in the correlations is, however, equivocal (probability of equality is 50%). In sum, these results suggest differences in vulnerability to dry periods between the two groups but all statistical measures of the relationship do not support this conclusion.

Table 9.1. Demand (Watershed Population Density) and Supply

(Proximity to Riverine Resources).

Temporal Intervals	Dry-Period Severity Indices	a. Rooms Located in High Density Watersheds Far from a Perennial Rivers (High Demand, Low Supply)			b. Rooms Located in Low Density Watersheds Near a Perennial River (Low Demand, High Supply)		
		occupied	abandoned		occupied	abandoned	
		n	n	%	n	n	%
1200 to 1249	14	2,618	220	8	642	117	18
1250 to 1299	28	4,153	2,099	51	984	15	2
1300 to 1349	26	5,973	1,085	18	1,838	140	8
1350 to 1399	38	5,629	5,268	94	1,698	1,383	81
1400 to 1449	44	361	361	100	315	315	100



a. High density, far from a perennial river (high demand/low supply)

b. Low density, near perennial river (low demand/high supply)

Figure 9.1. Scatterplots of rooms located in a high or low density watershed far and near perennial rivers.

Table 9.2. Probability of Equality of Slopes, Intercepts, and Correlation Coefficients of Relationship Between Rooms Located in High and Low Density Watersheds Far and Near Perennial Rivers.

Room Locations	Slopes		Intercepts		Correlation Coefficients	
	slope	probability of equality	intercept	probability of equality	r	probability of equality
High density, far from a perennial river	3.5	88%	-49	41%	.95	50%
Low density, near perennial river	3.2		-55		.82	

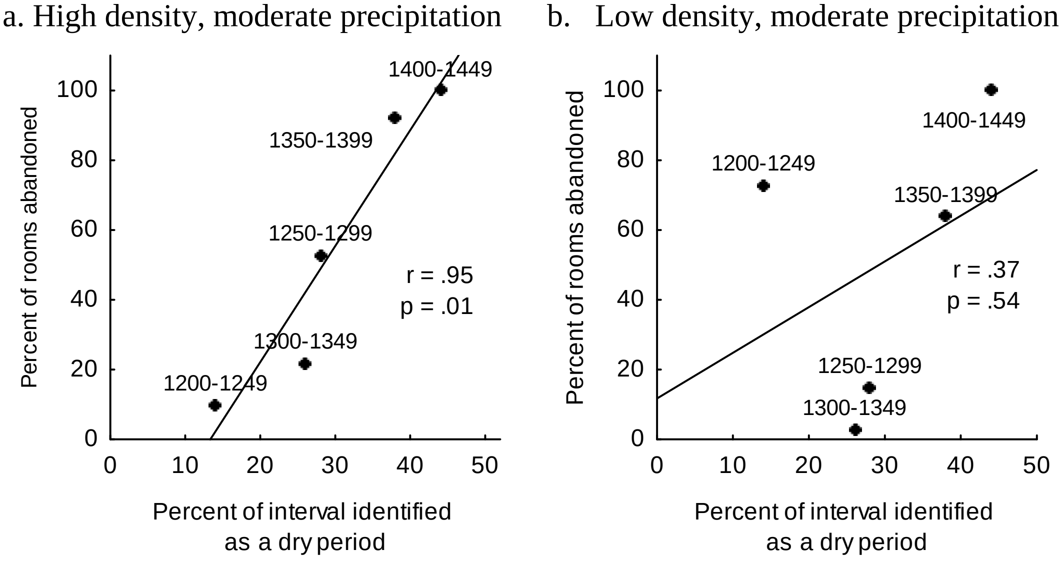
Results also demonstrate that high watershed population density is associated with greater vulnerability to dry periods in two out of three productivity scenarios (settlements located in areas with moderate precipitation levels, settlements located far from perennial rivers). That is, when we hold potential productivity constant among settlements and vary watershed population density, residential abandonment is usually more sensitive to changes in dry-period severity and/or changes in dry-period severity explain more of the variance in residential abandonment in high density watersheds than in low density watersheds. I support this conclusion by varying population density by settlement area precipitation levels and riverine proximity and comparing relationships.

Moderate Precipitation Levels

Among all settlements located in areas with moderate average annual precipitation levels (14” to 22”), the relationship between dry-period severity and residential abandonment is clearly stronger and more sensitive in high density watersheds than in low density watersheds (Figure 9.2 and Table 9.3, 9.4). The slope of the regression line in the high density/moderate precipitation group scatterplot (m = 3.3) is steeper than the slope of the line in the low density/moderate precipitation group (m = 1.3). Steeper slopes indicate greater sensitivity to changes in dry-period severity. For every one percent change in dry-period severity, residential abandonment increased 3.3% in the high density group and 1.3% in the low density group. The probability of equality of the slopes is 35%--more likely to be different than the same. The intercept values for the high density group (b = -44%) and the low density group (b = -12) are more likely the same than different (p = 84%). Correlation coefficients (high density r = .95; low density r = .37) and the scatterplots indicate that the fit of the high density group data to the line is very strong and much better than the fit with the low density group data. The probability of equality of these correlations is low, p = 15%. The r^2 values indicate that 90% of the variance in residential abandonment in the high density group is explained by differences in dry-period severity while only 14% of the variance in residential abandonment is explained in the low density group. Factors other than dry-period severity are influencing changes in residential abandonment in the low density group. In sum, these results imply that vulnerability to dry periods was greater among those living in high density watersheds when precipitation levels are held constant.

Table 9.3. Demand (Watershed Population Density) and Supply (Precipitation Levels).

Temporal Intervals	Dry-Period Severity	a. Rooms Located in High Density Watersheds Receiving Moderate Precipitation (High Demand, Low Supply)			b. Rooms Located in Low Density Watersheds Receiving Moderate Precipitation (Low Demand, High Supply)		
		occupied	abandoned		occupied	abandoned	
		n	n	%	n	n	%
1200 to 1249	14	4,343	448	10	966	707	73
1250 to 1299	28	6,522	3,461	53	661	100	15
1300 to 1349	26	7,763	1,689	22	2,528	80	3
1350 to 1399	38	6,518	6,020	92	2,448	1,571	64
1400 to 1449	44	438	438	100	877	877	100


a. High density, moderate precipitation

b. Low density, moderate precipitation

Figure 9.2. Scatterplots of rooms located in a high or low density watershed receiving moderate precipitation.

Table 9.4. Probability of Equality of Slopes, Intercepts, and Correlation Coefficients of Relationship Between Rooms Located in High and Low Density Watersheds Receiving Moderate Precipitation.

Room Locations	Slopes		Intercepts		Correlation Coefficients	
	slope	probability of equality	intercept	probability of equality	r	probability of equality
High density, moderate precipitation	3.3	35%	-44	84%	.95	15%
Low density, moderate precipitation	1.3		-12		.37	

Far From Perennial Rivers

Among all settlements located far from perennial rivers, the relationship between dry-period severity and residential abandonment is clearly stronger and more sensitive in high density watersheds than in low density watersheds (Figure 9.3 and Table 9.5, 9.6). The slope of the regression line in the high density/distant riverine group scatterplot (m = 3.5) is steeper than the slope of the line in the low density/distant riverine group (m = 1.3). Steeper slopes indicate greater sensitivity to changes in dry-period severity. For every one percent change in dry-period severity, residential abandonment increased 3.5% in the high density group and 1.3% in the low density group. The probability of equality of the slopes is 29%--more likely to be different than the same. The intercept values for the high density group (b = -49%) and the low density group (b = 12) are more likely the same than different (p = 92%). Correlation coefficients (high density r

= .95; low density r = .41) and the scatterplots indicate that the fit of the high density group data to the line is very strong and much better than the fit of the low density group data. The probability of equality of these correlations is low, p = 16%. The r^2 values indicate that 90% of the variance in residential abandonment in the high density group is explained by variation in dry-period severity while only 17% of the variance in residential abandonment is explained in the low density group. Factors other than dry-period severity are influencing changes in residential abandonment in the low density group. In sum, these results demonstrate that in settlement locations far from perennial rivers, vulnerability to dry periods was greater in high density watersheds than in low density watersheds.

Table 9.5. Demand (Watershed Population Density) and Supply (Far from a Perennial River).

Temporal Intervals	Dry-Period Severity Indices	a. Rooms Located in High Density Watersheds Far From Perennial Rivers (High Demand, Low Supply)			B. Rooms Located in Low Density Watersheds Far From Perennial Rivers (Low Demand, Low Supply)		
		occupied	abandoned		occupied	abandoned	
		n	n	%	n	n	%
1200 to 1249	14	2,618	220	8	1,014	694	68
1250 to 1299	28	4,153	2,099	51	558	176	32
1300 to 1349	26	5,973	1,085	18	1,766	40	2
1350 to 1399	38	5,629	5,268	94	1,726	1,026	59
1400 to 1449	44	361	361	100	700	700	100

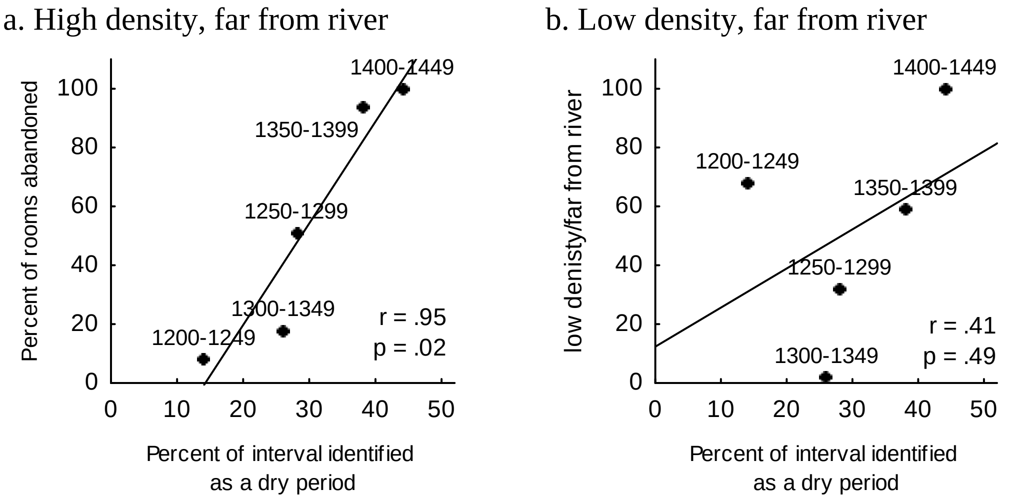


Figure 9.3. Scatterplots of rooms located in a high or low density watershed far from a perennial river.

Table 9.6. Probability of Equality of Slopes, Intercepts, and Correlation Coefficients of Relationship Between Rooms Located in High and Low Density Watersheds Far From a Perennial River.

Room Locations	Slopes		Intercepts		Correlation Coefficients	
	slope	probability of equality	intercept	probability of equality	r	probability of equality
High density, far from a perennial river	3.5	29%	-49	92%	.95	16%
Low density, far from a perennial river	1.3		12		.41	

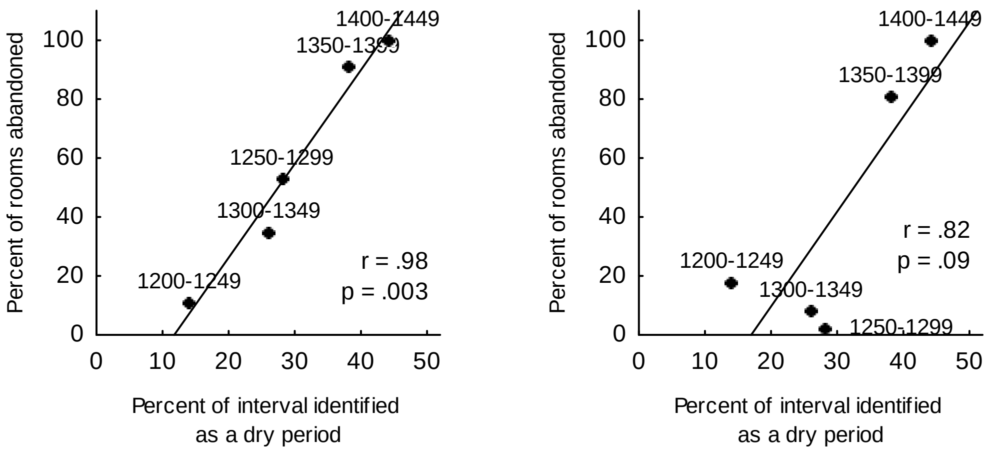
Near Perennial Rivers

Among all settlements located near perennial rivers, the relationship between dry-period severity and residential abandonment in low and high density watersheds is too similar to convincingly argue that the relationships were different (Figure 9.4 and Table 9.7, 9.8). The slopes of the regression lines are the same (high density $m = 3.2$; low density $m = 3.2$) with a probability of equality of 98%. Thus, there is no statistical basis to argue that one group was more sensitive to dry periods than the other. The intercept values for the high density group ($b = -37$) and the low density group ($b = -55$) are more likely different than the same ($p = 25\%$). The intercepts suggest residential abandonment may have been lowest in the low density group in the absence of dry-period years. The linear fit of the data values to the regression line is better in the high density/near riverine group ($r =$

.98) than in the low density/near riverine group (r = .82). Differences in the r^2 values demonstrate that changes in dry-period severity explain 96% of the variance in the relationship between dry-period severity and residential abandonment in the high density group and only 67% of the variance in the low density group. The correlations are statistically more likely to be different than the same (p = 25%). Differences in the fit of the data values to the line suggest that factors other than changes in dry-period severity influenced changes in residential abandonment in low density watersheds. In sum, differences in the relationship between dry-period severity and abandonment are evident between the two groups but a strong argument for differences in vulnerability to dry periods cannot be supported.

Table 9.7. Demand (Watershed Population Density) and Supply (Near a Perennial River).

Temporal Intervals	Dry-Period Severity Indices	a. Rooms Located in High Density Watersheds Near Perennial Rivers (High Demand, High Supply)			b. Rooms Located in Low Density Watersheds Near Perennial Rivers (Low Demand, High Supply)		
		occupied	abandoned		occupied	abandoned	
		n	n	%	n	n	%
1200 to 1249	14	2,226	224	11	642	117	18
1250 to 1299	28	3,533	1,859	53	984	15	2
1300 to 1349	26	3,711	1,292	35	1,838	140	8
1350 to 1399	38	2,622	2,378	91	1,698	1,383	81
1400 to 1449	44	244	244	100	315	315	100



a. High density, near river

b. Low density, near river

Figure 9.4. Scatterplots of rooms located in a high or low density watershed near a perennial river.

Table 9.8. Probability of Equality of Slopes, Intercepts, and Correlation Coefficients of Relationship Between Rooms Located in High and Low Density Watersheds Near a Perennial River.

Room Locations	Slopes		Intercepts		Correlation Coefficients	
	slope	probability of equality	intercept	probability of equality	r	probability of equality
High density, near river	3.2	98%	-37	25%	.98	25%
Low density, near river	3.2		-55		.82	

Demand (Settlement Population Levels) and Supply

This analysis compares the relationships between dry-period severity and residential abandonment where resource demands were high (rooms located in settlements with high population levels) and potential supplies low (rooms located far from perennial rivers and rooms in areas of low precipitation) to the relationships between dry-period severity and residential abandonment where resource demands were low (rooms located in settlements with low population levels) and potential supplies high (rooms located near perennial rivers and rooms in areas of high precipitation).

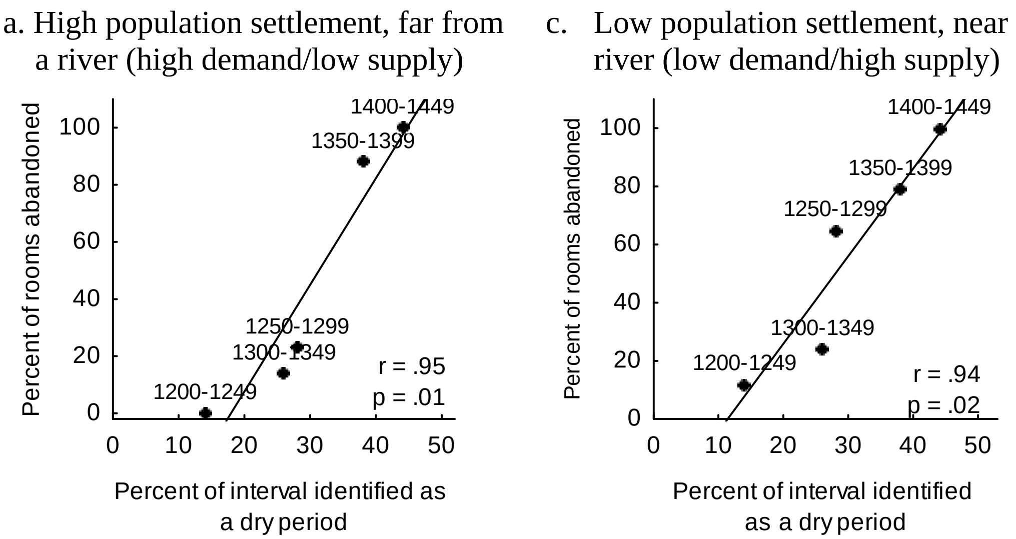
To identify rooms located in these extreme conditions, I classified all rooms in the study area as located in a settlement with high population levels (high demand) or low population levels (low demand) based on the classifications used in Chapter Seven, Table 7.4. Among rooms located in settlements with high population levels, I identified those far from perennial rivers and in areas of low precipitation. This procedure identified rooms where demands were high and supplies low. Among rooms located in settlements with low population levels, I identified those near perennial rivers and in areas of high precipitation. This procedure identified rooms where demands were low and supplies high. I identified the total number of rooms occupied, abandoned, and the percent of rooms abandoned during each 50-year interval for each of these groups of rooms (Table 9.9). I then calculated the slopes, intercepts, and correlations between dry-period severity and residential abandonment (the percent of rooms abandoned) for both combinations (Table 9.10). I exclude the Lower Salt watershed as demographically and productively unique and because conditions there would dominate all results.

Results do not support the expectation that vulnerability to dry periods was strongly influenced by population-resource imbalances when settlement population levels are used as the indicator of resource demands (Table 9.10; Figure 9.5). The relationship between dry-period severity and residential abandonment in the high population settlement/far from riverine group is too similar to the relationship in the low population settlement/near riverine group to convincingly argue that the relationships were different. The slopes of the regression lines are both relatively steep (high population/far from riverine: m = 3.7; low population/near riverine: m = 3). Statistical support for differences in the slopes is equivocal (probability of equality 48%)--almost as likely to be the same as different. The intercept values for the high population group (b = -67%)

and the low population group (b = -34) both suggest low rates of residential abandonment when there were no dry-period years (probability of equality 30%). Correlation coefficients (high population/far from riverine r = .95; low population/near riverine r = .94) and the scatterplots indicate that the fit of the data to the regression lines are very similar. The probability of equality of the correlations is also very high--93%. The good linear fits of the data values demonstrate that changes in dry-period severity explain a similar extent of variance in residential abandonment in both relationships. In sum, these results do not provide a strong basis to conclude that vulnerability to dry periods was different under these circumstances.

Table 9.9. Demand (Settlement Population Levels)
and Supply (Riverine Proximity).

Temporal Intervals	Dry-Period Severity	a. Rooms Located in Settlements With High Population Levels Far From Perennial Rivers (High Demand, Low Supply)			b. Rooms Located in Settlement With Low Population Levels Near to Perennial Rivers (Low Demand, High Supply)		
		occupied n	abandoned n	%	occupied n	abandoned n	%
1200 to 1249	14	120	0	0	1,065	131	12
1250 to 1299	28	1,614	370	23	1,373	892	65
1300 to 1349	26	4,367	600	14	1,269	304	24
1350 to 1399	38	4,377	3,842	88	965	766	79
1400 to 1449	44	535	535	100	199	199	100


a. High population settlement, far from a river (high demand/low supply)

c. Low population settlement, near river (low demand/high supply)

Figure 9.5. Scatterplots of rooms located in a settlement with high or low population levels, far or near a perennial river.

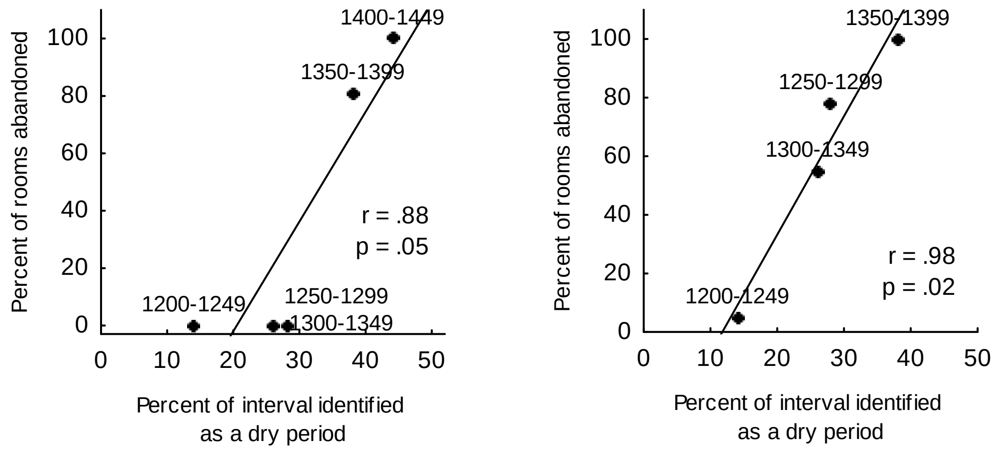
Table 9.10. Probability of Equality of Slopes, Intercepts, and Correlation Coefficients of Relationship Between Rooms Located in Settlements with High or Low Population Levels Far or Near a Perennial River.

Room Locations	Slopes		Intercepts		Correlation Coefficients	
	slope	probability of equality	intercept	probability of equality	r	probability of equality
High population, far from river	3.7	48%	-67	30%	.95	93%
Low population, near river	3		-34		.94	

These results are consistent with those that use settlement area precipitation levels as the indicator of differences in resource supplies (Table 9.11, 9.12; Figure 9.6). The relationship between dry-period severity and residential abandonment in the high population settlement/low precipitation group is too similar to the relationship in the low population settlement/high precipitation group to convincingly argue that the relationships were different. It is important to note that the reliability of these results may be somewhat compromised by the low numbers of settlements and associated rooms in these extreme conditions. The slopes of the regression lines are both relatively steep (high population/low precipitation: m = 3.8; low population/high precipitation: m = 4). The probability of equality of the slopes is 89%--much more likely to be the same than different. These similarities provide no statistical basis to argue that one group was more sensitive to dry periods than the other. The intercept values for the high population group (b = -78%) and the low population group (b = -48) both suggest low rates of residential abandonment when there were no dry-period years (probability of equality 4%). Correlation coefficients and the scatterplots show that the data values in the low population/high precipitation group (r = .98) better fit the regression line than the data values in the high population/low precipitation group (r = .88). The correlations are more likely to be different than the same (p = 45%). The associated r^2 values indicate that 96% of the variance in the relationship between dry-period severity and residential abandonment in the high settlement population group is explained by changes in dry-period severity. Only 77% of the variance in the relationship between dry period severity and residential abandonment is explained by changes in dry-period severity in the low population group. In sum, the evidence does not demonstrate that people living in settlements with high population levels and low potential resource supplies were more vulnerable to dry periods than people living in settlements with low population levels and high potential resource supplies, as expected. Instead, the evidence suggests vulnerability may have been greater for those living where demands were the least and supplies the greatest, contrary to model expectations.

Table 9.11. Demand (Settlement Population Levels) and Supply (Precipitation Levels).

Temporal Intervals	Dry-Period Severity	a. Rooms Located in Settlements With High Population Levels Receiving Low Precipitation (High Demand, Low Supply)			b. Rooms Located in Settlements With Low Population Levels Receiving High Precipitation (Low Demand, High Supply)		
		occupied n	abandoned n	%	occupied n	abandoned n	%
1200 to 1249	14	362	0	0	301	16	5
1250 to 1299	28	662	0	0	399	311	78
1300 to 1349	26	662	0	0	343	190	55
1350 to 1399	38	662	537	81	153	153	100
1400 to 1449	44	125	125	100			


a. High population settlement, low precipitation (high demand/low supply)

b. Low population settlement, high precipitation (low demand/high supply)

Figure 9.6. Scatterplots of rooms located in a settlement with high or low population levels and high or low precipitation levels.

Table 9.12. Probability of Equality of Slopes, Intercepts, and Correlation Coefficients of Relationship Between Rooms Located in Settlements with High or Low Population Levels and Low or High Precipitation Levels.

Room Locations	Slopes		Intercepts		Correlation Coefficients	
	slope	probability of equality	intercept	probability of equality	r	probability of equality
High population, low precipitation	3.8	89%	-78	4%	.88	45%
Low population, high precipitation	4		-48		.98	

As in the previous analysis of resource demands using watershed population density, I examine the influence of settlement population levels on vulnerability to dry periods while holding potential productivity constant among settlements. Results (not included) demonstrate that the relationship between dry-period severity and residential abandonment is similar in each case. This similarity provides no support for the influence of settlement population levels on vulnerability to dry periods across a range of environmental conditions. These results are consistent with those identified in the evaluation of demand models (Chapter Seven) wherein no influence of settlement population levels on vulnerability to dry periods was detected.

Watershed-Scale Demand and Supply

This analysis examines the influence of watershed-scale population-resource balance on the relationships between dry-period severity and residential abandonment within each watershed, as identified in Chapter Six. The purpose of this analysis is to understand the contribution of population-resource balance to the identified variation in inter-watershed vulnerability to dry periods.

To identify inter-watershed differences in potential population-resource imbalances, I create a demand/supply index for each watershed (Table 9.13; Figure 9.7). Demand is represented by each watershed's population density (as assessed in Chapter Five, Table 5.2). Supply is represented by the weighted average annual precipitation level of settlements by watershed (as identified in Chapter Five, Table 5.4). I use precipitation levels as the indicator of potential resource supplies because it affects all settlements in the watershed, as opposed to the streamflow discharge levels which primarily affect those living near perennial rivers. To create the indices, I divide a watershed's density by the weighted average annual precipitation level of all settlements within each watershed. Lower numbers represent relatively low demand and high supply; thus, places where population-resource imbalances should have been least likely. Higher numbers represent relatively high demand and low supply; thus, places where population-resource imbalances should have been most likely. Hence, the lower the number, the lower the expected vulnerability to dry periods. I rank the index for comparison to the ranked vulnerability index, with 1 representing the shallowest slope of the relationship between dry-period severity and residential abandonment (inferred low vulnerability) and 6 representing the steepest slope (inferred high vulnerability). I exclude the Lower Salt watershed from this analysis because both population density and precipitation levels are extreme outliers in this study and potential resource supplies in the Lower Salt were most strongly related to discharge levels of the Lower Salt River.

Results as displayed in the scatterplot (Figure 9.7 a.) indicate that as potential population-resource imbalances increased, the slope of the regression line representing the relationship between dry-period severity and abandonment in each watershed increased in steepness (that is, inferred vulnerability to dry periods increased). Using a ranking index of the slope values for consistency also demonstrates a positive and strong relationship between potential population-resource imbalances and vulnerability to dry periods (Figure 9.7 b.; Spearman’s rho = .87). Thus, differences in population-resource balance among watersheds explain much of the differences in the relationship between dry-period severity and residential abandonment identified by the aridity model (Chapter Six).

Table 9.13. Watershed-Scale Potential Population-Resource Imbalances.

Watershed	Slopes Representing Relationship Between Dry-Period Severity and Residential Abandonment (See Table 6.2)		Watershed Population Density (See Table 5.2)	Weighted Average Annual Precipitation of All Settlements (See Table 5.4)	Index of Potential Population-Resource Imbalances[1] (Density Divided by Precipitation Multiplied by 100)	
	slopes	rank			index	rank
Agua Fria	1.0	1	.19	16.4	1.2	1.5
Upper Verde	3.1	2	.17	14.7	1.2	1.5
Upper Salt	3.2	3	.54	20.3	2.7	4
Lower Verde	3.3	4	.37	17.2	2.2	3
Tonto	3.9	5	.61	18.5	3.3	5

[1] Lower numbers represent relatively low demand, high supply--places where population-resource imbalances should have been least likely.

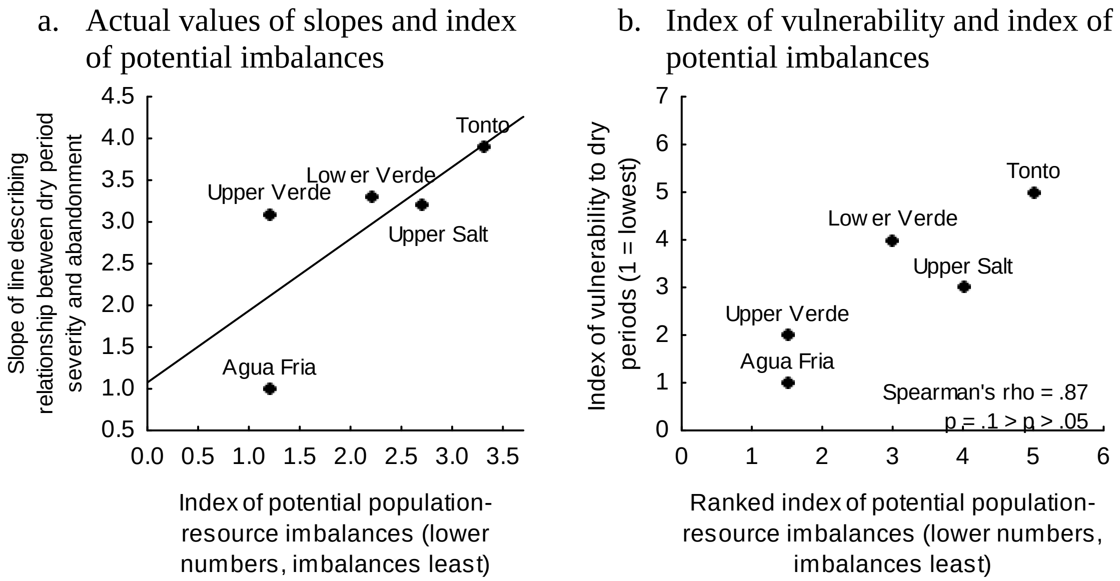


Figure 9.7. Scatterplots of relationship between potential population-resource imbalances and the slope of the lines describing the relationship between dry-period severity and residential abandonment.

Summary and Implications

Models of vulnerability to dry periods that emphasize watershed-scale differences in the extent of population-resource imbalances to explain variation in vulnerability to dry periods are supported by this study. Evidence supporting this conclusion includes: first, stronger and more sensitive relationships between dry-period severity and residential abandonment where density was high and supplies low than where density was low and supplies high; and, second, as watershed-scale differences in potential imbalances increased, the slope of the regression lines describing the relationship between dry-period severity and residential abandonment in each watershed generally became steeper. Results do not, however, support the expectation that vulnerability to dry periods was influenced by imbalances in settlement-scale resource demands and supplies. Evidence supporting this conclusion includes the similarity in the relationships between dry-period severity and residential abandonment where settlement population levels were high and supplies low compared to where settlement population levels were low and supplies high.

Further support was also identified for the independent influence of high watershed population density on vulnerability to dry periods. People living in watersheds with high population density (excluding the Lower Salt) were more vulnerable to dry periods than those living in watersheds with low population density when potential productivity was held constant in two of three productivity scenarios. This result is consistent with the evaluation of demand models of vulnerability to dry periods wherein differences in watershed population density was identified as an influence on vulnerability to dry periods without considering differences in potential productivity among settlements (Chapter Seven). I have discussed the implications of finding a relationship between high watershed population density, residential abandonment, and vulnerability to dry periods at the end of Chapter Seven and will not repeat those arguments here.

Identification of the persistent influence of watershed-scale population-resource imbalances and watershed population density on vulnerability to dry periods in the context of the substantial social changes occurring throughout central Arizona during the period of study (see Chapter Four) justifies a continuing focus on the basic issues of resource supply and demand in our study of vulnerability to dry periods. Evaluating and integrating the influence of sociocultural changes and events into existing models of vulnerability is the next necessary step.

CHAPTER 10:

SUMMARY OF RESULTS AND CONTRIBUTIONS

This study investigates the influence of demographic and environmental conditions on the vulnerability of subsistence agriculturalists to dry periods. My approach to this investigation is to evaluate prominent and often implicit models of vulnerability to dry periods that have been used by archaeologists and others to explain and predict spatial and temporal differences in human vulnerability to dry periods. The foundation of these models is an assumption of resource marginality that presumes widespread vulnerability to dry periods due to regional-scale aridity. This effort is motivated by the strong impact these models have had on our understanding of climatic influences on human behavior and the lack of careful scrutiny of both the models and marginality assumption. This final chapter summarizes the empirical results of Chapters Six through Nine and discusses the contributions of this effort to archaeological research in the U.S. Southwest, climate-human behavior studies, and methodological contributions to similar studies.

Summary of Results

For central Arizona during the 1200 to 1450 period, results of this study (summarized in Table 10.1) support conceptual models that emphasize the contribution of high watershed population density and watershed-scale population-resource imbalances to relatively high vulnerability to dry periods. Models that emphasize the contribution of: (1) settlement population levels, (2) settlement locations distant from perennial rivers, (3) settlement locations in areas of low average annual precipitation; and (4) settlement-scale population-resource imbalances to relatively high vulnerability to dry periods are, however, not supported by this study. Results also suggest that people living in watersheds with the greatest access to and availability of water were the most vulnerable to dry periods, or at least most likely to move when confronted with dry conditions. Thus, commonly held assumptions of differences in vulnerability due to settlement population levels and inherently water-poor environmental conditions are not supported. The assumption of regional-scale resource marginality and widespread vulnerability to dry periods due to low average precipitation is also not consistently supported throughout the study area.

Table 10.1. Summary of Results.

Model Type	Conditions Expected To Influence Vulnerability To Dry Periods	Expected Influence On Vulnerability To Dry Periods	Actual Influence On Vulnerability To Dry Periods
Aridity	regional scale aridity	increase as dry-period severity increases	increased as severity increased in three of six watersheds
Demand models	settlement population levels	increase as settlement population levels increase	no influence
	watershed population density	increase as watershed population density increases	increased as watershed population density increased[1] usually regardless of the potential productivity of settlement locations
Supply models	settlement proximity to perennial rivers	greater among settlements far from perennial rivers than among those near perennial rivers	no influence[2]
	settlement area precipitation levels	increase as precipitation levels decrease	may have increased as precipitation levels increased
	settlement area precipitation levels in locations near and far from perennial rivers	greater among settlements far from perennial rivers	living near a perennial river had no effect on influence of precipitation levels on vulnerability
	watershed precipitation levels	decrease as precipitation levels increased	increased as precipitation levels increased

Model Types	Conditions Expected To Influence Vulnerability To Dry Periods	Expected Influence On Vulnerability To Dry Periods	Actual Influence On Vulnerability To Dry Periods
Supply models (cont.)	watershed precipitation levels plus streamflow discharge levels	greater among settlements with least access to water	increased as precipitation plus streamflow levels increased
Demand and supply models	population–resource imbalances (high watershed population density, low resource productivity)	increase as resource demands exceed supplies	increased as resource demands exceed supplies
	population-resource imbalances (high settlement population levels, low resource productivity)	increase as resource demands exceed supplies	no influence

[1] Lower Salt is an exception.
[2] Upper Salt is an exception.

Contributions to Archaeological Research in the U.S. Southwest

This study contributes to our understanding of the prehistory of central Arizona and the U.S. Southwest by enhancing understanding of conditions that affect human vulnerability to dry periods. This understanding allows us to appraise arguments that rely on untested models of vulnerability and assumptions of widespread resource marginality. It also suggests new strategies for advancing our interpretations of some of the critical events in prehistory including the depopulation of central Arizona and hypotheses of rising warfare in the region, as I discuss below.

14th and 15th Century Depopulation of Central Arizona

The evaluation of models of vulnerability to dry periods resulting in the identification of specific demographic and environmental conditions that contribute to this vulnerability provides us with a new method for evaluating arguments that invoke climatic influences on human behavior. We can use this method to evaluate dry-period influences on the depopulation of central Arizona and elsewhere. I (Ingram 2008) have previously argued that two prolonged and severe dry periods during the late 14th and mid-15th centuries were a catalyst for the depopulation. Stahle et al. (2000, 2007:142) refer to these dry periods as “megadroughts,” which imply a “very large-scale drought more severe and sustained than any witnessed during the period of [modern] instrumental weather observations.” Only five have been identified in the western U.S. since A.D. 1300 (Stahle et al. 2007).

As a test of the influence of these dry periods on regional depopulation, we can compare the actual temporal order of settlement abandonment and the demographic and environmental characteristics of settlements abandoned to an expected pattern if the depopulation were influenced by a dry period. We can expect a regional, dry-period related, spatial and temporal pattern of abandonment to begin with those identified as most vulnerable to dry periods transitioning over time to those least vulnerable. In other words, if dry-period risks of shortfall influenced the depopulation, we would expect that the pattern of abandonment might reflect differences in vulnerability to dry periods.

Based on current results, we should expect settlements located in high density watersheds to be abandoned earlier than settlements located in low density watersheds. We should also expect settlements located in areas with the greatest access to or availability of water to be abandoned earlier than settlements located in areas with the least access to or availability of water. These expectations will not, however, apply in the Lower Salt where results differed from the rest of central Arizona. An advantage of this approach is that the destinations of population movements need not be known since the focus is on patterns of abandonment in response to dry periods. This allows for the possibility of both movement elsewhere and in situ demographic decline, as suggested by Hill et al. (2004). The approach will be most effective if the period of study is lengthened to include an earlier and longer pre-depopulation period for the analysis of vulnerability to dry periods. In central Arizona, further progress also needs to be made in understanding the conditions that contributed to vulnerability to dry periods in the Lower Salt River watershed. The proposed approach, while imperfect, is an improvement over simply relying on space-time coincidences between severe dry periods and regional depopulation to argue dry-period influences. It is also an improvement over simply dismissing climatic influences on a depopulation because previous dry periods did not result in depopulation.

Investigation of dry-period influences on the depopulation will also require explaining why in watersheds where there was little long-term or prior evidence of the influence of dry-period severity on residential abandonment (e.g., Agua Fria, Upper Verde, Lower Salt), circumstances changed such that people in those watersheds moved when dry-period severity increased. It might be that we can use the principle of space-for-time substitution to examine short-term changes in vulnerability. That is, the strong and sensitive long-term relationship between dry-period severity and residential abandonment among settlements located in watersheds with high population density demonstrates the influence of high areal population density on vulnerability to dry periods. In watersheds without long-term evidence of a relationship between dry-period severity and residential abandonment, perhaps a sudden shift in conditions understood to increase vulnerability will explain an increase in vulnerability to dry periods where it had not been previously identified. In the case of high watershed population density, a rapid influx of immigrants that increases density could explain why conditions abruptly changed.

This proposed method of evaluating dry-period influences on a regional depopulation need not be limited to central Arizona but may be applied in any region with adequate prehistoric or modern data. It is especially important to apply these methods in the prehistoric northern Southwest where dry periods have been implicated in two regional depopulations (Chaco and the Mesa Verde region). Temporal resolution of the abandonment dates of many settlements are well known, demographic characteristics are better documented, and climatic and environmental data are at least comparable if not superior to the data available for central Arizona. Efforts in the northern Southwest and other regions that explore and test these methods should begin with identifying the conditions that contribute to long-term vulnerability to dry periods. Conditions identified in central Arizona may or may not apply elsewhere. Studies that identify these conditions will allow us to compare results, and perhaps further understand how and why particular conditions contribute to vulnerability to dry periods.

Finally, this study's results for the Lower Salt River watershed should remind us that there is no formula for predicting or detecting vulnerability to dry periods in all locations. Population density was high in the Lower Salt but vulnerability to dry periods as identified by residential abandonment was not detected. Despite the unique conditions in this watershed (discussed in Chapters Three and Seven), attention to increases in population density as a factor influencing residential abandonment and ultimately depopulation are still warranted. That residential abandonment was not associated with changes in dry-period severity in the high density Lower Salt may suggest that opportunities for improving conditions through movement were not available or preferred--not necessarily that people there were invulnerable to dry periods. Low overall rates of residential abandonment in the Lower Salt also suggest the effectiveness of strategies to manage declines in streamflow-related productivity. The negative influence of increasing population density on Phoenix basin residents has been identified by Abbott and Foster (2003) in a large, well-documented village (Pueblo Grande) in the early Classic period. This population increase is coincident with a decline in the health of village residents and a number of social changes that they argue contributed to a prolonged period of decline. My findings of the relationship between population density and residential abandonment outside of the Lower Salt are consistent with the argument that increasing population density in the Phoenix basin contributed to the decline of conditions that ultimately led to the depopulation of the Lower Salt. The residents of the Lower Salt, unlike people living elsewhere in central Arizona, did not immediately move away but were instead able to hold on through “centuries of decline”, as argued by Abbott and colleagues (Abbott 2003:227; Abbott 2003 ed.).

Conflict and Warfare

Rising conflict and warfare has been argued for central Arizona during the period of study (LeBlanc 1999; LeBlanc and Rice 2001; Rice 2001; Wilcox et al. 2001a, 2001b; Wilcox and Holmlund 2007 and others). Crucial evidence of this conflict includes a pattern of population movement that resulted in clusters of settlements surrounded by unoccupied areas. Conflict can produce settlement clusters and unoccupied zones if people aggregate to decrease their real or perceived risk of harm associated with increases in hostilities. Settlements in close proximity may gain defensive or offensive strength in numbers and provide early warnings of attack to nearby settlements (e.g., Wilcox and Haas 1994; Wilcox et al. 2001a, 2001b; Rice 2001). Unoccupied zones may reduce the potential for conflict by raising the transportation costs between people and providing resources in emergency situations (e.g., DeBoer 1981; LeBlanc 1999; Martin and Szuter 1999). Unoccupied zones also delineate settlement clusters and spatial associations may indicate a political relationship or polity (Wilcox 1981; Upham 1982).

The identification of specific demographic and environmental conditions that contribute to vulnerability to dry periods provides us with a method of evaluating evidence relied on in models of conflict and warfare in the region. The reliance of these models on patterns of population movement into settlement clusters and out of surrounding areas allows us to compare these patterns of movement to what we would expect if these movements were related to increases in dry-period shortfall risks and vulnerability to these risks. Such an evaluation is warranted in central Arizona because the formation of a number of buffer zones and settlement clusters is temporally coincident with the "Great Drought" of 1276 to 1299. If settlements abandoned in buffer zones are located in areas of greater potential vulnerability to dry periods and if settlements that remain and increase in size are located in areas identified as among the least vulnerable to dry periods, then dry-period influences on the pattern of population movement will be implicated. Such a finding does not contradict models of conflict; rather, it introduces a problem of equifinality associated with the settlement patterns used to support the warfare models. That is, two processes (warfare and dry periods) can be argued to have influenced the same settlement pattern. Consequently, more weight will need to be placed on the other supporting lines of evidence for increasing warfare (defensive site locations and architecture, line-of-site connections, patterns of burned or abandoned settlements on the edges of clusters, etc.).

The challenge to the marginality assumption identified in this study questions economic and environmental bases of conflict in the region. Rice (2001) has argued that escalating conflict due to resource disparities between canal irrigators of the Phoenix basin and their immediate non-irrigating neighbors (generally to the north) created a gradual rise in the frequency and scale of demands for the canal irrigators' resources. While irrigation-based productivity in the Phoenix Basin was not matched elsewhere, the results of my study do not demonstrate a pattern of long-term vulnerability to dry periods in the Agua Fria or Upper Verde watersheds, which contains some of the immediate and non-irrigating neighbors as well as settlement clusters and buffer zones of the hypothesized Verde Confederacy (Wilcox et al. 2001b). The spatial distribution of vulnerability to dry periods identified in this study questions the notion of impoverished peripheral farmers raiding the Phoenix Basin for food resources. For the Southwest in general, LeBlanc (1999:32-42) suggests the basis of conflict was also competition over scarce resources. Increasing population levels across the Southwest in the 1200s, he argues, coincided with declines in resource productivity associated with a period of global cooling. The result was increasing competition for resources that resulted in escalating violence. Again, the spatial distribution of vulnerability to dry periods identified in my study provide no support for widespread resource marginality, even in the context of the hypothesized period of lowered regional-scale productivity due to a period of cooling.

In sum, advancing archaeological understanding of the depopulation and increasing warfare involves, in part, understanding population movements. The results of this study demonstrate that in three of the six watersheds considered, population movements were strongly related to variation in dry-period severity during the 1200 to 1450 period. Arguments that attempt to explain these movements or rely on these movements as evidence of other phenomena, then, will be incomplete without considering the role of vulnerability to dry periods on these movements.

Contributions to Climate-Human Behavior Studies

This study is the most comprehensive examination of the influence of climate on human behavior yet conducted in central Arizona. It is also the only effort in the U.S. Southwest to systematically evaluate models of vulnerability to dry periods and identify the influence of specific demographic and environmental conditions. The results of this study, when considered generally, make an effective case for a substantially more complex and nuanced relationship between climate and human behavior than those implied by assumptions of resource marginality, endemic shortfalls, and widespread vulnerability to climatic conditions. With this recognition, archaeologists and other scholars can pursue much needed advancements in understanding the important and dynamic contribution changing climatic conditions have played and will play in the course of human history. Improving understanding of human vulnerability to changing climatic conditions and changes in this vulnerability over time and under varying conditions is the necessary next step. By taking this step and employing a vulnerability approach, archaeologists provide a vital connection between modern studies of vulnerability of relatively short duration to archaeological studies of vulnerability of substantially longer duration. The results of such an effort will undoubtedly prove beneficial for archaeologists and the global change community, who are rapidly advancing both methods and theories of vulnerability to climatic conditions.

An important implication of this study is that we should begin our thinking about climatic influences on human behavior with the assumption that there was no influence. This is an obvious point (the null hypothesis) but the widespread acceptance of the assumption of resource marginality (demonstrated by its frequent use and a paucity of challenges to the assumption) suggests that we are beginning our thinking with assuming the influence of climatic conditions. Argument seems to be necessary to demonstrate that there was (is) <u>no</u> climatic influence on human behavior in arid climates. Furthermore, efforts that empirically demonstrate rather than assume particular relationships will ultimately be more convincing and testable.

A productive next step for investigations of climatic influences on human behavior is to consider other aspects of climate that affect resource productivity and the risk of food shortfalls. Flood induced stream channel change (Graybill et al. 2006), unprecedented warm or cool temperatures (Salzer 2000a, 200b), variation in intra-annual precipitation patterns (Gregory and Nials 2007), and changes in temporal or spatial variability of precipitation and streamflow (Dean 1996) can individually or in combination affect resource productivity and human decision making. The methods developed in this study are amenable to testing the influence of any of these conditions on population movement or other potential indicators of vulnerability to dry periods.

Attention to the study of vulnerability to potentially harmful events/processes may stimulate renewed interest and progress among archaeologists and others interested in climate-human behavior studies. A vulnerability approach may address one of the primary weaknesses of climate-human behavior studies: explaining why at some times and places climate appears to influence human behavior and at other times it does not. An emphasis on vulnerability may also help explain why the magnitude of a climate-related risk often does not explain the magnitude of the response, contrary to predictions generated by studies of risk (e.g., Halstead and O'Shea 1989a). Attention to vulnerability to climatic conditions or other environmental changes could also provide archaeologists a point of entry into global environmental changes studies concerned with both vulnerability and adaptation to climatic, environmental, and social change. Archaeologists, with long-term datasets, are particularly well positioned to contribute to these growing research emphases (van der Leeuw and Redman 2002).

Methodological Contributions

The focus on long-term relationships between dry-period severity and residential abandonment is a unique methodological contribution of this study. I consider this relationship over 250 years, or roughly 10 human generations. This focus addresses the challenge of distinguishing a space-time coincidence from a likely causal relationship. Problems of distinguishing the two, also understood as a problem of correlation vs. causation, are a source of weakness of many climate-human behavior studies. When long-term relationships are the analytical focus, these problems are diminished as relationships detected during longer periods will be much more reliable than relationships detected during shorter periods. Increasing the period of study and using more temporally refined archaeological data will be beneficial but it will create other types of problems. If a dry-period occurs, when should we expect a human response if the dry-period had an impact? Because there are lags in both behavioral and environmental responses to decreases in precipitation (and sometimes no response), determining vulnerability and impacts will not be as simple as identifying temporally coincident dry periods and settlement abandonment.

The multiple spatial scales used in this study are also a unique methodological contribution to climate-human behavior studies. Spatial scales considered include settlements, watersheds, and combinations of watersheds. Investigating climate's potential influence at multiple scales is in contrast to those that consider potential impacts at the scale of a single settlement, river, or across entire regions at particular times such as during a regional depopulation.

Considering multiple scales provides redundancy necessary for increasing validity and minimizing the analytical impact of influences on human behavior other than those of primary interest. The availability of regional-scale settlement data such as those used in this analysis offers unprecedented opportunities to examine the relationship between climate and human behavior at multiple spatial scales. Multi-scale analyses can also be applied to historic and modern climate-human behavior studies.

The spatial scale at which one considers vulnerability to climatic conditions has a strong impact on results. For example, during data exploration for this study I found a sensitive and strong positive relationship between dry-period severity and residential abandonment throughout the central Arizona study area, excluding the Lower Salt watershed. This relationship supports the assumption of marginality, endemic shortfalls, and widespread vulnerability to dry periods. When I examined the relationship between dry-period severity and residential abandonment at the watershed scale, however, differences among watersheds were evident. These differences demonstrate critical differences in the relationship between dry periods and residential abandonment and potential vulnerability. Thus, vulnerability to dry periods no longer appeared widespread. Perhaps differences in results due to the use of different spatial scales in other climate-human behavior studies are responsible for both the diversity of opinions regarding climatic influences on human behavior and a lack of overall consistency in results.

Establishing a broad-scale spatial pattern at the watershed or regional level provides a method of evaluating relationships at smaller scales and potentially identifying factors that contributed to or lessened vulnerability to dry periods. When a long-term relationship between dry periods and population movement is established in particular places (as in some watersheds in this study), individual settlement histories can be better understood. For example, if a particular settlement is abandoned during a dry-period and the broad-scale and long-term pattern in the relationship between dry periods and abandonment has demonstrated that as dry-period severity increased, settlement abandonments increased, then the likelihood of climatic influences on this settlement is increased. Without a broad-scale and long-term climate-settlement history (or alternative lines of evidence), the possibility of a space-time coincidence between the dry-period and the abandonment of the settlement cannot be reduced. If the settlement's trajectory differed from the broad-scale, long-term pattern, then specific investigation will be necessary to explain why the trajectory of the settlement did not follow patterns seen over long periods and large spatial scales. Such exceptions will be useful in identifying factors that contributed to or lessened vulnerability to dry periods.

The approach used in this study to examine the potential influence of demographic and environmental conditions on vulnerability to dry periods can be used to examine the influence of other conditions. For example, differences in climate's influence based on differences in social, political, and cultural conditions should also be considered as well as other environmental conditions that affect resource productivity (e.g., soil type and quality). The approach used in the study is a basic, well understood scientific procedure with broad applicability. It is essentially an analysis of variance. I compare changes in dry-period severity to variation in the extent of residential abandonment. To understand the extent to which demographic and environmental factors influenced the extent of abandonment I varied these conditions. Differences in the sensitivity and strength of the relationship between dry periods and abandonment under these different conditions were used to infer the influence of these conditions.

This study also demonstrates the importance of the selection of indicators of resource supply and demand for an evaluation of different types of vulnerability models. For example, results of the evaluation of demand models identified support for the influence of watershed population density on vulnerability to dry periods but no support for the influence of settlement population levels. If only one indicator of resource demands had been used, results would have supported or refuted demand models. Instead, multiple indicators of demand revealed the impact of different scales of demand on vulnerability to dry periods. Future efforts to evaluate vulnerability models or identify the influence of particular conditions on vulnerability to dry periods will also benefit from employing multiple indicators that reflect different spatial scales.

Conclusion

In conclusion, I hope this study provokes renewed interest in climate's influence on human behavior in the U.S. Southwest and elsewhere. When we are unburdened by an assumption of resource marginality that considers endemic shortfalls and widespread vulnerability to dry periods as a pre-existing condition of life in arid and semi-arid regions, renewed opportunities to investigate climate's influence on human behavior and the course of human history become available. A vulnerability approach, because of its focus on social conditions rather than environmental hazards, is particularly well suited to anthropologically-oriented archaeological research. I also hope that this study has effectively demonstrated alternative methods to investigate potential climatic influences on human behavior that do not rely on single space-time coincidences. It is well understood that these coincidences do not demonstrate climate's influence. Refinements in approaches to evaluating climatic influences on human behavior must keep pace with accumulating paleoclimatic and archaeological data or frustration with the particularistic aspects of the variable relationship may discourage continued interest and analytical and interpretive advancements. In the context of the worldwide dialog on the potential impacts of increases in atmospheric temperatures on human subsistence and well being, interpretive and methodological advancements are particularly important.

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