Hydrological Modeling and Prehistoric Settlement on Santa Rosa Island, California, USA

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Fresh water availability was an important variable that influenced prehistoric human settlement on California's northern Channel Islands. Previous attempts to understand settlement on the islands use watershed size as a proxy for water at canyon mouths. In semi-arid regions, this approach has limitations because streams may lose much or all of their flow to groundwater. We developed a distributed hydrological model for Santa Rosa Island that incorporates geospatial and temporal data for climate (precipitation, solar radiation, wind speed, relative humidity, temperature), soils, vegetation, and topography to simulate the complex land-surface-groundwater behavior of island hydrology for hypothetical wet, dry, and median centuries. Our simulations show that water flow is greatest in drainages on the northwest and east coasts of the island. This correlates with some of the earliest and most persistent settlement on the island. During the most extreme droughts of the last 2000 years during the Medieval Climatic Anomaly (1150–600 cal BP), island populations contracted to a small number of large coastal villages. We argue that this was related in part to the greater availability of surface water at these locations. This study expands the theoretical and methodological scope of past studies that have applied hydrological simulation to archaeological investigations. © 2016 Wiley Periodicals, Inc.

INTRODUCTION

The availability of fresh water influences the location of human settlement worldwide. Water availability is a fundamental metric for sustaining habitation and it is often infeasible to transport over long distances. The location and distribution of water sources therefore have been an important determinant for the location of permanent settlement throughout human history (e.g., Childe, 1951; Wittfogel, 1957; Butzer, 1976; Isaac, 1993; Kirch, 1994; Raab & Larson, 1997; Jones et al., 1999; Scarborough, 2003, 2008; Scarborough & Lucero, 2011; French, Duffy, & Bhatt, 2012; Kennett et al., 2012; Bocinsky & Kohler, 2014). This is particularly true in arid and semi-arid regions where fresh water sources are limited under the best conditions and are highly sensitive to drought. In locations with a distinct wet and dry season, under drought conditions, the lack of rainfall (i.e., atmospheric drought) during the monsoon also decreases runoff during the dry season (i.e., hydrologic drought), limiting critical water supplies (e.g., French, Duffy, & Bhatt, 2012; Kennett et al., 2012). During multi-year atmospheric drought, other variables such as topography, geology, vegetation, and solar radiation either exacerbate or mitigate drought impact (French, Duffy, & Bhatt, 2012). Modeling the distributed hydrology of a region allows a deeper understanding of semi-arid response to drought or flood conditions and the possible impact of water availability. Plausible scenarios of catchment simulation can in turn be used to understand past settlement patterns and the distribution of permanent sites during different climatic regimes.

In this paper, we model how changes in precipitation impact the availability of potable water on Santa Rosa Island, the second largest of California's northern Channel Islands (NCI). The NCI include four islands, San Miguel, Santa Rosa, Santa Cruz, and Anacapa, ~40 km off the California coast (Figure 1). The islands are an extension of the Santa Monica Mountain range and have

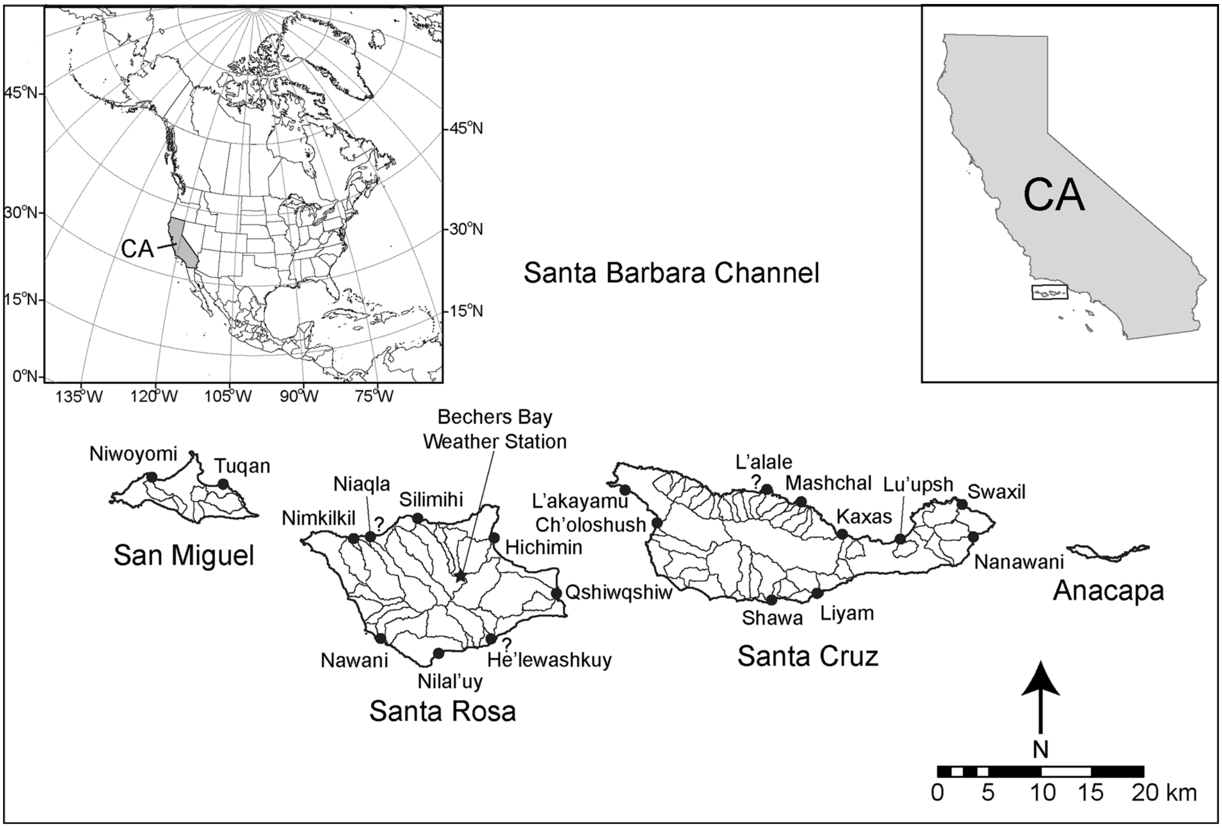

Figure 1 California's northern Channel Islands with drainage outlines indicated. Village locations are based on those presented in Johnson (1982, 1993) and Kennett (2005). The Bechers Bay weather station is indicated. The spellings of village names are as in Kennett (2005).

significant topographic variation, with Diablo Peak on Santa Cruz Island reaching 740 m above sea level (Junak et al., 1995). The largest islands, Santa Cruz and Santa Rosa, have the greatest relief and the largest volume of fresh water. Both islands are dissected by a series of deeply cut canyons that descend from the interior ridges of the islands out to the coast. The largest and most persistently occupied settlements on these islands were located at or near the mouths of these drainages (Kennett, 2005; Kennett et al., 2009; Winterhalder et al., 2010; Jazwa, Kennett, & Winterhalder, 2013). The earliest documented settlement sites on the NCI are on Santa Rosa (Kennett et al., 2009; Winterhalder et al., 2010), and at least eight large coastal villages were distributed around the island at historic contact (Johnson, 1982, 1993, 2001; Kennett, 2005; Glassow et al., 2010).

In this study, we use the Penn State Integrated Hydrological Model (PIHM) system to simulate changes in fresh water availability on Santa Rosa Island, the second largest of the NCI, during hypothetical wet, dry, and average regimes based on available climate data for the region. The hydrologic model scenarios are then compared with existing paleoclimatic records to associate these periods with important cultural events during the middle (~7550–3600 cal. yr B.P.) and late Holocene (after ~3600 cal. yr B.P.). Important events include the first establishment of large permanent settlements during the middle Holocene and periods of rapid sociopolitical change during the late Holocene. An important result is that the northwest coast, a major hub of settlement for much of the prehistoric past, has the highest fresh water storage and runoff in all seasons and is also among the most resilient to multi-year drought conditions. The response of each drainage to drought conditions (more or less negatively affected) also influenced people's decisions about where they settled during and after the Medieval Climatic Anomaly (MCA; 1150–600 cal BP). This provides us with a more nuanced model of past human response to changing fresh water availability and drought through time that can be compared with regional rainfall records derived from relict tree stumps or lake sediments.

WATER AND SETTLEMENT ON SANTA ROSA ISLAND

Climate and Culture History

Archaeologists have long recognized the limiting role of fresh water availability for human settlement on the NCI. The most prominent period of drought on the islands was associated with the Middle to Late Period Transition (MLT; 800–650 cal. yr B.P.). The MLT was a particularly important period of rapid cultural change when many of the complex social and political institutions that were evident at historic contact appeared (Arnold, 1991, 1992a, 1997, 2001b; Arnold & Tissot, 1993; Arnold, Colten, & Pletka, 1997; Raab & Larson, 1997; Kennett & Kennett, 2000; Kennett & Conlee, 2002; Kennett, 2005; Jazwa, Kennett, & Hanson, 2012). Despite never having agriculture, the islands were more densely populated than other areas in California and most other regions occupied by hunter-gatherers throughout the world (Moratto, 1984; Kelly, 1995; Winterhalder et al., 2010). The residents of the NCI lived in large coastal villages under the control of chiefs. These villages were located around the perimeters of the islands, typically at the mouths of drainages where fresh water and marine foods were available (Johnson, 1982, 1993; Kennett, 2005; Glassow et al., 2010; Figure 1). Craft specialists under the oversight of chiefs manufactured shell beads and sophisticated plank canoes, allowing islanders to be part of an extensive trade network (Johnson, 1982, 1993; Arnold, 1987, 1990, 1992a, 1992b, 1995, 2001a; King, 1990; Williams & Rosenthal, 1993; Arnold & Munns, 1994; Munns & Arnold, 2002; Gamble, 2002; Raab et al., 2002, 2009; Fagan, 2004; Kennett, 2005; Rick, 2007).

The NCI were occupied as early as 13,000 cal. yr B.P. (Johnson et al., 2002; Agenbroad et al., 2005), with clear evidence for the early use of marine resources (Erlandson et al., 2011). The first evidence for coastal village sites dates to the middle Holocene, although it is possible that earlier village sites may have been submerged by rising sea levels (Kennett et al., 2009; Winterhalder et al., 2010). Middle Holocene settlement patterns included permanent settlement sites and logistical camps for collecting specific resources (Jazwa et al., 2015). This period also had early evidence for status differences and the roots of sociopolitical complexity (King, 1990; Glassow, 2004). During the late Holocene, a series of interrelated environmental, technological, economic, and sociopolitical changes occurred on the NCI (Rick et al., 2005; Glassow et al., 2010). Beginning around 1300 cal. yr B.P., island populations increased and the number of permanent settlements expanded along the coasts (Arnold, 2001a; Kennett & Conlee, 2002; Kennett, 2005; Winterhalder et al., 2010). This coincided with the first evidence for institutionalized social and political hierarchies on the NCI (Kennett et al., 2009). A particularly important period of rapid cultural change was the MLT. There is debate over the influence of sea surface temperature on marine productivity at this time (see Pisias, 1978; Arnold, 1992a, 2001a; Raab & Larson, 1997; Kennett & Kennett, 2000; Kennett, 2005), and we will not discuss this further here. However, drought during this period seems to have played a role in the cultural changes and settlement shifts of the MLT.

The MLT occurred during a period of extreme drought conditions associated with the MCA (Stine, 1994; Raab & Larson, 1997; Jones et al., 1999; Yatsko, 2000; Kennett, 2005; Jones & Schwitalla, 2008). Stine (1994) used a radiocarbon record from relict tree stumps found in lakes, marshes, and streams in California to argue that the MCA included two extended periods of extreme drought, lasting from ~AD 892–1112 and ~AD 1209–1350. Benson et al. (2007) recalibrated the tree stump record and argued that there were actually three drought periods, lasting from AD 990–1060, AD 1135–1170, and AD 1276–1297. Regardless of the exact timing of the individual drought periods, they were pronounced enough to influence the archaeological record. These droughts were widespread and had broad impacts on human populations living throughout the American Southwest (Jones et al., 1999; Jones & Schwitalla, 2008; Bocinsky & Kohler, 2014). In the Santa Barbara Channel region, Lambert & Walker (1991; Walker, 1989; Walker & Lambert, 1989; Lambert, 1993, 1997) documented declining health and increased violence in skeletal collections from the MLT, which they associate with an increase in sedentism and diminishing supplies of fresh water and terrestrial foods.

As an example of the extreme conditions, during the mid-12th century drought, the Colorado River had a decrease of more than 15% in mean annual flow averaged over 25 years and there was an absence in high annual flows for about six decades (Meko et al., 2007). In addition to the extreme drought periods of the MCA, the intervals between droughts were among the wettest periods of the past two millennia (Stine, 1994). These abrupt hydroclimatic swings during this period would have been a further cause of stress for the human inhabitants of California (see Kennett & Kennett, 2000; Ingram & Malamud-Roam, 2013).

Although the MCA is the best dated and understood extended period with prominent extreme droughts, changes in fresh water availability were important for human settlement patterns throughout the occupational history of these islands. Climate records from throughout California and the North American Great Basin suggest that the middle Holocene was largely a dry interval (e.g., Antevs, 1948, 1952, 1955; LaMarche, 1973, 1974; Lindström, 1990; Thompson, 1992; Quade et al., 1998; Hughes & Graumlich, 2000; Benson et al., 2002; Kennett, 2005; Kennett et al., 2007). Specific records are available from the southern and central coast of California (e.g., Morgan, Cummings, & Rudolph, 1991; Cole & Liu, 1994; Erlandson, Rick, & Peterson, 2005). Benson et al. (2002) used records of total inorganic carbon and δ^{18}O from Owens Lake to characterize the early Holocene ($\sim$11,500–7550 cal. yr B.P.) interval from 10,000–8800 cal. yr B.P. as relatively wet. Records of water level from an algal tufa mound on the east side of the Winnemucca Lake subbasin, Nevada, confirm that the period from 10,000–9200 cal. yr B.P. was wet (Benson et al., 2013). Benson et al. (2002) use high-resolution δ^{18}O records from cored sediments of Pyramid Lake, Nevada to generate a high-resolution climate record starting at 7630 cal. yr B.P. They use the Owens and Pyramid Lake records to show that 8000 to 6500 cal. yr B.P. was a drying period that was interspersed with periodic wet intervals (Benson et al., 2002). The rest of the middle Holocene (6500–3800 cal. yr B.P.) was dominated by drought conditions. Dry conditions during the middle Holocene were also observed from marshland sediments in the Ruby Valley in northeastern Nevada (Thompson, 1992), a decrease in black mats in the southern Great Basin (Quade et al., 1998), a lowstand in Lake Tahoe (Lindström, 1990), and a dry interval in the bristlecone pine record from the White Mountains (LaMarche, 1973, 1974; Hughes & Graumlich, 2000). The beginning of the late Holocene appears to have been an increasingly wet period (Lindström, 1990; Davis, 1992; Thompson, 1992; Quade et al., 1998; Benson et al., 2002; Kennett et al., 2007).

In this paper, we model water flow dynamics within watersheds on Santa Rosa Island to assess patterns of fresh water availability and resilience during drought periods. During the middle Holocene, dry conditions would have increased the suitability for habitation of more resilient drainages. Kennett and his colleagues (Kennett et al., 2009; Winterhalder et al., 2010; Jazwa, Kennett, & Winterhalder, 2013) argue that the increase in permanent settlements during the late Holocene is related to an increase in population density and the resultant decreasing relative suitability of preferred locations. Wet conditions during the late Holocene would have provided more fresh water at new locations, thus increasing their attractiveness and contributing to population expansion.

Island Geography

Watersheds provide the most practical units for dividing up the Santa Rosa Island landscape. The physiography of the island, including geology, vegetation cover, topography, and other factors, has important implications for the varying responses of watersheds to changes in precipitation and groundwater. For example, a drainage may have less surface water available during a rainy period but it may be more resistant to drought conditions when subsurface water bolsters downstream flow.

The north coast of the island is a broad coastal plain through which a series of drainages flow from the mountainous central ridges of the island out to the ocean. Most of the largest drainages with perennial water flow are in the north (Figure 2). The eastern and southern parts of the island also have medium-to-large sized drainages and the smallest watersheds are found in the west (see Kennett et al., 2009). Water catchment size provides only a first-order approximation of the amount of water it contains. In the Santa Barbara Channel region, prevailing northwesterly winds carry weather systems that soak the west and northwest coasts of the island. These coasts are much wetter, foggier, and cooler than the more protected southern side (Hochberg, 1980; Junak et al., 1995; Fischer, Still, & Williams, 2009). For this reason, we would expect the drainages on the north and west coasts of Santa Rosa to be wetter than those on the south and east coasts.

PENN STATE INTEGRATED HYDROLOGICAL MODEL

PIHM is a modeling system developed by hydrologists at Penn State to model the internal dynamics of watersheds (Qu & Duffy, 2007; Kumar, 2009; Kumar, Bhatt, & Duffy, 2009; Leonard & Duffy, 2013). Unlike many other hydrological models that provide only the inflow and outflow to the system, PIHM simulates spatially distributed physical hydrologic processes for entire drainage basins. Directional surface flow, groundwater availability, soil moisture, and other variables for each drainage rely on parameterization using national and local data sets for soils, topography, land cover, geology and climate (Qu & Duffy, 2007; French, Duffy, & Bhatt, 2012; Leonard & Duffy, 2013).

PIHM generates a grid of triangles (triangular irregular network or TIN) to characterize the island watersheds and stream networks and to simulate the dynamic hydrological processes within all drainage basins. Each triangle is projected vertically downward from the surface to create a prism. Data are assigned within each prism to model the flow and complex interplay of surface water, groundwater, soil moisture, and vegetation type with parameters estimated from national and local data sets (Qu & Duffy, 2007; French, Duffy, & Bhatt, 2012; Leonard & Duffy, 2013). This model simulates stream flow for

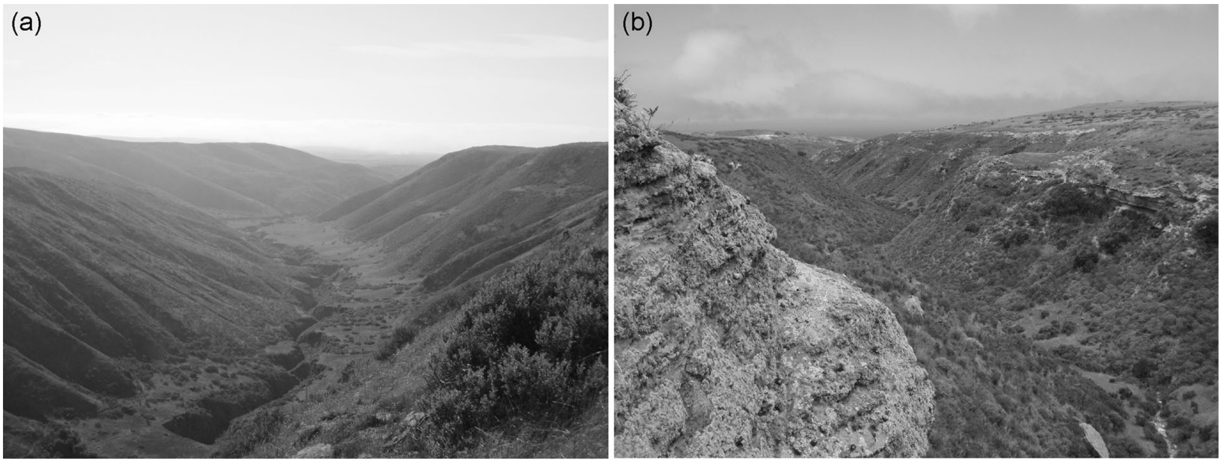

Figure 2 The two major types of drainage morphology on Santa Rosa Island. (a) Cañada Verde, a large U-shaped canyon. Note the deep channel cut that is likely a product of historic grazing. (b) Cow Canyon, a smaller V-shaped canyon.

specific drainages and also generates information about the coupled hydrodynamics of the entire landscape. It is available online at http://www.pihm.psu.edu.

French, Duffy, and Bhatt (2012) were the first to apply PIHM to archaeological questions by exploring the availability of water in the Maya lowlands in the prehistoric past. They modeled the flow at six streams at the site of Palenque in northern Chiapas, Mexico. French, Duffy, and Bhatt (2012) show that although other Maya centers may have been adversely affected by drought, even the worst hydrological conditions in the Palenque watershed are not particularly severe, and it is unlikely that drought would have been the primary reason for the eventual abandonment of the site. In our study, PIHM is implemented to examine the spatial and temporal patterns of water availability and the relation to human settlement patterns. Because Palenque was a large urban center with many permanent structures, population mobility was relatively limited. The cost to move and establish a similar settlement elsewhere would have been high. On Santa Rosa Island, the populations of hunter-gatherer-fishers would have been more mobile, especially prior to the MLT (King, 1990; Arnold, 1992a, 2001a; Arnold & Graesch, 2004; Kennett, 2005; Jazwa & Perry, 2013). During periods of drought, the cost to move from a severely affected watershed to one that was more resilient would have been relatively low.

In this study, we use PIHM to simulate plausible scenarios of the surface and subsurface flow regimes of the island hydrology based on estimated parameters from national soil and surface geologic data sets (see Leonard & Duffy, 2013). Site-specific streamflow and groundwater data are limited on the island, preventing their use for calibration. We therefore validated the model by adjusting *a priori* hydraulic properties to simulate ephemeral and perennial stream reaches for each of the hypothetical weather regimes. This strategy works reasonably well where relative change is desired but would not be suitable where detailed water balances are necessary. Previous studies have verified the numerical representation, code, and output of the PIHM simulations by comparing them to field observations and results generated by community distributed models (see Qu & Duffy, 2007; Kumar, 2009; Kumar, Bhatt, & Duffy, 2009). The modeling system has been successfully applied to watershed studies in the United States, Mexico, Guatemala, Greece, Wales, Switzerland, and the Czech Republic as part of the NSF-Critical Zone Observatory Network and the European Commission-SoilTrEC project (http://criticalzone.org/national/, http://www.soiltrec.eu). Examples of test cases can be found on the PIHM website.

FRESH WATER AND HUMAN SETTLEMENT ON SANTA ROSA ISLAND

We expect fresh water availability to be one of the primary determinants in the distribution of human settlements in semiarid environments like the NCI (see Kennett et al., 2009; Winterhalder et al., 2010; Jazwa, Kennett, & Winterhalder, 2013; Jazwa, 2015). Therefore, both the difference in fresh water flow between drainages and for individual drainages during periods with different environmental conditions should influence settlement patterns and population movement on Santa Rosa Island. It is important to note that in this study, we do not generate values for water flow or depth for specific periods in the past, as French, Duffy, and Bhatt (2012) did for Palenque. Instead, we model hypothetical wet, dry, and median regimes that can be used to test the sensitivity of the different drainages on the island to variations in precipitation. These are then associated with different climatic intervals for California to try to understand changes in settlement patterns. Therefore, the goal is to develop scenarios of relative changes in the water flow regimes within different drainages in response to climatic inputs. The intention is to understand the relative responses of different drainages to different environmental conditions. Note that PIHM simulates the entire island and thus flows between basins are also admitted.

There are four primary predictions for the application of the results of the PIHM simulation to settlement patterns on Santa Rosa Island. First, because fresh water availability is the most important variable in ecological models of human settlement patterns (see Winterhalder et al., 2010), settlement should be more intensive in drainages with higher water flow. The other predictions stem from this primary projection. Second, settlement during the middle Holocene between 6500 and 3800 cal. yr B.P. should favor drainages that are resilient to dry conditions. The period of earliest permanent settlement, beginning around 8000 cal. yr B.P. (Winterhalder et al., 2010), may be less influenced by drainage resilience, but the dry conditions of most of the middle Holocene should favor those habitats that maintain highest water flow during our hypothetical dry century. Third, the wetter conditions at the beginning of the late Holocene should be associated with an expansion to previously uninhabited drainages, particularly those that may not have been occupied previously because they responded poorly to dry conditions. Fourth, the droughts that occurred during the MCA could lead to a contraction in settlement distribution, again favoring those watersheds that are most resilient to dry environmental conditions.

METHODS

Weather Modeling

We first generated data for daily weather using the WXGN version 3020 weather generator (after Richardson, 1981; Richardson & Wright, 1984; available online at http://epicapex.tamu.edu/model-executables/wxgn-v-3020/). This allowed us to extend 25 years of data collected from a weather station on Santa Rosa Island to daily values of a greater number of variables over longer periods of time and to eliminate gaps in the data.

Hourly instrument data from a weather station at Becher's Bay in northeastern Santa Rosa Island (Figure 1) have been collected by Channel Islands National Park since April 1990. These data are available online from the Western Regional Climate Center of the Desert Research Institute (http://www.wrcc.dri.edu). We incorporated daily or hourly data from April 23, 1990 through September 24, 2014. This span of time includes extended drought periods (1987–1992, 1995–1996, 2012–2014) and wet periods (early 2000s), along with periods of intermediate or average rainfall conditions. It is important to note that using 25 years of data to simulate past weather conditions cannot produce the full range of variability in the past, in part because of shifts in the climate. However, by incorporating observed data, we can model a statistically realistic long-term weather record, even if it does not precisely match weather during any specific time range in the past. WXGN uses observed monthly average data for temperature, precipitation, solar radiation, humidity, and wind speed, along with the standard deviation and skew coefficient for precipitation, and constructs the daily series from a stochastic model. WXGN also requires the number of rain days per month and the probability of a wet day after a wet or dry day (Table I). This system generates long-term daily values for solar radiation, maximum and minimum temperature, rainfall, relative humidity, and wind velocity.

PIHM Methodology

We generated a hypothetical 2500 years of weather using WXGN and selected the 100-year spans of data that represented the wettest, driest, and median centuries by average daily rainfall. We chose 100 years to incorporate multiple wet periods and dry periods. In our simulations, PIHM used data for daily rainfall, average temperature, relative humidity, wind velocity, and solar radiation (short and long wave). We modified the precipitation input to include 178 mm of fog water per year, the highest value estimated by Fischer, Still, and Williams (2009) for Santa Cruz Island. Santa Rosa Island is positioned farther to the west in the channel and therefore receives more fog cover than Santa Cruz Island (Junak et al., 1995). We scaled the contribution of fog water to the system by monthly average overnight relative humidity (Table I).

PIHM uses a Digital Elevation Model to generate a TIN that also represents the basin boundary and all perennial and ephemeral stream channels of the island. We assigned segments with at least 1000 pixels flowing into them to be part of the stream channels (Figure 3). For each element, a complete water budget was calculated and the storages (surface pond depth, soil moisture, groundwater level, stream depth) and fluxes (evapotranspiration, ground evaporation, canopy interception, infiltration, groundwater recharge, and runoff) were simulated. The model generates water flow and

Table I Climate data input into the weather generator, along with fog water estimates.

Measurement	January	February	March	April	May	June	July	August	September	October	November	December
Average Monthly Maximum Air Temperature (°C)	24.5	23.5	23.7	26.5	27.2	26.2	27.2	29.3	32.0	30.7	27.6	23.9
Average Monthly Minimum Air Temperature (°C)	4.3	4.3	4.2	4.6	6.0	7.2	8.8	9.5	9.6	8.5	6.2	4.1
Monthly Average Standard Deviation of Daily Maximum Temperature (°C)	4.6	4.4	4.6	4.8	4.5	4.2	4.2	4.4	5.1	5.4	5.0	4.2
Monthly Average Standard Deviation of Daily Minimum Temperature (°C)	2.8	2.5	2.3	2.2	1.9	1.8	1.9	2.0	2.9	3.0	3.0	2.4
Average Monthly Precipitation (mm)	56.9	69.1	44.0	16.4	16.4	1.8	0.9	1.0	2.2	7.5	18.2	40.7
Monthly Standard Deviation of Daily Precipitation (mm)	4.4	5.8	4.8	1.6	0.7	0.2	0.1	0.1	0.3	1.1	2.0	3.8
Monthly Skew Coefficient for Daily Precipitation	3.3	3.6	3.7	3.9	3.5	2.9	2.7	2.5	3.3	4.1	3.8	3.5
Monthly Probability of Wet Day After Dry Day	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2
Monthly Probability of Wet Day After Wet Day	0.5	0.6	0.5	0.4	0.4	0.4	0.3	0.4	0.3	0.5	0.4	0.5
Average Number Days of Rain Per Month	7.6	8.2	7.7	5.8	3.8	3.2	2.6	3.0	2.6	4.3	4.5	7.2
Monthly Maximum Half Hour Rainfall (mm)	12.7	7.5	43.2	5.7	5.2	1.4	0.5	11.4	3.7	6.1	8.9	8.4
Average Monthly Solar Radiation (MJ/m^2)	11.7	14.1	19.3	23.4	26.1	26.2	26.3	25.2	21.9	16.5	12.6	10.3
Monthly Average Relative Humidity (Fraction)	0.7	0.8	0.8	0.8	0.8	0.8	0.9	0.8	0.8	0.7	0.7	0.7
Average Monthly Wind Speed (m/s)	5.9	6.5	6.8	7.9	7.8	7.0	6.0	5.9	5.6	5.5	5.8	5.9
Daily Fog Water Deposition (mm)	0.4	0.0	0.5	0.5	0.5	0.5	0.6	0.5	0.5	0.4	0.4	0.4

level data for each branch of the stream from the uplands to the mouths of each channel. We are interested in the drainage mouths because they are the locations of most of the large, permanent settlement sites on the NCI (Kennett, 2005; Kennett et al., 2009). The model was run once for each of the dry, median, and wet centuries.

RESULTS

A clear result from PIHM was that each drainage has a unique pattern of stream water availability (flow volume and level; Table II; Figure 4; Supplementary Tables SI–SIV). Several pairs of drainages had mouths that were adjacent to each other (~1 km from one another). Anyone living at the mouth of one of these drainages would have had easy access to surface water from the other drainage as well.

In general, drainage basin surface water yield is greatest in the northwestern canyons (Table II; Figure 4). This result is supported by qualitative observations of stream flow by Kennett during the 1990s and Jazwa during summer and fall of 2012–2015. As a whole, drainages in this part of the island have greater surface water flow during longer periods of the year than in other parts of the island. The two drainages with the greatest flow in all model conditions are Tecolote and Arlington, making the region at the mouth of these drainages attractive for human populations. This fits the archaeological record. Permanent settlement at the mouth of these canyons is among the earliest on the island and it persists until historic contact (Kennett, 2005; Kennett et al., 2009; Winterhalder et al., 2010). With the exception of Trancion Canyon, surface water flow is lowest in the west. This also fits the archaeological record as permanent settlement appears on the western part of the island later than the other geographic regions (Kennett et al., 2009; Winterhalder et al., 2010).

This pattern was accentuated when adjacent drainages were combined. The Tecolote-Arlington and Soledad-Dry complexes are the two areas with the greatest water flow and are along the northwest coast of the island. They both had average surface water flow (discharge) of over 500 m^3/day during a median century. Water-Cherry and Old Ranch complexes on the eastern end of the island had high flow rates, with the former over 400 m^3/day and the latter over 300 m^3/day during a median century. Bee and Whetstone Canyons had some of the lowest flow rates, both under 200 m^3/day under median conditions (Figure 4). We note again that these stream discharge numbers are modeled estimates and can only be used in a comparative sense.

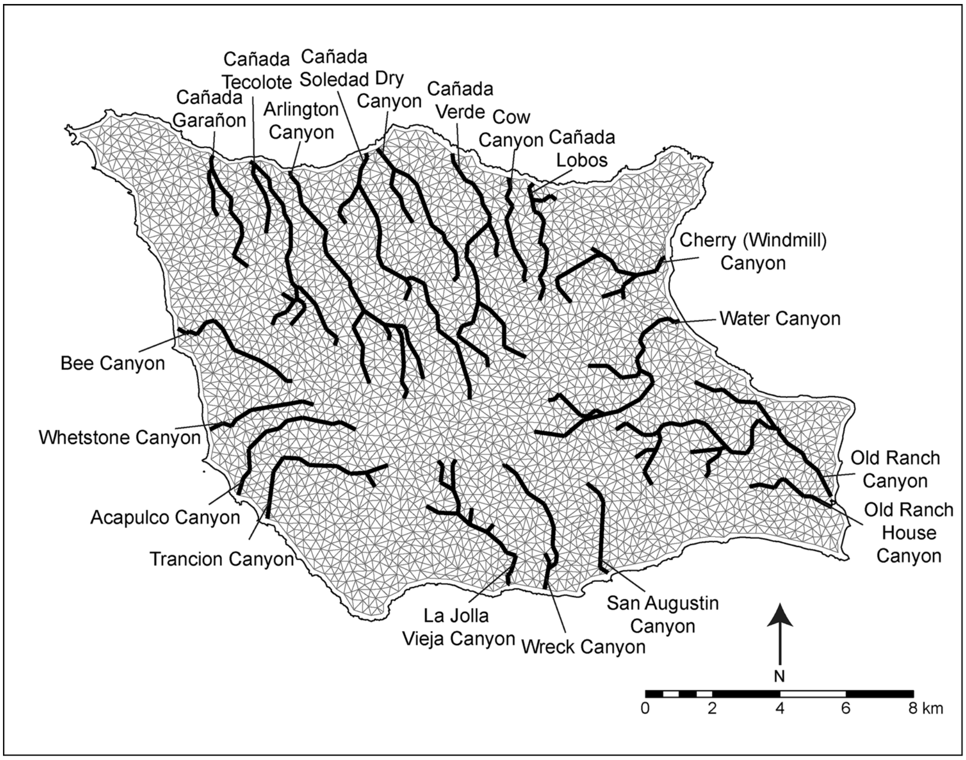

Figure 3 Tiles used to represent Santa Rosa Island in PIHM, along with the stream networks, labeled by drainage name.

Table II Overall PIHM daily average data output for outflow during all three modeled centuries.

		Outflow (m^3/day)		
Drainage	Location	Wet Century	Median Century	Dry Century
Tecolote	Northwest	405	338	329
Arlington	Northwest	352	304	296
Soledad	Northwest	327	285	275
Dry	Northwest	260	228	220
Garañon	Northwest	233	200	193
Cow	North	275	250	236
Verde	North	272	242	233
Lobos	North	132	113	109
Water	East	318	277	267
Old Ranch	East	231	194	189
Old Ranch House	East	186	160	154
Cherry	East	164	133	129
San Augustin	South	241	215	207
La Jolla Vieja	South	189	168	160
Wreck	South	178	156	147
Trancion	West	345	303	292
Whetstone	West	211	185	178
Bee	West	192	160	156
Acapulco	West	189	158	154

The output from PIHM supports the expectation that periods of greater precipitation result in greater water flow for all drainages. An important component of this model is how the unique physiographic attributes of each drainage can cause different relative responses to periods of more and less precipitation. We calculated the difference in surface water flow in each drainage between median centuries and both wet and dry centuries, presented as a percent of median century water flow (Table III; Figure 5). Cherry Canyon, on the east coast, makes the greatest gain in water flow during a wet century, at 23.3% of median century flow. The smallest gain during the wet century is Cow Canyon, which gains only 10.0% of median century flow. Similar to overall flow values, the areas that gain the greatest proportion of water flow during wet periods are along the northwest and east coasts of the island. On the west coast of the island, Bee and Acapulco Canyons both respond favorably to wet conditions, despite their relatively low water flow. The canyons on the south coast respond the least positively to wetter conditions. Much of the water flow in that part of the island is likely lost to evaporation.

Perhaps more important for understanding human settlement patterns on the NCI is how drainages respond to

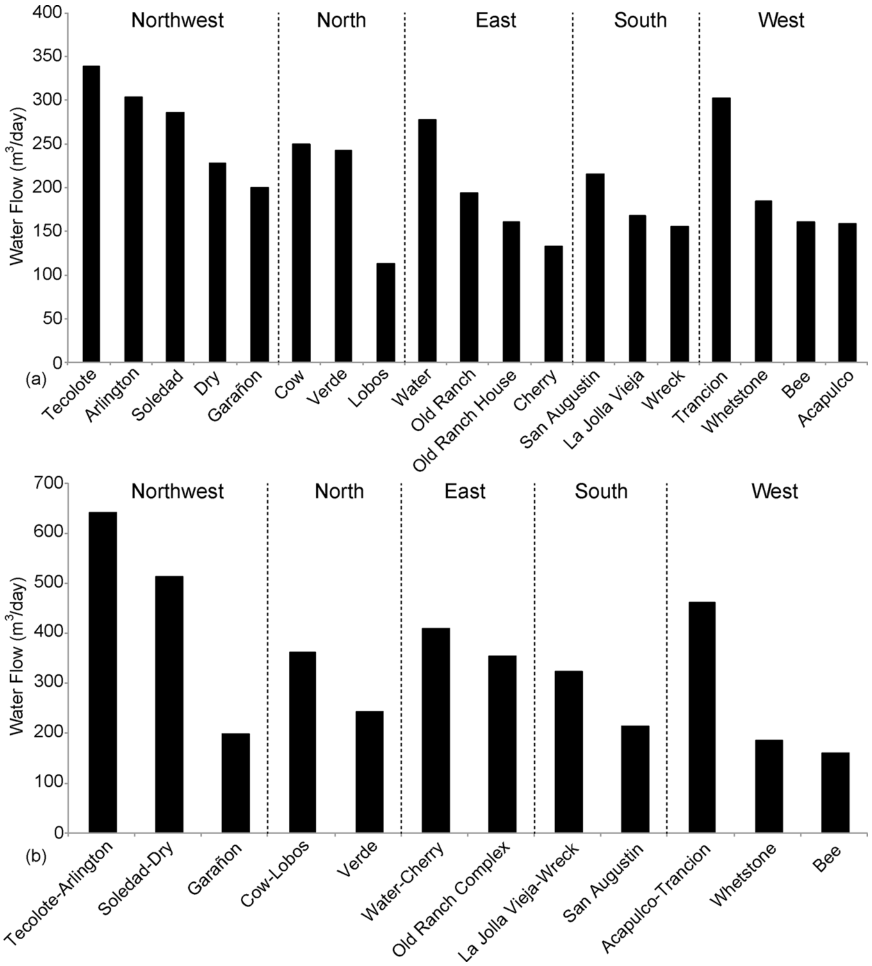

Figure 4 Average daily water flow over a median rainfall century. (a) Individual drainages. (b) Adjacent drainages that would have been easily accessible from each other are combined.

drought conditions. Overall, the difference in surface water flow between the median and wet centuries is much greater than the difference between the median and dry centuries. This suggests that the drainages on Santa Rosa Island are less negatively affected by dry conditions than they are positively affected by wet conditions, at least in the context of this model. The canyons with water flow that decrease the most are Wreck Canyon at 5.7% and Cow Canyon at 5.5%. The canyons that are least affected by the dry conditions are Old Ranch Canyon at 2.1% and Arlington Canyon at 2.6% (Figure 5). Canyons on the northwest and east coasts are the most resilient to drought by this measure, although the drainages on the west coast are also relatively resilient, despite the fact that they are dry overall. The least resilient drainages by percent of water flow lost during a dry century are on the south and north coasts.

Instead of just looking at average water flow, which can be affected by a few extreme years, another approach is to look at the number of years of low water flow during each weather regime (Table IV). We arbitrarily selected half of the median century average flow as the cut off for a dry year. The response of each drainage to drought conditions is calculated in two ways. First, we look at the number of years that each drainage had an average daily flow less than half of the median century average for that drainage (Figure 6). This is a measure of resilience. By this metric, Arlington and Dry Canyons are the least impacted by drought conditions, gaining only two dry years between the median and dry centuries. The most resilient drainages are again along the northwest and east coasts of the island. Drainages along the north, west, and south coasts are the least resilient, with all drainages adding four or five dry years during the dry century. The southern

Table III Drainage ranks by size, average water flow and level for a median century, and resilience derived from average water flow.

	Location	Drainage Area (km^2)	Size Rank	Water Flow (m^3/day)	Flow Rank	Avg Water Depth (mm)	Depth Rank	Resilience (% Med Century Flow)	Resilience Rank	Overall Rank
Tecolote	Northwest	12.1	4	338	1	6.1	3	2.8	4	1
Old Ranch	East	18.6	1	194	11	6.3	2	2.1	1	2
Water	East	12.3	2	277	5	7.6	1	3.6	12	3
Arlington	Northwest	11.9	5	304	2	2.3	13	2.6	2	4
Soledad	Northwest	12.3	2	285	4	3.2	8	3.7	13	5
Trancion	West	7.4	10	303	3	6.0	4	3.6	10	6
Garañon	Northwest	6.8	12	200	10	3.7	7	3.4	7	7
Cherry	East	8.8	8	133	18	4.1	6	3.1	6	8
Dry	Northwest	6.8	11	228	8	2.7	11	3.6	9	9
Verde	North	11.8	6	242	7	2.2	14	3.9	15	10
Bee	West	3.8	16	160	15	3.0	9	2.7	3	11
Acapulco	West	4.8	13	158	16	2.8	10	3.0	5	12
San Augustin	South	3.6	17	215	9	2.6	12	3.6	11	13
Old Ranch House	East	4.2	15	160	14	5.2	5	4.0	16	14
Whetstone	West	2.8	18	185	12	2.1	15	3.5	8	15
La Jolla Vieja	South	9.3	7	168	13	2.0	17	4.5	17	16
Cow	North	2.7	19	250	6	2.1	16	5.5	18	17
Wreck	South	7.4	9	156	17	1.8	18	5.7	19	18
Lobos	North	4.7	14	113	19	1.6	19	3.8	14	19

canyons also tend to lose the lowest number of dry years during wet centuries.

We also compare the number of dry years for all drainages under each condition to the average median century, again using half of the median flow as the cutoff (Figure 7). This provides a comparison of which drainages have the greatest number of dry years during each century. Overall, the northwest coast and the north coast except for Cañada Lobos have the fewest dry years overall. This is an important factor in the establishment of permanent settlements. As people become less mobile, they are likely to gravitate toward and perhaps control locations with the lowest risk of experiencing drought conditions. Another way to view surface

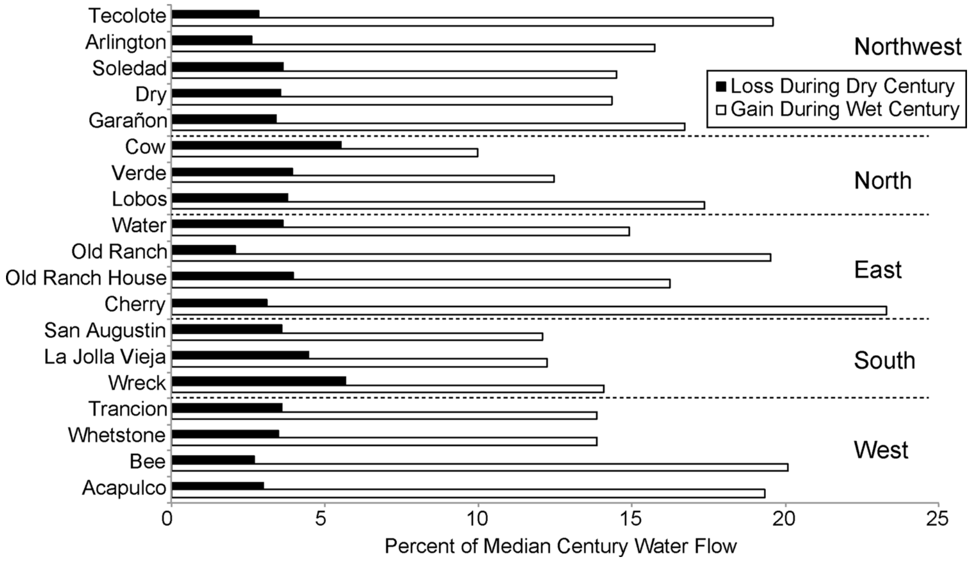

Figure 5 Change in water flow by percent of median century water flow for all drainages.

Table IV Number of dry years for each drainage during each modeled century.

	Dry Years vs. Median Century Average for Drainage			Dry Years vs. Overall Median Century Average		
	Wet Century	Median Century	Dry Century	Wet Century	Median Century	Dry Century
Garañon	47	51	55	47	53	56
Tecolote	47	52	55	43	48	48
Arlington	47	53	55	43	48	52
Soledad	46	51	55	43	48	52
Dry	47	53	55	46	51	55
Verde	46	51	55	44	50	53
Cow	43	48	52	42	48	49
Lobos	46	50	55	60	62	67
Water	47	51	55	44	48	53
OR House	47	52	55	51	56	61
Old Ranch	49	53	57	49	55	58
Cherry	47	52	55	58	62	64
La Jolla Vieja	47	50	55	49	55	59
Wreck	46	51	55	50	56	61
San Augustin	46	50	55	46	50	55
Bee	48	53	58	56	58	62
Whetstone	46	50	55	47	52	56
Acapulco	48	53	58	56	59	63
Trancion	46	51	55	43	48	49

Dry years are estimated in comparison to median century average for the individual drainage and for all drainages

water flow and drainage resilience together is through the use of Flow Duration Curves (Figure 8). This provides a way to qualitatively see the difference in the distribution of daily flow rates between wet, median, and dry centuries.

DISCUSSION

This study expands on the hydroarchaeological method developed by French, Duffy, and Bhatt (2012) to understand the relationship between human settlement

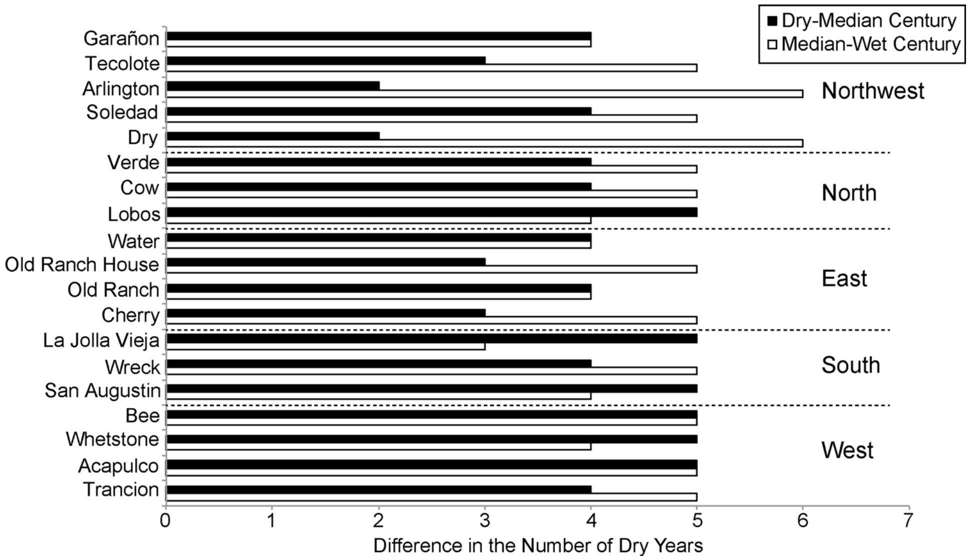

Figure 6 Change in number of dry years from a median century. A dry year is defined as daily average flow less than half of the flow of *that drainage* during a median century.

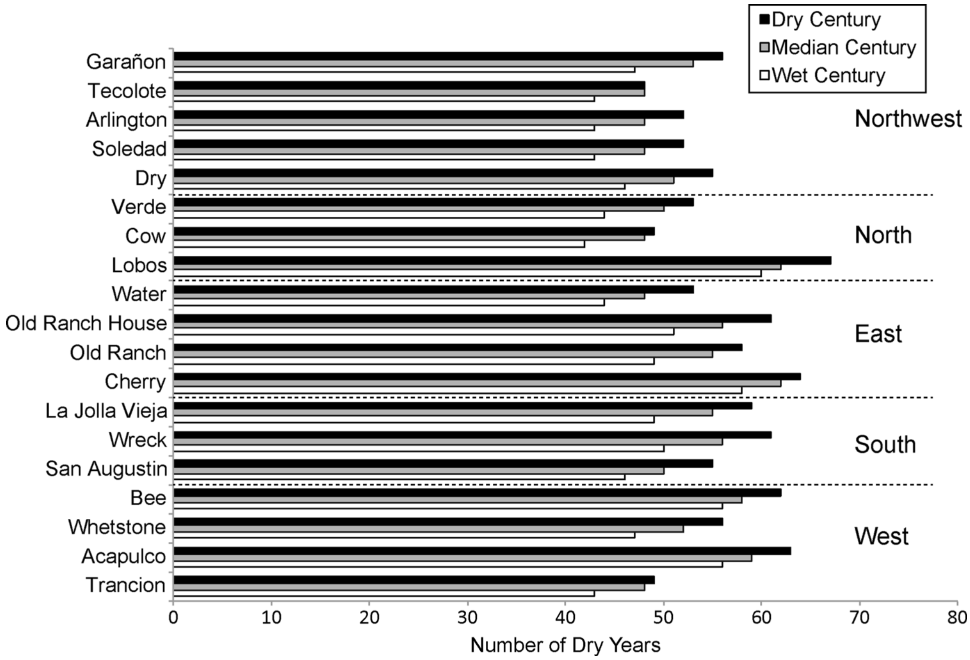

Figure 7 Number of dry years per century by climate. A dry year is daily average flow less than half of the flow of *all drainages* during a median century.

patterns and fresh water abundance and scarcity. Using this method, we model the abundance/scarcity, persistence, and resilience of surface water flow at different locations on Santa Rosa Island. Overall, we find that canyons along the northwest and east coasts of the island provide the best opportunities for settlement with respect to water availability. The canyons along the south coast generally have the poorest hydrological conditions for persistent human settlement. The drainages along the north and west coasts have intermediate conditions.

The quantity of fresh water and resilience of these drainages is important for our understanding of the early establishment of permanent settlements, population expansion, and the establishment of historically documented coastal villages. Kennett et al. (2009; also Winterhalder et al., 2010; Jazwa, Kennett, & Winterhalder, 2013) found that drainage size, which can be used as a proxy for water availability, is the most important environmental variable for modeling settlement establishment and persistence. There is evidence of early permanent settlement dating to the beginning of the middle Holocene distributed around the island (Table V; see Jazwa, 2015 for more details). This is likely a combination of the fact that small populations needed limited resources and that climate was still in an intermediate stage between the previous wet interval and the middle Holocene dry interval (e.g., Antevs, 1948, 1952, 1955; LaMarche, 1973, 1974; Lindström, 1990; Morgan, Cummings, & Rudolph, 1991; Thompson, 1992; Cole & Liu, 1994; Quade et al., 1998; Hughes & Graumlich, 2000; Benson et al., 2002; Erlandson, Rick, & Peterson, 2005; Kennett, 2005; Kennett et al., 2007). Intensive settlement during the drier middle Holocene occurred along the northwest coast of the island, with the establishment of sites at the mouth of Tecolote and Arlington (CA-SRI-3 and -5) and Soledad and Dry Canyons (CA-SRI-19 and -821; Kennett et al., 2009; Winterhalder et al., 2010; Jazwa et al., 2015; Jazwa, 2015). These pairs of drainages have the greatest water flow in all conditions (Figures 4, 7). These are also among the most resilient drainages on the island so they would not have been affected as negatively by dry conditions.

The drainage rankings established by this model help to explain some of the patterns in initial settlement that did not fit rankings based on drainage size alone (Table V; Kennett et al., 2009; Winterhalder et al., 2010; Jazwa, 2015). We created an overall drainage rank, which is a ranked sum of the median century water flow, median century water level (a proxy for drainage wetness), resilience, and drainage size rank for each of the drainages (Table III). Both our overall ranking and size ranking suggest that Water Canyon should have been settled relatively early, but the first evidence of occupation of that drainage is 1300-1070 cal. yr B.P. This drainage is 12th in resilience, which may have been a more important variable during the dry middle Holocene. Our study

Table V Comparison of drainage ranking from this analysis with size ranking and radiocarbon dates for initial settlement of each drainage.

	Overall Rank	Size Rank	Resilience Rank	Conventional ^{14}C Age (B.P.)	ΔR	2σ ca. yr B.P.	Material	Site	Reference
Tecolote	1	4	4	7480 ± 90	261 ± 21	7890-7520	*Haliotis rufescens*	CA-SRI-3	Winterhalder et al. (2010)
Old Ranch	2	1	1	7750 ± 40	261 ± 21	8050-7840[a]	Marine Shell	CA-SRI-187	Kennett (1998); Jazwa, Kennett, & Winterhalder (2013)
Water	3	2	12	1800 ± 30	153 ± 44	1300-1070	Marine Shell	CA-SRI-77	Winterhalder et al. (2010)
Arlington	4	5	2	6980 ± 120	261 ± 21	7470-6960	*Haliotis* spp.	CA-SRI-4	Winterhalder et al. (2010)
Soledad	5	2	13	5220 ± 20	261 ± 21	5425-5240	*Mytilus californianus*	CA-SRI-19	Jazwa et al. (2015)
Trancion	6	10	10	—	—	—	—	—	—
Garañon	7	12	7	2250 ± 90	88 ± 44	1990-1520	*Mytilus californianus*	CA-SRI-2	Kennett (1998)
Cherry	8	8	6	—	—	1500-1100	Artifact	CA-SRI-60	Winterhalder et al. (2010)
Dry	9	11	9	5755 ± 20	261 ± 21	5945-5760	*Haliotis cracherodii*	CA-SRI-821	Jazwa et al. (2015)
Verde	10	6	15	4260 ± 90[b]	—	5210-4530	Charcoal	CA-SRI-41	Winterhalder et al. (2010)
Bee	11	16	3	3470 ± 80	261 ± 21	3240-2790	*Haliotis rufescens*	CA-SRI-31	Kennett (1998)
Acapulco	12	13	5	2090 ± 60	92 ± 44	1770-1390	*Mytilus californianus*	CA-SRI-28	Winterhalder et al. (2010)
San Augustin	13	17	11	2280 ± 80	92 ± 44	2010-1560	Marine Shell	CA-SRI-432	Winterhalder et al. (2010)
Old Ranch House	14	15	16	7750 ± 40	261 ± 21	8050-7840[a]	Marine Shell	CA-SRI-187	Kennett (1998); Jazwa, Kennett, & Winterhalder (2013)
Whetstone	15	18	8	2410 ± 50	109 ± 44	2100-1750	*Haliotis rufescens*	CA-SRI-96	Kennett (1998)
La Jolla Vieja	16	7	17	7235 ± 20	261 ± 21	7545-7415	*Mytilus californianus*	CA-SRI-138	Jazwa (2015)
Cow	17	19	18	4320 ± 20	261 ± 21	4205-3975	*Mytilus californianus*	CA-SRI-115	Jazwa (2015)
Wreck	18	9	19	—	—	—	—	—	—
Lobos	19	14	14	6060 ± 70	261 ± 21	6380-6020	*Haliotis rufescens*	CA-SRI-116	Kennett (1998)

All dates were calibrated in OxCal 4.1 (Bronk Ramsey, 2009) using the most recent marine calibration curves, Marine13 (Reimer et al., 2013), and IntCal13 (Reimer et al., 2013; where noted). We used a variable ΔR value for the Santa Barbara Channel region for samples with dates of less than 2600 ^{14}C yr B.P. Variable ΔR values were calculated by Brendan Culleton (personal communication, 2015) using AMS radiocarbon dates from paired organic and planktonic marine foraminiferal carbonate in laminated varves published by Hendy et al. (2013) from a sediment core from Santa Barbara Basin. For older samples, we used an updated ΔR value for the Santa Barbara Channel region (261± 21 ^{14}C yr; Brendan Culleton, personal communication, 2012; Jazwa, Kennett, & Hanson, 2012).

[a] Old Ranch and Old Ranch House Canyons have adjacent mouths near CA-SRI-187. There is a gap in occupation at CA-SRI-187 from 6470-6315 to 3325-3145 cal. yr B.P. (Jazwa, Winterhalder, & Kennett, 2013).

[b] Calibrated with IntCal13.

improves on the rankings of Dry, Soledad, Tecolote, San Augustin, Verde, Cow, Whetstone, and Bee Canyons, but provides worse rankings for Jolla Vieja, Lobos, and Garañon Canyons. Other variables are also important and any estimate of drainage ranking must take them into account (e.g., shoreline type, toolstone availability, kelp forest abundance) to fully understand settlement chronology (Kennett et al., 2009; Winterhalder et al., 2010; Jazwa, Kennett, & Winterhalder, 2013; Jazwa, 2015).

The very end of the middle Holocene is associated with increasingly wet conditions in California (Antevs, 1955; Lindström, 1990; Davis, 1992; Thompson, 1992; Quade et al., 1998; Benson et al., 2002; Kennett, 2005; Kennett et al., 2007). The transition from the middle to late Holocene is associated with population expansion and subsistence shifts (see Rick et al., 2005; Jazwa & Perry, 2013). There is an increase in the number of settlement sites across the NCI during this period. Permanent settlements were established in multiple drainages with lower

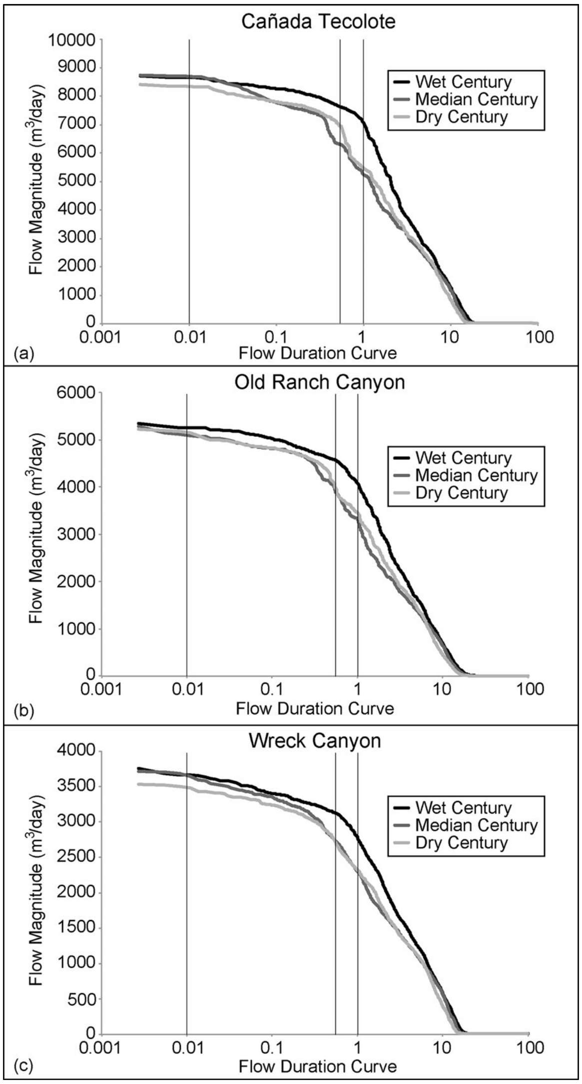

Figure 8 Flow duration curves for three representative drainages during wet, median, and dry centuries. (a) Cañada Tecolote, a drainage with high flow that gains a large percent of flow during a wet century and loses a small percent of flow during a dry century. (b) Old Ranch Canyon, a drainage with medium flow that gains a large percent of flow during a wet century and loses a small percent of flow during a dry century. (c) Wreck Canyon, a drainage with low flow that gains a small percent of flow during a wet century and loses a large percent of flow during a dry century.

predicted suitability after 3000 cal. yr B.P. (Winterhalder et al., 2010). An example of this is the initial settlement of CA-SRI-31 at the mouth of Bee Canyon, the first evidence of permanent settlement along the western coast of the island. Although Bee Canyon is relatively dry compared to many of the other drainages, it is one of the only two drainages with water flow that increases more than 20% during a median-to-wet century (Figure 5). Additionally, Bee Canyon has five fewer dry years during a wet century than the median century and ten fewer than the dry century (Figure 6). The increasingly wet conditions would have increased the relative suitability of Bee Canyon and attracted people to settle there.

An important application of our hydrological model is the response of island populations to the dry conditions during the MCA drought intervals. At the time of historic contact, there were at least eight coastal village locations on Santa Rosa Island (Johnson, 1982, 1993, 2001; Kennett, 2005; Glassow et al., 2010; Table VI; Figure 1). These large village sites appeared after the contraction in settlement during the MLT. We compared water flow and resilience rank for the drainages associated with each of the historic village locations. Four of the villages, Hichimin, Qshiwqshiw, Silimihi, and Nawani, have well-established locations adjacent to the mouth of at least one drainage. We also know that there was a historic village between Garañon and Tecolote Canyons, although it is unclear whether it is Nimkilkil or Niaqla (Glassow et al., 2010). Nimikilkil/Niaqla and Qshiwqshiw are adjacent to the Tecolote/Arlington and Old Ranch complexes, the two areas that are the wettest and most hydrologically resilient to dry conditions (ranked first and second). If the site of CA-SRI-2 at the mouth of Tecolote/Garañon Canyon is the location of Nimkilkil, it is likely that Niaqla, a smaller village by total baptisms in mission records from the 1820s, was at the mouth of Arlington Canyon (Glassow et al., 2010). Nawani is located at the mouth of Trancion and Acapulco Canyons, the former of which has the third highest water flow and sixth rank overall. Hichimin is at the mouth of Cherry Canyon, which has relatively low water flow, but overall high resilience (eighth rank). Silimihi is at the mouth of Cañada Verde, which has relatively high water flow and is ranked tenth overall. Nilal'uy and He'lewashkuy are both located along the south coast, associated with lower ranked drainages. The closest drainage to the former is Jolla Vieja Canyon, which is ranked 16th overall, although it is approximately 2 km away. Although the exact location of the latter is unknown, it is likely closer to San Augustin Canyon, ranked 13th overall.

The placement of historic villages along the south coast of the island suggests that factors beyond fresh water availability were important for the locations of historically documented villages. The importance of plank canoes during this period (see Arnold, 1992a, 1995, 2001a; Gamble, 2002; Fagan, 2004) emphasized the benefits of good harbors with sandy beaches where canoes could be pushed off or pulled out of the water. Additionally, highly productive rocky intertidal regions and nearby kelp forests provide marine food resources for people across the island. Access to canoes provided

Table VI Historic villages on Santa Rosa Island with ranks for adjacent drainages.

Village	Sites	Largest Adjacent Drainage	Water Flow Rank	Resilience Rank	Overall Rank
Qshiwqshiw	CA-SRI-84, -85, -87, -88, 187	Old Ranch Canyon	11	1	2
Hichimin	CA-SRI-60	Cherry Canyon	18	6	8
Silimihi	CA-SRI-40	Cañada Verde	7	15	10
Niaqla	CA-SRI-5, -6?	Arlington Canyon?	2	2	4
Nimkilkil	CA-SRI-2?	Cañada Tecolote?	1	4	1
Nawani	CA-SRI-97	Grouse Canyon	3	8	6
Nilal'uy	CA-SRI-62	La Jolla Vieja Canyon	13	17	16
He'lewashkuy	CA-SRI-436?	San Augustine Canyon?	9	11	13

abundant opportunities for trade of many resources, including fresh water. There is ethnographic and archaeological evidence that people transported water in baskets sealed with asphaltum (Hudson & Blackburn, 1983). Because of the potential for rapid transportation over water, villages and chiefs could spread out across the landscape. This would also maximize the territory of each village to prevent conflict from competition over resources. This is likely the reason that a wet area like the mouth of the Soledad/Dry Complex, which is very close to the mouth of Tecolote/Arlington, was not the location of a historic village. An area like the south coast of Santa Rosa Island, while drier than other parts of the island, is generally warmer, with less fog and wind, and calmer seas, and therefore was the location of two village sites (Engle, 1994; Johnson, 2001; Kennett, 2005).

The relationship between drought conditions and settlement patterns is also evident on the southern Channel Islands, particularly during the MCA (Yatsko & Raab, 2009). The southern islands tend to be even drier than the northern ones, with San Clemente Island, for example, averaging fewer than 25 cm of rainfall per year (Yatsko & Raab, 2009). On San Clemente, there appear to be important changes in settlement during the MCA, starting with an apparent decrease in island population at this time. This likely led to settlement realignments across the southern Channel Islands (Yatsko & Raab, 2009). The subsequent pattern of residential settlement was positioned to take advantage of the availability of surface water. It is not surprising that drought periods would have influenced all of the Channel Islands and mainland southern California. Expanding PIHM to model fresh water flow on the other islands could help to better understand these changes.

This iteration of PIHM does not take into account all factors that influence hydrodynamics on Santa Rosa Island. Models are simplifications of reality that help us understand the world (Winterhalder, 2002). This is the first attempt to create a hydrological model for Santa Rosa Island and is necessarily simplified. This study provides a starting point for our understanding of the hydrology of the NCI, and can be expanded upon in numerous ways. First, future runs of PIHM will take more variables into account. We initially tried to model this system while incorporating only rainfall as a water source, which is highly seasonal. It became clear that fog water input was necessary to generate realistic model outputs. Without fog, the drainages returned zero flow during drought periods. The fog water contribution is strongest during the summer months on the islands when rainfall is lowest (Table I; Fischer & Still, 2007; Williams et al., 2008; Fischer, Still, & Williams, 2009). Future iterations of this model will include a more nuanced look at fog between different climatic regimes. Additionally, the output of the weather generator did not replicate drought periods as severe as those that occurred during the MCA. The overall difference in rainfall between the wettest and driest hypothetical centuries that we modeled is 10.6% of the rainfall during the wettest century. Because drought conditions during the MCA were more severe (e.g., Stine, 1994; Cook, Seager, & Miller, 2011), the importance of drainage resilience would have been magnified. Stine (1994) references 6–7 year drought periods between 1928 and 1934 and between 1987 and 1992 in which runoff in the Sierras was ~70% of normal. Severe droughts were rarely, if ever, a full century long (see Benson et al., 2007; cf., Stine, 1994). A future model run focused on shorter drought periods could more accurately predict surface water flow during periods of extreme drought. It is also important to model the effects of seawater intrusion to coastal fresh water sources during periods of drought. During especially dry periods, it may have been necessary for island inhabitants to look inland for potable fresh water. Finally, PIHM could be run using paleoclimatic data for particular periods in the past, including the MCA. However, many of the weather variables for past periods would still need to be stochastically modeled because paleoclimate data is often only available for temperature and precipitation.

CONCLUSION

In this study, we use a distributed hydrological model (PIHM) to understand the establishment, persistence, and contraction of settlement on Santa Rosa Island, California. Because Southern California has a semiarid climate, access to fresh water was an important consideration for prehistoric populations. Previous environmental models (Kennett et al., 2009; Winterhalder et al., 2010; Jazwa, Kennett, & Winterhalder, 2013; Jazwa, 2015) have suggested that fresh water availability was one of the most important factors influencing where permanent settlements were established on the NCI. This study supports this observation. The northwest coast of the island, which has the highest amount of surface water flow in all conditions and is among the most resilient to drought conditions, was a major hub of settlement throughout prehistoric occupation of the island. Additionally, it appears that one of the important factors influencing where populations chose to congregate during and immediately following the MCA is the response of those drainages to drought conditions.

The availability of fresh water is an essential consideration for survival and therefore is an important variable driving settlement patterns for all human populations. Our study expands on and generalizes the hydroarchaeological method that was developed by French, Duffy, and Bhatt (2012) to better understand the relationship between rainfall and fresh water availability in archaeological contexts. We have also enlarged the application of this method to include maritime hunter-gatherers who were more mobile than Maya populations at Palenque. The use of hydrological models like PIHM can have broad implications for studying the human past both because they can provide a more nuanced perspective of fresh water availability during different climate regimes and because they are scalable to model small test cases like the NCI and much larger regions. These models can provide important information about variables influencing the movement of populations across the landscape and provide us with a better understanding of human decision-making in the past.

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