American Antiquity (2024), **89**, 58–77
doi:10.1017/aaq.2023.67

ARTICLE

Combining Paleohydrology and Least-Cost Analyses to Assess the Vulnerabilities of Ancestral Pueblo Communities to Water Insecurity in the Jemez Mountains, New Mexico

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(Received 11 April 2023; revised 28 July 2023; accepted 13 August 2023)

Abstract

We developed a new approach to identify vulnerabilities to water insecurity across entire archaeological culture areas by combining a paleohydrological model of the sensitivites of hydrological systems to droughts with least-cost analyses of the costs to acquire domestic water. Using a custom Python script integrated into ArcGIS Pro software, we calculated the pairwise one-way cost in time for walking between 225 water sources and 5,446 Ancestral Pueblo cultural sites across the Jemez and Pajarito Plateaus of the Jemez Mountains, New Mexico. This allowed us to identify whether periodic hydrological droughts occurring between AD 1100 and 1700 increased water acquisition costs across these regions. We found that hydrological droughts increased travel times in both regions to durations exceeding modern standards for water insecurity. Beginning in the fourteenth century, greater underlying hydrogeological sensitivities to droughts and the decline of a dual-residence pattern caused by population losses made the remaining aggregated communities of the Pajarito Plateau much more vulnerable to water insecurity than those on the Jemez Plateau. This would have upended long-standing relationships between communities and water on the Pajarito Plateau during a time when socioeconomic integration across the northern Rio Grande Valley pulled people toward valley bottoms.

Resumen

Desarrollamos un nuevo enfoque para identificar vulnerabilidades a la inseguridad hídrica en toda una zona arqueológica al combinar un modelo paleohidrológico de la sensibilidad de los sistemas hidrológicos a las sequías con análisis de costos mínimos de los costos de adquisición de agua doméstica. Utilizando un script personalizado integrado en el software ArcGIS Pro, calculamos el costo de tiempo de ida para caminar entre 225 fuentes de agua y 5.446 sitios culturales de los Pueblos Ancestrales en las mesetas de Jemez y Pajarito de las montañas de Jemez, Nuevo México. Esto nos permitió identificar si las sequías hidrológicas periódicas que ocurrieron entre 1100 y 1700 dC. aumentaron los costos de adquisición de agua en estas regiones. Las sequías hidrológicas aumentaron los tiempos de viaje en ambas regiones a duraciones que superan los estándares modernos de inseguridad hídrica. A partir del siglo XIV, las mayores sensibilidades hidrogeológicas subyacentes a las sequías y el declive de un patrón de residencia dual asociado a las pérdidas de población hicieron que las comunidades agregadas restantes de la meseta de Pajarito fueran mucho más vulnerables a la inseguridad hídrica que las de la meseta de Jemez. Esto habría trastornado las relaciones de larga duración entre las comunidades y el agua en la meseta de Pajarito durante un momento en que la integración socioeconómica en todo el valle del Río Grande del norte atraía a la gente hacia las partes bajas del valle.

Keywords: water security; least-cost analysis; paleohydrology; Ancestral Pueblo; climate change

Palabras clave: seguridad hídrica; análisis de costos mínimos; paleohidrología; Pueblos Ancestrales; cambio climático

Archaeological studies investigating the vulnerabilities of communities to climate change rely on the argument that a particular aspect of material culture can serve as a proxy for the dynamic relationships between climate and human behavior in the past. Archaeologists working in the North American Southwest have made strong claims that proxies for these relationships can be found in archaeological records of food systems (Nelson et al. 2016; Schwindt et al. 2016; Strawhacker et al. 2020), irrigation practices (Nelson et al. 2010), population movement (Ingram 2018), and social networks (Borck et al. 2015). Identifying vulnerabilities of communities to droughts is a frequent subject of climate-focused archaeological inquiry. Some archaeologists have argued that too often the impacts of droughts, which are defined broadly as a deficiency in precipitation over a given time (Wilhite and Glantz 1985), and hydrological droughts, which are defined as abnormal deficiencies in water within hydrological systems (Van Loon 2015), are only considered in relationship to agriculture (Ingram 2015; Ingram 2018; Kintigh and Ingram 2018). We argue that studying how communities met their domestic water needs during hydrological droughts presents an additional avenue to understand how climate change affects culture.

The UN-Water program defines water security in part as "the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water" (UN-Water 2013). The time it takes for a household to acquire water is an important variable in classifying water insecurity (Cairncross and Feachem 2018), which occurs when demands for water abstraction—the taking of water from a natural source—exceeds supply. The WHO guideline (World Health Organization [WHO] and the United Nations Children's Fund [UNICEF] 2017:Figure 11) states that a sustainable water system should have drinking water available within a half-hour by any means of travel. If travel takes longer, people will only collect the bare minimum of water they need for drinking, and other uses of water, such as for cleaning, sanitation, waste disposal, and food or domestic production, can fall to the wayside (Reed 2005). Ethnographic literature and autobiographies reflecting life in the late nineteenth and early twentieth centuries at Santa Clara Pueblo and the Hopi communities at Walpi and Orayvi show that droughts reduced the number of water sources, leading to long travel times and severe water conservation (Hill 1982:41; Owens 1892:163–164; Sekaquaptewa 1969:19). These examples demonstrate that, in historical Pueblo communities, droughts could increase the time it took to acquire domestic water beyond present-day thresholds for water insecurity. This raises the potential that water insecurities occurred among Pueblo communities deeper in history.

Water and Culture Histories of the Jemez Mountains, New Mexico

In this article, we present a new proxy for identifying water insecurities among Ancestral Pueblo communities of the Jemez and Pajarito Plateaus in the Jemez Mountains of New Mexico by combining models of domestic water acquisition costs with paleohydrological reconstructions of water availability. The people and places of these regions are ideal for an archaeological case study examining the relationships among culture histories, droughts, and domestic water. Both regions consist of broad mesa-top surfaces dissected by canyons, at the bottoms of which are springs and streams with the most reliable sources of drinking water (Figure 1). The mesa tops of these regions fall within what Bocinsky and Kohler (2014) model as one of the most reliable "maize agricultural niches" for dryland farming in the North American Southwest. Their study found very few periods when rainfall could not support maize agriculture across these regions— even in dry years. These mesa-top surfaces served as attractors for dryland farmers in the Late Developmental (AD 1050–1200) and Coalition Periods (AD 1200–1350; see Wendorf and Reed 1955, with minor updates in Kulisheck 2005 and Ortman 2016). Communities of dispersed households and small hamlets aggregated into plaza-focused villages through the Coalition Period on the Pajarito Plateau and by the end of the Coalition Period on the Jemez Plateau.

Yet, for all the benefits that this geographic setting provided for maize agriculturalists in the Developmental and Coalition Periods, the culture histories of the Jemez and Pajarito Plateaus diverged in the Classic Period (AD 1350–1600; Figure 2). Through the preceding Coalition Period on the Pajarito Plateau and potentially by the very end of this period during the Vallecitos Phase on the Jemez Plateau, Ancestral Pueblo communities practiced a dual-residence settlement pattern, with

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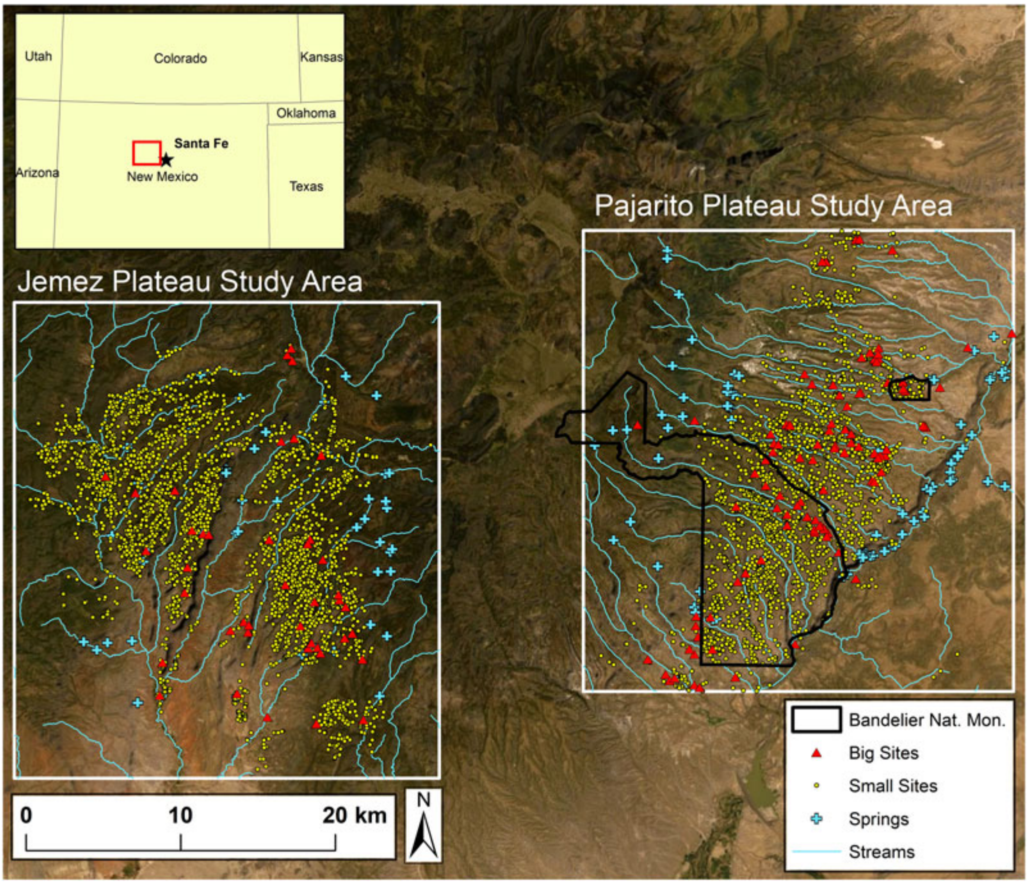

Figure 1. The Jemez and Pajarito Plateaus of the Jemez Mountains, New Mexico, with Ancestral Pueblo site locations and water sources. (Color online)

families living for parts of the year in permanent villages and in fieldhouses (1–12 rooms per site) and in smaller hamlets (13–49 rooms per site) in or near agricultural areas during the growing and harvesting seasons. The evidence for this are household-sized fieldhouses spread out across the mesa tops in prime agricultural lands and contemporaneous aggregated community centers that are found spaced from one mesa top to the next (Dolan et al. 2019; Preucel 1990). The number of Ancestral Pueblo people living on the mesa tops of the Pajarito Plateau decreased in the Classic Period from approximately 6,000 to 2,000, with only aggregated communities remaining by late in the Classic Period (Kohler et al. 2004; Orcutt 1999; Ortman 2016). New studies of site-specific occupation chronologies across the mesa tops of the Pajarito show that, along with this population loss, fieldhouses and smaller hamlets fell out of use, suggesting the breakdown of the dual-residence pattern on the Pajarito Plateau (Aiuvalasit 2017; Gabler 2009; Ortman 2016). The remaining aggregated communities were increasingly integrated into regional economies centered in the valley bottoms of the northern Rio Grande (Curewitz and Foit 2018; Duwe 2019; Kohler et al. 2004; Ortman and Davis 2019). By the eve of Spanish contact, there were only a small number of Keres- and Tewa-speaking communities on the mesa tops of the Pajarito Plateau. This history stands in contrast to the mesa tops of the Jemez Plateau where populations of Ancestral Pueblo communities of Towa speaking Hemish increased through the Classic Period. The dual-residence pattern of seasonal occupation of both fieldhouses and large villages continued until the forced removal of the ancestors of the modern Jemez Pueblo by the Spanish in the very late sixteenth and early seventeenth centuries (Kulisheck 2005; Liebmann et al. 2016; Sando 1982; Tosa et al. 2019).

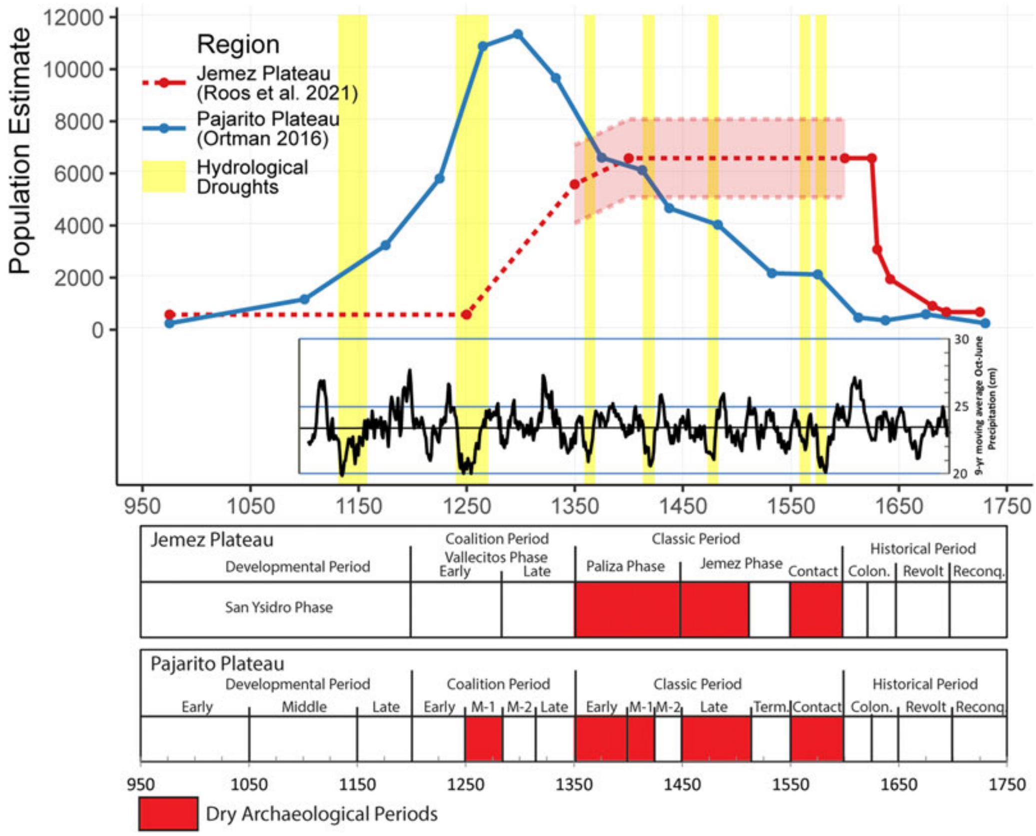

Figure 2. Integrated models of Ancestral Pueblo population estimates, dendroclimatological precipitation reconstructions with modeled hydrological droughts, and dry periods within the cultural chronologies of the Jemez and Pajarito Plateaus. (Color online)

Drought and environmental change have long been seen as drivers of culture change on the Pajarito Plateau (Bandelier 1892; Henderson and Robbins 1912; Stuart 2011), but archaeologists have not considered how communities on the Jemez Plateau persisted under similar conditions. Artificial water-catchment features, referred to as reservoirs and located near most of the large mesa-top villages and towns in both regions, provide evidence that Ancestral Pueblo villagers were concerned about securing domestic water (Elliott 1982; Powers and Orcutt 1999). A geoarchaeological study of these features found that they could only be relied on for seasonal supplies of domestic water (Aiuvalasit 2017, 2019). This would pose a significant challenge for the peoples of the Pajarito Plateau during the Classic period, when Ancestral Pueblo peoples lived in villages and towns year-round, because water needs would greatly outstrip what could be collected and stored in reservoirs.

In this article, we address a series of questions to understand whether water insecurity due to drought-induced increases in water costs played a role in the divergence of cultural histories in the Jemez Mountains. Could the droughts reflected in dendroclimatological records have led to hydrological droughts? Did hydrological droughts reduce discharges of water from springs and streams to the point at which water acquisition costs would exceed the half-hour travel time used to define water insecurity? If so, were differences between the Jemez and Pajarito Plateaus in the sensitivities of hydrological systems to droughts significant enough to be a factor in the divergence in their culture histories?

Building a Model of Socio-hydrological Vulnerabilities

We integrate multidisciplinary data through a series of stepped analyses to address these questions (Figure 3). Archaeological data on water users comes from site location data, site-specific chronologies,

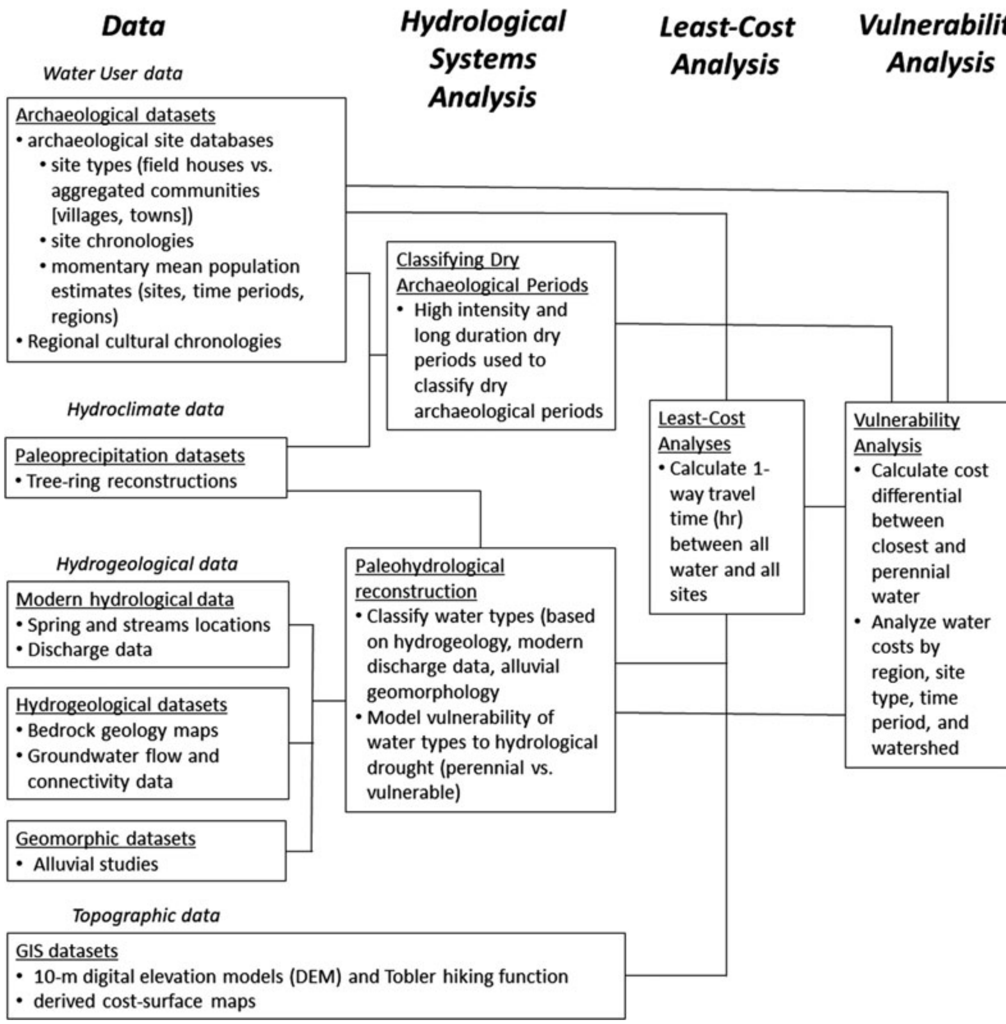

Figure 3. Flow chart of data and analyses used in this study.

momentary-mean population estimates, and geoarchaeological studies of Ancestral Pueblo water-management features. There are 5,446 Ancestral Pueblo cultural habitation sites within the 8.47 km^2 Jemez and 8.31 km^2 Pajarito Plateau study areas (Figure 1). Habitation sites are categorized based on room counts as either small (fieldhouses or hamlets with less than 50 rooms) or big (villages with 50–499 rooms and towns with 500+ rooms). On the Jemez Plateau 3,117 small sites and 39 big sites are included, whereas 2,187 small sites and 103 big sites are included on the Pajarito Plateau. Jemez Plateau population estimates are based on the work of Roos and colleagues (2021), whereas chronologies of culture histories come from research by Kulisheck (2005) and Liebmann and coworkers (2016). Because the dual-residence pattern persists through time on the Jemez Plateau (Kulisheck 2005), population estimates based on village and town sizes account for fieldhouse residents. On the Pajarito Plateau, Ortman's (2016) synthesis of architectural, ceramic, and ethnohistorical data provides site-specific momentary-mean population estimates for both small and big sites, which we sum by archaeological periods to generate a regional momentary-mean population within the project area. Finally, geoarchaeological studies of Ancestral Pueblo water reservoirs located at the largest villages in both regions are incorporated into models of when these artificial water sources were available (Aiuvalasit 2017, 2019).

Hydroclimate and hydrogeological data come from a variety of sources. Paleoprecipitation records are derived from a Jemez Mountains–specific tree-ring record (Touchan et al. 2011). Hydrological data of historical stream-discharge measurements come from gauging stations (US Geological Survey [USGS] 2016a, 2016b), whereas Aiuvalasit (2017) compiled data on the locations and discharges from springs from multiple sources. Relationships between subsurface geology and groundwater flow come from geological mapping and cross-section block models (Broxton and Vaniman 2005; Green and Jones 1997; Kelley et al. 2007; Smith et al. 1970; Tafoya 2012), as well as studies of the sensitivities of groundwater discharge to precipitation (Longmore et al. 2007; Purtymun 1995; Vuataz and Goff 1986). Insights into Late Holocene stream behavior and eolian processes relevant to this study come from multiple sources (Drakos and Reneau 2007, 2013; Hall and Periman 2007; Reneau 2000).

We conducted two hydrological systems analyses (HSAs) in this study (Engelen and Kloosterman 2012): a classification of dry archaeological dry periods and a paleohydrological model of the sensitivity of hydrological systems to drought. Intervals of reduced precipitation of magnitudes and durations severe enough to induce hydrological droughts are identified in the tree-ring record (Touchan et al. 2011), using an approach to classify archaeological dry periods developed by Dean (1988) and modified by Ingram (2015). We draw on paleohydrological methods used by Kolm and Smith (2012) in the Mesa Verde region to produce a semi-quantitative model of hydrological sensitivities of water resources to dry periods. We classify water resources as being either *vulnerable* to reduced discharge if there is hydrological and hydrogeological evidence for sensitivities to short-term precipitation deficits or *perennial* if water sources maintain discharge through hydrological droughts. Vulnerable water sources would not be available during dry archaeological periods, leaving only perennial water sources available to users. In periods that are not dry, all water sources are available for domestic water in our model.

Our analyses of water costs come from calculations of one-way pairwise least-cost analyses (LCAs) of travel time between each Ancestral Pueblo cultural site to each of the documented spring and stream water sources in their region (Figure 3). Archaeologists use LCA to identify potential routes of travel between sites (e.g., Caseldine 2022; Hart et al. 2019; Herzog 2013; White and Barber 2012) and to serve as proxies for resource acquisition costs measured in distance, time, or energy (e.g., Ladefoged et al. 2019; McCoy et al. 2011; White and Surface-Evans 2012). LCA is amenable to modeling how droughts affect water acquisition costs at regional scales because water and cultural sites are found at fixed locations but are not uniformly distributed through time and space.

Analyzing transportation costs between hundreds of water sources and thousands of sites exceeds the capabilities of built-in Spatial Analyst tools and Modelbuilder applications in ArcGIS software. The analysis and quantification of least-cost paths were automated through a custom Python 3.6 script calling the ArcPy module in ArcGIS Pro 1.4 (Jorgeson 2020). Inputs for this model were locations of cultural sites (points) and springs (points), streams (polylines), and cost surfaces (rasters) derived from a 10 m digital elevation model (DEM) raster. Tobler's (1993) hiking function serves as the vertical factor in the raster analyses to classify travel time under different degrees of slope. Even with the script, we divided each study area into overlapping subregions to reduce computer-processing time. The outputs of the script are raster and polyline files of the least-cost paths, as well as compiled tables of travel time (hours) and path distances (km) between water sources and cultural sites.

Finally, the vulnerability analysis integrates the paleohydrological models of water availability with the least-cost analysis of water costs in travel time (Figure 4). Undertaking LCA between all water sources and all cultural sites means that sites closest to water sources vulnerable to hydrological droughts also had measurements to their alternative closest perennial water source. This allowed us to calculate cost differentials for acquiring water from the closest perennial source during a hydrological drought. This cost difference, in time, becomes the measure on which community-level vulnerabilities are identified relative to the 0.5-hour threshold for water insecurity.

Results

Classifying Dry Archaeological Periods

We identified dry archaeological periods from low-frequency long-duration dry intervals between AD 1100 and 1700 in Touchan and coworkers' (2011) tree-ring-based paleoprecipitation reconstructions.

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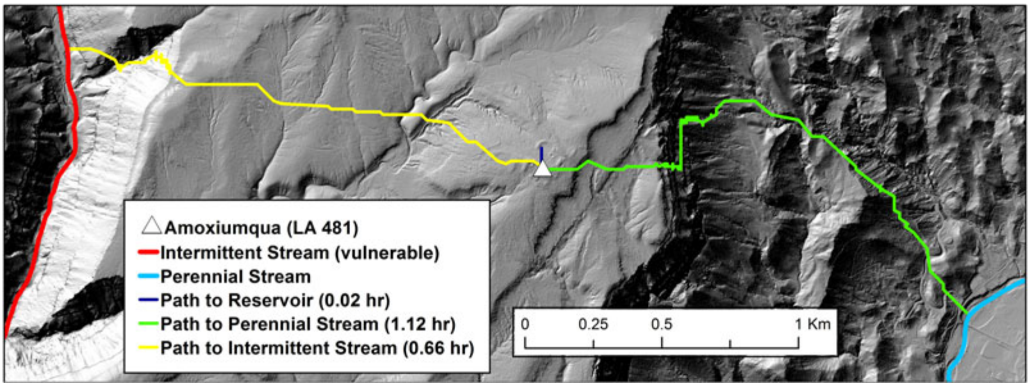

Figure 4. Example of least-cost paths and travel times from Amoxiumqua (LA481) to nearby water sources. (Color online)

The mean for the entire record is 23.42 cm of precipitation per water year, with a standard deviation of 4.61 cm, and we calculated z-scores for each water year. We identified seven dry intervals longer than nine years in duration, with z-scores less than zero for more than 70% of the years within the period; and with more than 20% of the years with precipitation 1 SD below the mean of the entire record (Table 1). We classified archaeological time periods as being a period of hydrological drought if most of the years within the cultural period fell within one of the seven dry intervals (Figure 2). We did not classify archaeological periods falling within the hydrological drought of AD 1131–1158 as dry because geomorphic studies show that it was not until the late thirteenth century that increased rates of eolian deposition on uplands coincided with downcutting of canyon-bottom alluvial systems (Drakos and Reneau 2013; Hall and Periman 2007). This suggests that canyon-bottom alluvial systems were less vulnerable to droughts in the twelfth century.

Paleohydrological Reconstructions

Eight water types (numbered 1–8) are identified from streams, springs, artificial reservoirs, and surface water across the Jemez and Pajarito Plateaus; each is classified as being either a perennial or vulnerable water source (Table 2) and is denoted in geological cross sections (Figure 5).

Jemez Plateau. There are 98 perennial water sources in our model across the Jemez Plateau (Figures 5a and 6; Table 2). Instrumental records show that the Jemez River is sensitive to annual precipitation deficits, but that there are no periods when flow ceased (Kelley et al. 2007; USGS 2016a), and there are many perennially flowing tributaries. Perennial springs discharge from two hydrogeological contexts. First, a perched aquifer (4 in Figure 5a) formed by impermeable mudstones at the top of the

Table 1. Dry Intervals Identified from Z-Scores of Paleoprecipitation Reconstructions

Dry Period	Period Duration (yrs)	Years z-score <0	Years z-score <−1	% of years z-scores <0	% of years with mean z-scores <−1
1131–1158	28	20	10	71	50
1240–1270	31	23	7	74	30
1359–1369	11	10	2	91	20
1413–1424	12	12	4	100	33
1473–1483	11	9	2	82	22
1558–1568	11	8	3	73	38
1573–1583	13	12	3	92	25

Source: Touchan et al. 2011.

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Table 2. Classification of Water Types and Paleohydrological Classification.

Water Type	Jemez Water Sources (*n* =)	Pajarito Water Sources (*n* =)	Water Group
1. Stream (perennial)	26	2	A
2. Stream (intermittent)	17	47	B
3. Spring (regional aquifer)	12	42	A
4. Spring (perched regional aquifer)	26	17	A
5. Spring (perched aquifer)	0	5	B
6. Spring (alluvial aquifer)	3	12	B
7. Artificial reservoirs	6*	9	B*
8. Surface water (*tinajas*)	1	0	B

Note: Water group A = perennial water; water group B = vulnerable water.
* Four of these Jemez artificial reservoirs are classified as perennial water sources.

Permian formations discharges as a series of springs along canyon walls across the western mesas of the Jemez Plateau. Tritium dating ($^3H/^3He$) of water from one of these springs estimates that meteoric water from this aquifer is 50–75 years old (Vuataz and Goff 1986). The half-century groundwater residence times and the continued use of many of these springs as a municipal water source for the Village of Jemez Springs indicate that the springs of the perched aquifer would not be sensitive to dry periods. The other perennial springs (3 in Figure 5a) are in canyon bottoms, and their source is the regional aquifer.

Twenty-three water sources are vulnerable to hydrological droughts on the Jemez Plateau (Figures 5a and 6; Table 2). We classify the intermittent streams (2 in Figure 5a) across the Jemez Plateau as vulnerable because they neither capture significant amounts of runoff snowmelt nor have sources of water from perennial springs. Geoarchaeological data from alluvial studies suggest no significant changes to canyon-bottom fluvial dynamics across the Jemez Plateau in the Late Holocene (Roos et al. 2021); therefore, present-day intermittent streams were also likely vulnerable to droughts in the past. Shallow alluvial aquifers (6 in Figure 5a) are also highly sensitive to precipitation, as are natural catchment basins like *tinajas* (8 in Figure 5a). Hydrological studies of surface runoff show that the artificial reservoirs (7 in Figure 5a) could only be seasonal water sources in both wet and dry years (Aiuvalasit 2017). Because Jemez villages were potentially occupied only seasonally (see the later discussion), these features may still have provided sufficient water for aggregated communities. Therefore, reservoirs at four cultural sites documented on the Jemez Plateau—Kwastiyukwa (LA482), Amoxiumqua (LA481), Boletsakwa (LA136), and Tovakwa (LA483/LA61641)—are considered perennial water sources for the least-cost analysis.

Pajarito Plateau. There are 61 perennial water sources across the Pajarito Plateau (Figures 5b and 6; Table 2), but only two are perennial streams (1 in Figure 5b): the Rito de los Frijoles within Frijoles Canyon where there is a large complex of cultural sites associated with the Ancestral Pueblo village of Tyuonyi, and the Rio Grande on the eastern margin of the region at the bottom of the steep-sided White Rock Canyon. Most of the perennial springs (3 in Figure 5b) discharge from the regional aquifer along the lower slopes and mouths of canyons on the far eastern edge of the plateau and flow directly into the Rio Grande. The other perennial springs discharge from a perched regional aquifer (4 in Figure 5b) along the far western edge of the plateau along the slopes of the Sierra de los Valles at the heads of drainages west of the Jemez Fault Zone. Although tritium and ^{14}C dating of spring water discharging from seven of these springs found the water to be modern, these springs are considered perennial sources because discharge rates hold steady through different precipitation regimes (Longmore et al. 2007). A few perennial springs and seeps emerge in deep canyon bottoms where alluvial units thin out above impermeable geologic units, such as the Cerros del Rio basalt. Some of these springs are near Ancestral Pueblo villages occupied into the early historic period, such as wetland marshes in Pajarito Canyon near Tsirege (Blake et al. 1995). Tritium dates of water from these springs

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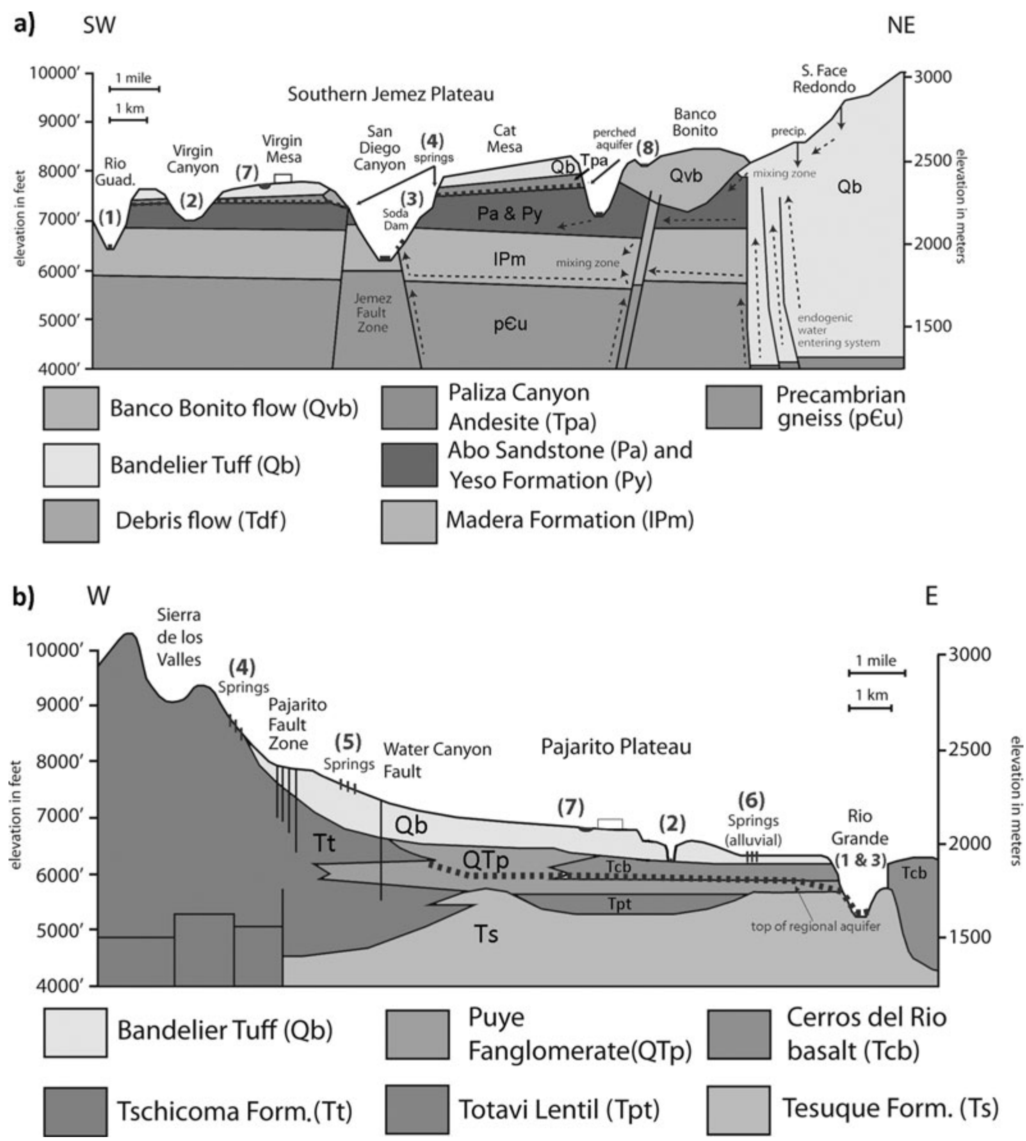

Figure 5. Hydrogeological cross section of the Jemez Plateau (a) and Pajarito Plateau (b). (Color online)

have wide age ranges (>10,000 to <100 yrs), and in some cases there is evidence for historical contamination from Los Alamos National Laboratory (Longmore et al. 2007).

All the other canyon-bottom drainages within our Pajarito Plateau study area support only seasonal and intermittent flows and are vulnerable to hydrological droughts (2 in Figure 5b; Figure 6; Table 2). This might not always have been the case. There is circumstantial evidence that some of these now-intermittent drainages once had perennial flows because channel incision, which can reduce stream flow and lower alluvial aquifers, did not begin in the nearby Rio del Oso until the 1200s (Hall and Periman 2007). This corresponds with episodes of eolian sedimentation on the mesa tops of the Central Pajarito, the sediments of which are inferred to derive from desiccated floodplains and fans (Drakos and Reneau 2007). The dry interval between AD 1240 and 1270 may have been a catalyst for hydrological change, making streams of the Pajarito vulnerable to reduced or no flow. These streams would certainly have experienced reduced flows at these times, but it is less likely that flows were reduced entirely during dry periods before the thirteenth century.

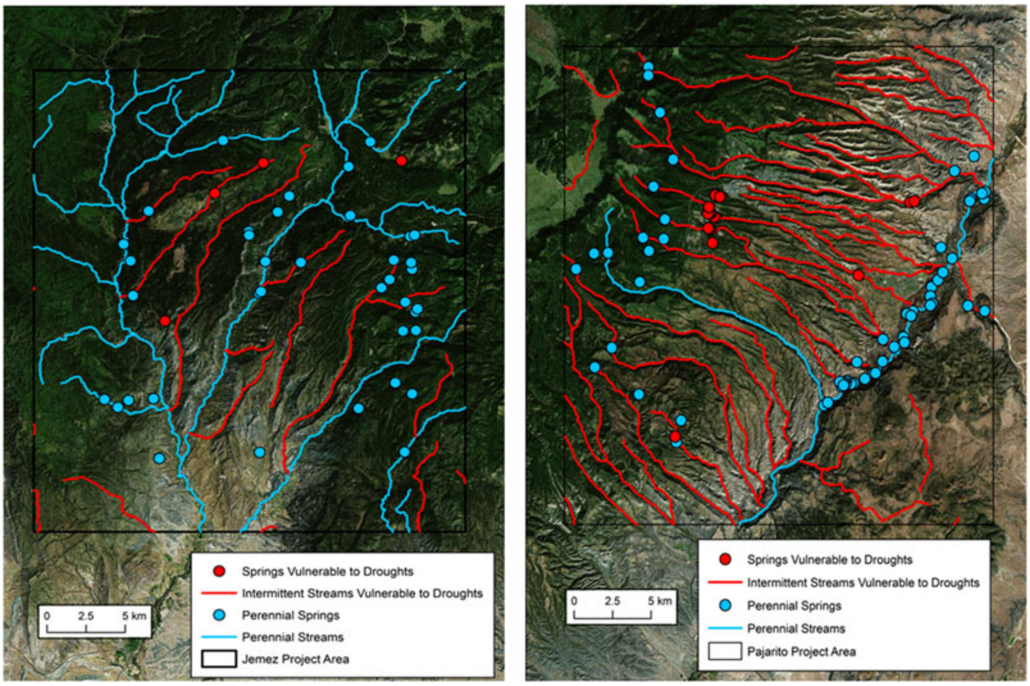

Figure 6. Paleohydrological models of the Jemez Plateau (*left*) and Pajarito Plateau (*right*) study areas. (Color online)

Other water sources vulnerable to hydrological droughts across the Pajarito Plateau study area are fault-controlled springs and seeps discharging in canyon bottoms of the westernmost portions of the Pajarito Plateau (5 in Figure 5b), isolated seeps and springs emanating from shallow alluvial and perched aquifers (6 in Figure 5b), and artificial reservoirs (7 in Figure 5b; Figure 6; Table 2). Springs on the east side of the Jemez Fault Zone are found in canyon bottoms along fractures in Bandelier tuff running parallel to the Pajarito fault zone near Los Alamos. These springs source from modern meteoric water, their flows are minimal, and they dry up in the summer (Dale and Yanicak 1996). Finally, all nine water reservoir features at four sites on the Pajarito Plateau—Tsankawi (LA211), Tsirege (LA170), Yapashi (LA250, LA70798), and Haatse/San Miguel (LA370)—tested by Aiuvalasit (2017) were too small to capture and store enough runoff to provide an appreciable volume of water to meet the household water needs of Ancestral Pueblo communities, particularly after they likely became year-round settlements in the Classic period.

Least-Cost Analyses of Water Acquisition Costs

To assess water acquisition costs of these landscapes independent of human settlement patterns, we conducted a least-cost analysis between each of the water sources and 500 randomly generated geographic coordinates within each study area. We excluded high-elevation areas and areas with no available archaeological survey data so that our random points were located in areas where cultural sites are located. We calculated the costs in travel time of 22,205 paths between water sources and 1,000 random points (Figure 7a). On the Jemez Plateau, the mean minimum distance from a natural water source, regardless of type, to a random coordinate is 0.26 hours, and 58% of the random points are closest to a perennial water source. There is little difference in the mean costs between traveling to the closest perennial source versus the closest vulnerable source (0.27 vs. 0.25 hours). The cost in travel time from a random point closest to a vulnerable water source to its nearest perennial water source increases to a mean of 0.71 hours on the Jemez Plateau. On the Pajarito Plateau, the mean distance to a natural water source, regardless of type, is only 0.19 hours; however, only 7% of the random coordinates are closest to perennial water sources. There is little difference in the mean costs between traveling to perennial sources versus to the closest vulnerable water sources on the Pajarito Plateau (0.18 vs. 0.25 hours), yet

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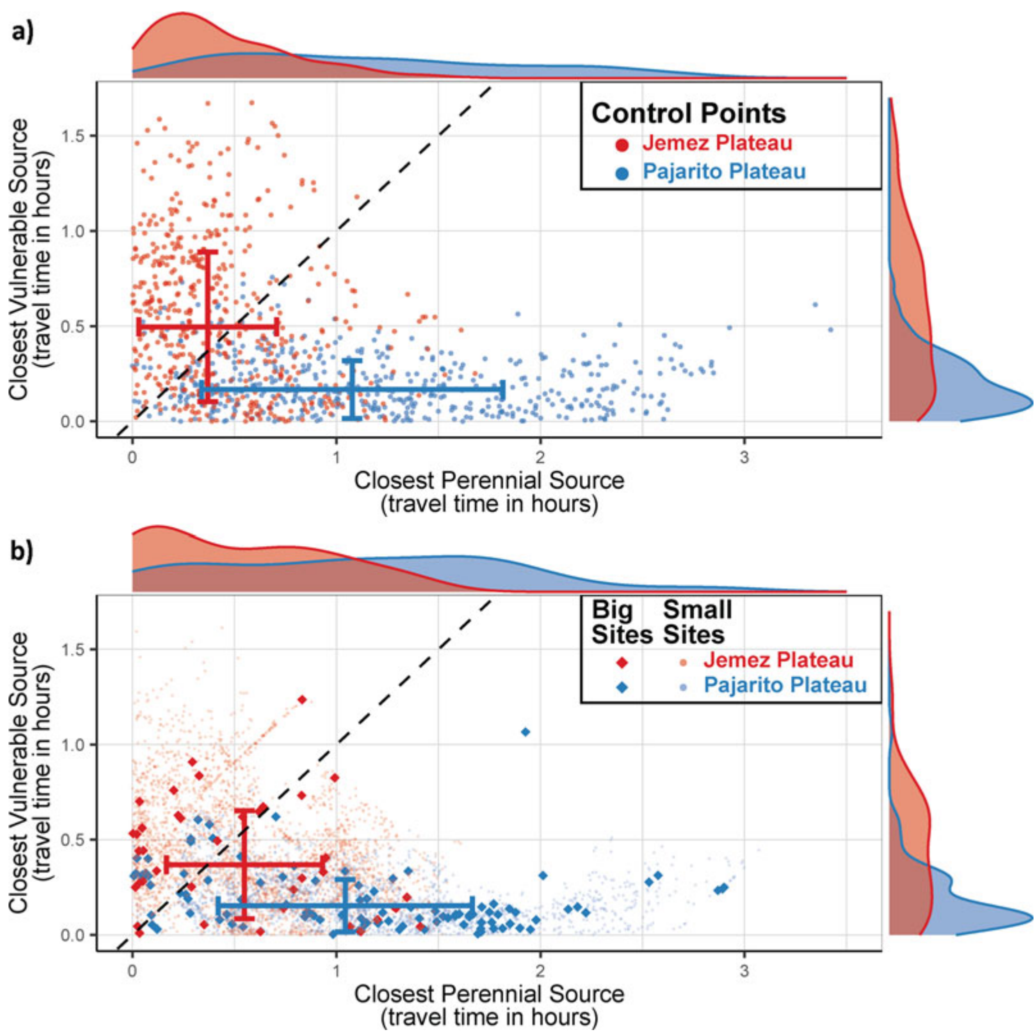

Figure 7. Distributions of one-way travel times in hours from the closest vulnerable and perennial water sources to control points (a) and big and small sites (b) on the Jemez and Pajarito Plateaus. Error bars represent 1 SD on either side of the median value, in both dimensions, whereas marginal distributions represent the kernel density estimate of univariate distributions using a gaussian smoothing kernel and standard bandwidth for that kernel. The diagonal dashed line represents equal travel times to the closest vulnerable and perennial water sources; sites above the line are closest to a perennial water source, whereas sites below the dashed lines are closest to a vulnerable water source and thus subject to increased water acquisition costs during drought conditions. (Color online)

the travel time from random points closest to a vulnerable water source to its closest perennial water source increases to an average of 1.27 hours. The combination of fewer perennial water sources and greater travel times suggests that landscapes of the Pajarito Plateau are inherently more vulnerable to hydrological droughts than the Jemez Plateau.

Because human settlement patterns are not randomly distributed, do the locations of habitation sites lead to lower water acquisition costs than randomly assigned spots on the landscape? On the Jemez Plateau, 41.2% of the small sites and 43.6% of the 39 big sites are closest to perennial water sources, a smaller proportion than in the control points (58%). For big sites, the mean travel times are the same (0.25 hours) whether to the closest perennial or closest vulnerable water source. The average travel times between small Jemez Plateau sites closest to perennial water and sites closest to vulnerable water are similar (0.24 hours vs. 0.28 hours). For the 1,830 vulnerable small sites on the Jemez Plateau, the average travel time from their closest perennial water sources increases to 0.83

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hours during a drought—a slight increase from the average of 0.71 hours in the control study. There is, as would be expected, an increase in travel time for the 17 big sites closest to vulnerable water sources during a hydrological drought. If water sources that are vulnerable to drought are unavailable, the mean one-way travel time from perennial water increases to 0.87 hours. Graphical comparisons of 1 SDs of median values and marginal distributions of archaeological data (Figure 7b) to the control data (Figure 7a) of the Jemez Plateau demonstrate relatively equal travel times between perennial and vulnerable water sources. Although a greater number of sites would experience higher travel times during hydrological droughts, there are still many sites close to perennial sources of water, and almost no sites see exceptional increases in distances to the closest perennial water. This implies that there were communities across the Jemez Plateau where water costs did not increase during droughts, and most Ancestral Pueblo households would not experience widespread increases in water acquisition costs during hydrological droughts.

Travel times between sites and water sources on the Pajarito Plateau are similar to those for the control points, reflecting a settlement system vulnerable to increased water acquisition costs during hydrological droughts. Figures 7a and 7b show the similarities in travel times, the proximity of sites to vulnerable water sources, and the much wider range in water costs to alternative perennial water sources across both the controls and the cultural sites. Only 6% of the small sites and 15% of the big sites are closest to perennial water sources. Average travel times to the closest water for small sites and big sites (0.17 and 0.15 hours) are similar to those for the controls and are shorter than those on the Jemez Plateau; however, increases in travel time during hydrological droughts are greater and would be experienced at many more sites. Our model indicates that hydrological droughts would increase the average travel time to the nearest source of water to 1.17 hours at small sites and 1.32 hours at big sites, a significantly larger increase in the cost of acquiring water than for those sites on the Jemez Plateau.

Vulnerability Analysis

The World Health Organization (WHO and UNICEF 2017) defines basic water security as having access to a water source that is available within a 30-minute round trip. Using a looser definition of a maximum of 30 minutes travel to the closest water source (consistent with Marchetti's constant [1994] for daily travel times), we classify sites into three categories: (1) those with modeled one-way travel times to the closest water source never exceeding 0.5 hours, regardless of hydrological conditions; (2) those sites with travel times that exceed 0.5 hours only during a drought (i.e., the closest source of water is vulnerable to drought, and the closest perennial source is more than 30 minutes away); or (3) those sites with travel times to the closest source of water that are always greater than 0.5 hours (Figure 8). This classification illustrates both the potential impacts of hydrological droughts to Ancestral Pueblo communities and the difference in the magnitude of those impacts between the Jemez Plateau and the Pajarito Plateau (Table 3). On the Jemez Plateau, just over half of the big sites and nearly half of the small sites are never more than 0.5 hours from a perennial water source; 31% of big sites would exceed the 0.5-hour threshold in dry periods, whereas the number of small sites vulnerable to water scarcity is roughly the same percentage as those that were not. These findings contrast with the Pajarito Plateau, where only one-quarter of the big sites and 17% of the small sites would always fall under the 0.5-hour threshold. Instead, most of the sites on the Pajarito see increases in travel times to perennial water during droughts, with 73% of the big sites and 82% of the small sites seeing one-way water costs greater than 0.5 hours. This situation would leave few options for households on the Pajarito Plateau—whether they were seasonally dispersed at fieldhouses or in communal villages and towns—to avoid major increases in water acquisition costs during droughts.

We can consider how hydrological droughts affect water acquisition costs through time by combining our LCA of travel times from water to big sites, momentary-mean population estimates during archaeological time periods, and our classification of archaeological time periods as being either drought or normal periods. Although water costs to villages and towns on the Jemez Plateau would increase due to hydrological droughts, the upper-quartile range during dry periods stays below one hour, and the median of one-way travel times never exceeds 0.5 hours even during droughts (Figure 9). This reflects the high percentage of big Jemez sites situated near perennial water sources

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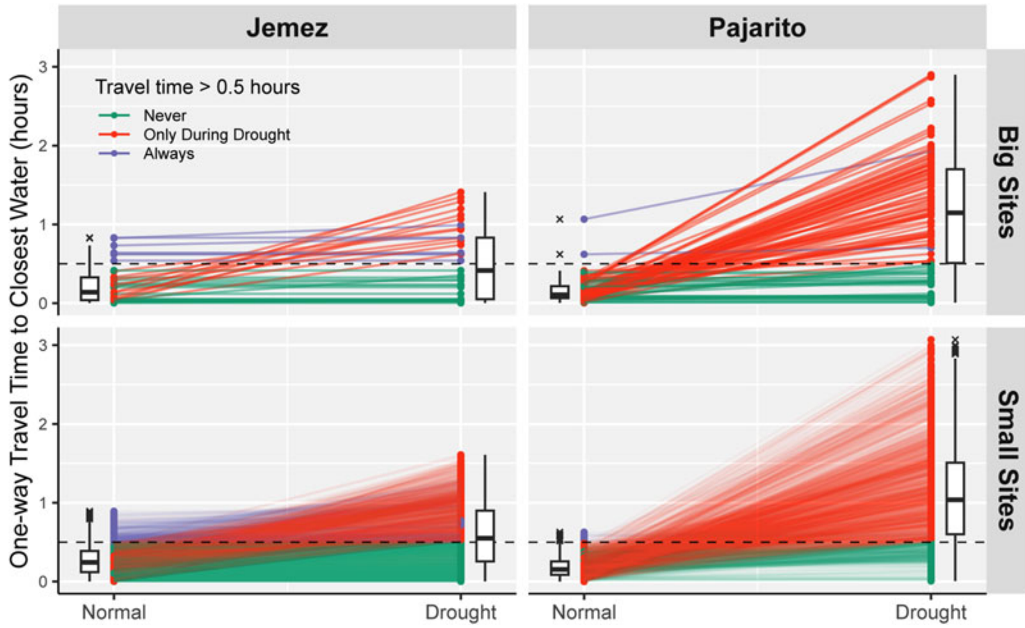

Figure 8. Boxplot charts comparing small site to big site cost differentials between the Jemez and Pajarito Plateaus.

and thus not affected by droughts. The very low travel times during the earliest cultural phases suggest that settlements were located close to water during a time when hydrological droughts were less common, and there were more opportunities to settle in advantageous locations because the population was smaller. Efforts to mitigate the risks of water insecurity at emerging villages in upland settlements were underway during this time period: geoarchaeological investigations found that reservoirs were already functioning during this Vallecitos phase (AD 1200–1350; Aiuvalasit 2019). The site of Wabakwa (LA478), which is closest to a vulnerable water source and may have a failed or incomplete water reservoir (Aiuvalasit 2017), was depopulated during a dry period at approximately AD 1450 (Roos et al. 2020). This shows that communities in particularly dry contexts of the Jemez Plateau could be vulnerable to droughts, but that these vulnerabilities were not widespread.

The wider distribution of perennial water sources buffered the risks of increasing water acquisition costs during hydrological droughts. Therefore, Ancestral Pueblo households and communities on the Jemez Plateau likely experienced strong positive feedbacks for maintaining the dual-residence settlement system and upland farming practices. Overall, even though costs increased during droughts on the Jemez Plateau, they did not increase tremendously or above the thresholds for travel time to water seen in ethnographic contexts or in agent-based models (Kolm and Smith 2012).

On the Pajarito Plateau, in contrast, hydrological droughts increased water costs substantially, declines in population generally correlated to periods of droughts, and over time settlement locations shifted toward perennial water sources (Figure 10). During the Developmental period (AD 950–1200)

Table 3. Categorization of Sites Based on Travel Time to the Closest Source of Water.

Location	Always < 0.5 Hours	Only > 0.5 Hours during Drought	Always > 0.5 Hours
Jemez small sites	44.7%	44.0%	11.0%
Jemez big sites	51.0%	31.0%	18.0%
Pajarito small sites	17.0%	82.0%	0.7%
Pajarito big sites	25.0%	73.0%	2.0%

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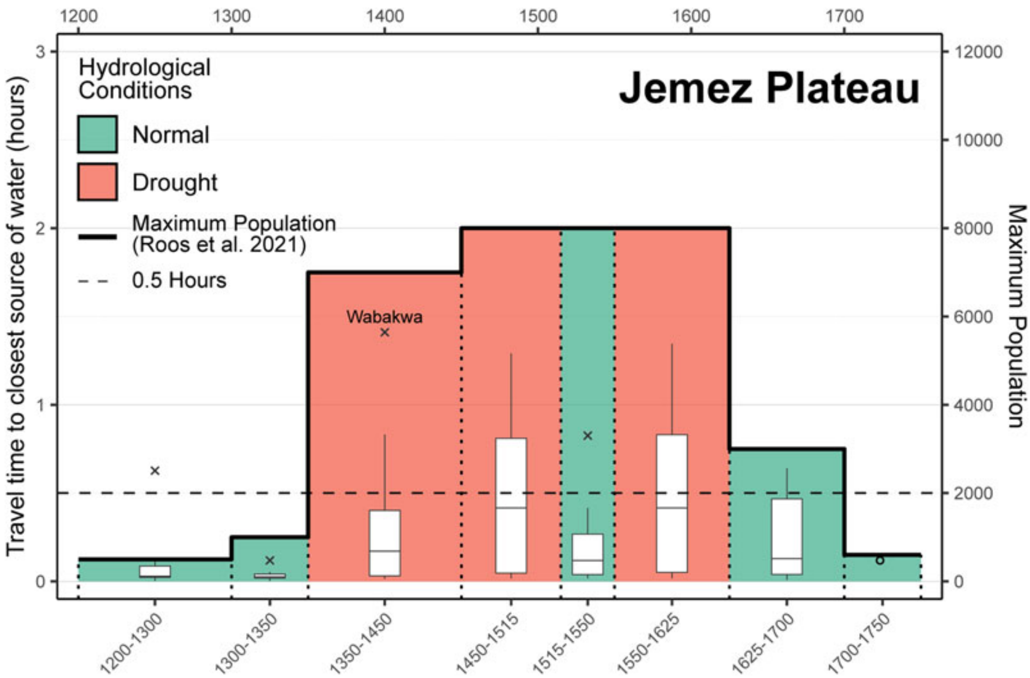

Figure 9. Diachronic model of momentary-mean population histories, drought periodicities, and water costs across the Jemez Plateau. (Color online)

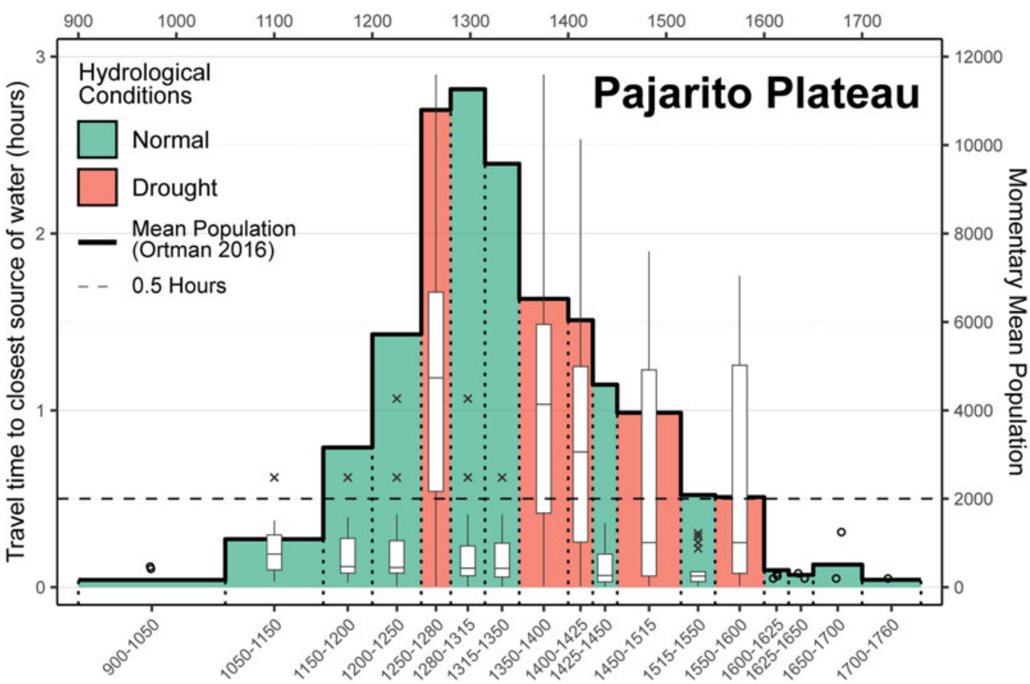

Figure 10. Diachronic model of momentary-mean population histories, drought periodicities, and water costs across the Pajarito Plateau. (Color online)

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the opportunity to settle in a region with low water acquisition costs during a wet period potentially facilitated the spread of early agriculturalist communities across the mesa tops. The time interval within the Coalition period with the greatest population increase also saw an increase in water scarcity (AD 1250–1280); however, the population was not yet at its peak. Uncertainty over the character of water discharge from streams that are intermittent today suggests that water availability was likely more variable than we can appreciate. This was followed by an approximately 70-year wet interval, which corresponded to the regional peak in population, when it is estimated that more than 60 big sites had populations larger than 50 people. The increasing frequency of dry periods starting in the late fourteenth century correlated to a decline in population: the AD 1350–1400 archaeological period of drought saw a 32% decline in momentary-mean population, with at least some people likely moving into the Chama Valley (Ortman 2016). Interquartile ranges largely exceeding the 0.5-hour travel time between AD 1350 and 1425 reflected much higher water costs. After the next wet period (AD 1425–1450), during which people from the Pajarito Plateau moved south to present-day San Ildefonso Pueblo, many sites were no longer occupied, and the villages that remained were near perennial water sources. This is reflected in the much smaller range of one-way travel times, which continued to shrink after the AD 1550–1600 dry period, when only three sites (LA170, LA77691, LA84090) with population estimates greater than 50 people remained on the Pajarito Plateau.

Conclusions

Our study presents a new way to understand the archaeological record of the Jemez Plateau. The distribution of perennial water sources there and the relatively low increases in water costs during droughts served as positive feedback for continuation of the dual-residence settlement system and mesa-top agriculture. Seasonal dispersals to fieldhouses across the landscape conferred advantages in lower water costs and reduced the reliance on artificial reservoirs when households were unlikely to store much water early in the growing season before summer monsoons. Water security may have also allowed Ancestral Jemez households to maintain greater control over their agricultural production than did communities living in villages year-round (Kohler 1992). A comparative study of fieldhouse excavation data found that fieldhouses of the Jemez Plateau, which are mainly Middle and Late Classic, are larger and have more storage features than those excavated on the Pajarito Plateau, which mostly date to the initial decline in populations during the early Classic (Dolan et al. 2019; Kulisheck 2005). These factors may have helped the Ancestral Hemish peoples of Jemez Plateau buck larger demographic trends in the Classic period of population decline, agricultural intensification, and village aggregation observed in other regional population centers (e.g., Hill et al. 2004; Kulisheck 2010; Wilcox et al. 2007).

In contrast, only villages near perennial water sources on the Pajarito Plateau persisted through the Classic period. Most of the villages on the Pajarito were closest to vulnerable water sources and experienced drastic increases in water acquisition costs during droughts. Such large increases support the argument that present-day intermittent streams of the Pajarito Plateau were likely perennial when the region was first settled by agriculturalists during the Developmental period and then became intermittent during the Coalition period due to channel incision. This change would mean that living in fieldhouses and practicing a dual-residence pattern would no longer minimize water acquisition costs as compared to living in centrally located villages close to one of the remaining perennial water sources. There is evidence for collective action responses to water scarcity, such as managing agricultural water using irrigation ditches, pumice gravel mulches, and terracing (Gauthier et al. 2007). As populations on the mesa tops of the Pajarito Plateau declined, abandoning fieldhouses to aggregate into a few larger communities near water seemed to yield the collective benefits of food sharing, mutual monitoring of scarce resources, and defense, which are considered long-standing attributes of Pueblo society in the northern Rio Grande Valley (Duwe 2020). Unfortunately, these practices could not provide enough low-cost water for many aggregated villages on the mesa tops of the Pajarito Plateau, which then became locked into the increasingly unreliable water resources closest to their communities.

Analyses of social networks across the North American Southwest identify the importance of social, information, and economic networks for mitigating climate-related risks (Gauthier 2021; Strawhacker

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et al. 2020), albeit with inherent trade-offs (Schoon et al. 2011). The northern Rio Grande Valley has robust evidence of a regional economy during the Classic period (Arbolino and Nelson 2014; Curewitz and Foit 2018; Duwe 2019, 2020; Kohler et al. 2004; Ortman and Davis 2019). Exchange networks and social institutions for resource management could certainly buffer against drought-induced food insecurities (Burger 2021; Eiselt 2019); however, in the absence of large-scale water infrastructures, domestic water needs in the Jemez Mountains could only be met locally. Time spent getting water would lead to lost opportunity costs for other pursuits, whether economic or otherwise, that could benefit individuals and their communities.

Although collective action in response to resource scarcity may not have mitigated high water costs on the Pajarito Plateau, the experience of water insecurity likely left its imprint on Pueblo peoples. In Tewa philosophy, water is an essential essence of life that flows through and interconnects beings, through which Tewa people strive to achieve balance and harmony (discussed in Duwe 2020). Watery places are sacred in Pueblo beliefs (Ford 2020). Cultural sites like shrines, trails, and petroglyphs in association with water reflect deep continuities between Ancestral Pueblo places and landscapes (Snead 2006, 2008) and the lived beliefs, histories, and experiences of Pueblo people today (Aguilar and Preucel 2019; Naranjo and Swentzell 1989, Swentzell 1993, Tosa and Seowtewa 2019). Climate-induced declines in discharges from springs and streams surely had repercussions beyond the economic, affecting cross-cutting relationships among people, community, water, and climate (e.g., Pauketat 2020).

Such experiences potentially facilitated aggregation into the increasingly large Classic period settlements in the northern Rio Grande Valley, as part of regional trends in population aggregation and agricultural intensification. Agricultural water management like what is seen on mesa tops, such as pebble mulch gardens, small-scale irrigation, and reservoirs, are also found in the lower elevations of the northern Rio Grande Valley (Anschuetz 1995; Camilli et al. 2019; Davis 2022; Duwe 2020; Kessler 2020; Ortiz 1969). Edward Dozier (1970:153), an anthropologist and member of Santa Clara Pueblo, believed there were continuities in social institutions for resource management and, particularly, irrigation from the precontact period into the historic Pueblo communities. It is not unreasonable to hypothesize that such institutional arrangements, particularly around resources as fundamental as water, may have emerged deeper in time (Ware 2014), which aligns with an increasing appreciation among archaeologists for studying the development of social institutions for resource management (e.g., Holland-Lulewicz et al. 2022; Lozny and McGovern 2019).

There are broader applications of the methodological approaches used in this study. This study presents a framework for developing metrics of travel time and resource costs across large areas using GIS software that is frequently used across disciplines. This approach has applications for examining intraregional variability in resource costs and routes of travel (e.g., Field et al. 2019; Verhagen et al. 2019) that is relevant to interdisciplinary and comparative research. For example, our observation of the one-way 0.5-hour travel time between Ancestral Pueblo sites and water is approximately the same length of time as Marchetti's constant (1994), which is a cross-cultural observation on the average length of time people will commute to work, regardless of the mode of transportation. These types of metrics make archaeological findings applicable to studies of contemporary and future resource insecurity, just like comparative studies of urbanization use settlement-scaling theory (e.g., Lobo et al. 2020). Such examples from archaeology will be increasingly relevant to a future where anthropogenic climate change influences hydroclimate cycles and strains the adaptive capacity of infrastructure and institutions.

Acknowledgments. This work was made possible through coordination with federal agencies (National Park Service, Department of Energy, and the US Forest Service) and in consultation with descendant Pueblo communities. No permitting was required to conduct these analyses. We would also like to thank Drs. Christopher Roos, Matthew Liebmann, and the rest of the Jemez FHiRE Project; Dr. Mark McCoy; the SMU Libraries Spatial Literacy Program; Dr. Alejandro Figueroa for assistance with the Spanish-language translation of the abstract; and two anonymous reviewers for their helpful comments. The Prairie Research Institute at the University of Illinois at Urbana-Champaign supported the completion of this manuscript.

Funding Statement. A Geological Society of America Grant Graduate Student Research Grant and grants from the Institute for the Study of Earth and Man and the William P. Clements Center for Southwest Studies at SMU funded data collection. The National Science Foundation's Doctoral Dissertation Research Improvement Award #1445083 and the Dynamics of Coupled Natural and Human Systems (CNH) Award #1114898 supported the analyses.

Data Availability Statement. Data tables of travel times and distances, polylines of routes, and raster files of cost surfaces are available on request from the corresponding author because sensitive site-location information can be inferred from the data.

Competing Interests. The authors declare none.

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Cite this article: Aiuvalasit, Michael J., and Ian A. Jorgeson. 2024. Combining Paleohydrology and Least-Cost Analyses to Assess the Vulnerabilities of Ancestral Pueblo Communities to Water Insecurity in the Jemez Mountains, New Mexico. *American Antiquity* **89**(1):58–77. https://doi.org/10.1017/aaq.2023.67.