THE HYDROARCHAEOLOGICAL METHOD: A CASE STUDY AT THE MAYA SITE OF PALENQUE

Kirk D. French, Christopher J. Duffy, and Gopal Bhatt

This research consists mainly of introducing the hydroarchaeological method, especially as related to issues of drought. The article outlines how this multidisciplinary method can provide insights into the success and failures of an archaeological site, in this case the Maya site of Palenque. We also detail convincing evidence that shows that the Maya of Palenque did not leave their city because of deficiencies of water, as some paleoclimatologists and archaeologists have asserted. The first logical step toward understanding any settlement's water system is to use basic hydrologic methods and theory and to understand the local watershed. There is great potential for watershed-climate modeling in developing plausible scenarios of water use and supply and of the effect of extreme conditions (flood and drought), all of which cannot be fully represented by atmosphere-based climate and weather projections. The research demonstrates how the local watershed, land-use, and ecological conditions interact with regional climate changes. The archaeological implications for this noninvasive "virtual" method are many, including detecting periods of stress within a community, estimating population by developing caps based on the availability of water, and understanding settlement patterns, as well as assisting present local populations in understanding their water cycle.

El objetivo principal de esta investigación es la introducción del método hidroarqueológico, especialmente en lo relacionado a temas como la sequía. El artículo describe cómo este método multidisciplinario ayuda a entender las causas del éxito y fracaso de un sitio arqueológico, en este caso, del sitio maya de Palenque. También detallamos evidencia convincente que muestra que—a diferencia de lo que algunos paleoclimatólogos y arqueólogos han afirmado—los mayas de Palenque no abandonaron su ciudad debido a escasez de agua. El primer paso lógico para entender el sistema hidráulico de cualquier asentamiento es usar la teoría y métodos hidrológicos básicos, y conocer la cuenca hidrológica local. Existe un gran potencial para los modelos climatológicos-hidrológicos para proporcionar posibles escenarios de uso y abasto de agua, y los efectos de posibles condiciones extremas (inundación y sequía), todo lo cual no puede ser representado totalmente mediante pronósticos del tiempo y del clima que se basan en la atmósfera únicamente. Esta investigación demuestra cómo interactúan las cuencas locales, el uso de la tierra y las condiciones ecológicas, con los cambios climáticos regionales. Las implicaciones arqueológicas de este método no-invasivo "virtual" son muchas, incluyendo: la detección de periodos de estrés en el interior de una comunidad; la estimación de la población al diseñar topes de crecimiento basados en la disponibilidad de agua; la comprensión de los patrones de asentamiento; así como la asistencia a las poblaciones actuales en la localidad para el entendimiento de su ciclo de agua.

Palenque, one of the best-known Classic Maya centers, has what is arguably the most unusual and intricate system of water management known anywhere in the Maya Lowlands. Years of archaeological research, including intensive mapping between 1997 and 2000 (Figure 1), reveal that this major center, situated on a narrow escarpment at the base of the Sierra de Chiapas in northern Chiapas, Mexico, began as a modest settlement about A.D. 100. Then, during the seventh and eighth centuries, Palenque experienced explosive growth, mushrooming into a dense community with an estimated population of 6,000 and approximately 1,500 structures—residences, palaces, and temples—under a series of powerful rulers (Barnhart 2001). This process

Kirk D. French ■ Department of Anthropology, Pennsylvania State University, University Park, PA 16802 (kirkdfrench@psu.edu)
Christopher J. Duffy ■ Department of Civil and Environmental Engineering, Pennsylvania State University, University Park, PA 16802
Gopal Bhatt ■ Department of Civil and Environmental Engineering, Pennsylvania State University, University Park, PA 16802

Latin American Antiquity 23(1), 2012, pp. 29–50

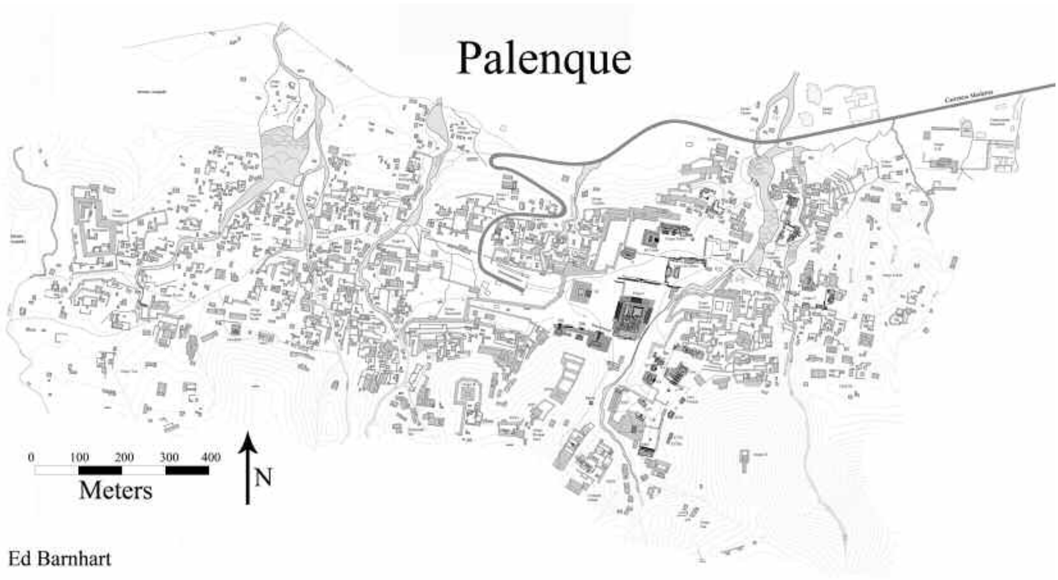

Figure 1. Map of Palenque (Barnhart 2001).

of "urban" growth led to predictable changes in land cover.

The desire to understand the effects of land-cover change on the availability of water for an ancient city prompted us to implement a spatially distributed hydrologic model. The hydroarchaeological method utilizes simulated daily paleoclimatic data, watershed modeling, and archaeology to explore the response to ancient human impact on a watershed. There is great potential for distributed watershed modeling in developing plausible scenarios of water use and supply and of the effect of extreme conditions (flood and drought), all of which cannot be fully represented by atmosphere-based climate and weather projections or by lumped hydrologic models. One outcome of these simulations is the demonstration that distributed land-cover change is a principal factor in watershed response to climatic inputs.

Palenque's environmental setting is very different from those found elsewhere in the Maya Lowlands. In general, the development of other large Maya centers in the region was constrained by low topographic relief with limited year-round water supplies. At these sites broad, flat depressions, called *bajos*, served to hold water during the rainy season. Their builders took advantage of occasional well-drained low-relief upland areas of the Maya lowland, and as a result cities such as Tikal and Calakmul grew in a broadly dispersed or rambling pattern that follows the terrain. Scarborough (2003, 2008) describes such centers as "labortasking," referring to the investment in highly efficient labor divisions that are generally the case for "still-water systems." On the other hand, the inhabitants of Palenque had to adapt their burgeoning settlement to a small and steep geomorphological space (ca. 2.2 km^2). This setting created a much more confined and crowded settlement pattern than that of most other Maya centers.

Although the steep terrain at Palenque provided an abundant year-round water supply from the spring-fed streams that naturally divided the landscape, it also contributed to the difficulties of constructing buildings on Palenque's spatially confined plateau. George Andrews (1975) claimed that this irregular natural terrain caused many problems for the city's builders, who were forced to reshape the existing topography in order to maintain a semblance of visual order within the site center. To meet the challenge of simultaneously controlling flooding, reducing erosion, and bridging divided civic space, the Maya of Palenque covered portions of the existing streams by constructing elaborate subterranean aqueducts that guided the water beneath plaza floors. This technique expanded the size of their plazas by 23 percent (French 2007).

The abundance of flowing water and the confined, steep terrain led to the unique method of settlement and construction at Palenque. It is clear that the Palencanos were challenged to modify their landscape in order to take advantage of hydrological resources and to accommodate their growing city. It was this urban challenge that resulted in a set of complex engineering adaptations unlike those found anywhere else in the Maya Lowlands or indeed in Mesoamerica. This brand of compact, extratropical urbanism fits Scarborough's (2003, 2008) model of "technotasking," an established societal investment in technology with a centralization of resources.

Environmental Setting

The Palencanos built their city on a narrow limestone shelf approximately 150 m above the plains of Tabasco, which stretch north to the Gulf of Mexico. There were many advantages to choosing this particular area. For one, the high escarpment afforded a good defensive position, a particularly important consideration in Classic times when warfare was increasingly frequent. Attackers from the east, west, or south would have been confronted with a series of steep and treacherous mountains. Alternatively, an assault from the north would have been detected early due to the commanding view the Palencanos had of the plains below.

An even greater advantage for early settlers was the presence of many natural springs. As in many cultures, water possessed both a practical and symbolic value for the Maya. Palenque's natural topography mimics the Maya image of the place of creation, described in the Maya epic *Popol Vuh* as the land where waters flow out of the mountains: "The channels of water were separated; their branches wound their ways among the mountains" (Tedlock 1985:74). Provided that this view of creation was held by the Classic Maya, a landscape such as this would have been emblematic to the early settlers of Palenque.

Practically speaking, freshwater and the rains that supplied it were vital for sustenance. Precipitation in the Maya Lowlands is generally seasonal, with the lowest rainfall from December to May (40–250 mm per month) and a rainy season from June through November (300–550 mm a month). October is the wettest month, and April, the driest. Total annual rainfall for the western periphery of the Maya Lowlands ranges from about 1,500 mm a year at the Gulf of Mexico to nearly 3,200 mm a year in the foothills of the Sierra de Chiapas at Palenque. This abundance of precipitation still falls short of records in such areas as the Maya Mountains in Belize, which can receive a staggering 4,000 mm of rainfall per year (Dunning et al. 1998). According to Magana et al. (1999), the annual cycle of precipitation over the Palenque area exhibits a bimodal distribution, with maxima during June and September–October and a relative minimum during July and August. The latter is known as the midsummer drought or *canícula*. The *canícula* is associated with fluctuations in the intensity and location of the eastern Pacific intertropical convergence zone. Tropical cyclones are the source of heavy precipitation in summer and fall. At Palenque convective precipitation and orographic influence (moist warm air encounters a mountain barrier, and the air cools and condenses as it rises and precipitates as rain) are also significant with increasing distance from the Gulf of Mexico. The average temperature at Palenque ranges from 22.9°C in December and January to 28.8°C in May. The great rivers in the region, the Usumacinta and Grijalva, discharge 30 percent of the total freshwater flow of Mexico.

The critical role of drought to our arguments requires that we distinguish among hydrological, meteorological, and agricultural droughts. A meteorological drought is defined on the basis of the atmospheric conditions and the duration of the dry period (and reduced precipitation [Palmer 1965]). For example, meteorological droughts identify periods of drought on the basis of the number of days with precipitation less than some specified threshold. A hydrological drought is associated with the terrestrial effects of periods with shortfalls of surface or subsurface water supply (i.e., streamflow, reservoir and lake levels, groundwater, etc.) that may or may not be the result of reduced precipitation (Tallaksen and van Lanen 2004). The frequency and severity of the drought are defined relative to its effect on the watershed or river basin. Clearly, hydrological droughts can cause severe problems for local populations. An agricultural or ecological drought links various characteristics of meteorological and hydrological droughts to agricultural or ecological impacts, such as reduced availability of soil moisture for plant and crop evapotranspiration (Palmer 1965). Demand for water depends on the stage of growth, properties of the soil, and prevailing weather conditions. At Palenque there are three main issues with regard to various forms of drought: (1) water for agricultural production, (2) water for household consumption, and (3) water control to reconfigure and protect the urban landscape. These will be discussed in turn.

Agricultural Resources at Palenque

Agricultural production was confined to the alluvial soils in the plains to the north of Palenque (Liendo 1999). The problems in the agricultural manipulation of the plains were seasonal flooding and meteorological/agricultural drought. The rainy season transformed the area into a wetland, while the winter drought created unsuitable conditions for large-scale maize production. These problems were solved with the construction of channelized fields (Liendo 1999; Figure 2).

Channelized fields serve two main functions: drainage and drainage-irrigation (Siemens and Puleston 1972; Turner and Harrison 1983). Drainage functions imply the removal of standing water from wetland areas through the digging of canals or ditches to drain water. Drainage-irrigation implies the manipulation of water table levels both within the canals and on field surfaces (Denevan and Turner 1985). Excavations of the channelized fields in Palenque during the 1990s by Rodrigo Liendo (1999) showed that the canals worked fine as devices to get rid of excess water during the rainy season by lowering the water table of the agricultural fields. He also found that during the dry season the canals seem to have maintained a permanent level of water, avoiding loss into the nearby Michol River. This occurred because of the narrowing of the canal as it gets closer to the river, suggesting the probable use of gates to obstruct the flow. Water retention and drainage would have allowed for year-round use of these fields (Liendo 1999).

Maize was the Maya staple and constituted 70 percent of the diet (Reed 1998). Based on a 2,200-calorie diet, each Palencano required 1,540 calories from maize per day. According to Barnhart (2001), an average of 5,183 people lived in Palenque. In order to fulfill the annual caloric requirements for the inhabitants of Palenque, 275 ha of land had to be under cultivation based on two harvests per year. Yet an estimated 3,000 ha of agricultural area existed, and of that, approximately 500 ha of channelized fields were excavated by Liendo (1999). A channelized field system that enabled year-round use might help explain Palenque's regional influence. Simultaneous production of all 500 ha of the channelized fields would have produced enough maize to support a population of approximately 8,000. Failure of this system could have contributed to Palenque's abandonment in A.D. 799, an issue addressed later in this article.

Paleoclimate

Maya archaeologists and paleoecologists have long hypothesized an intimate relationship between climate change and ancient lowland Maya cultural dynamics (e.g., Dahlin 1983; Dahlin et al. 1987; Folan et al. 1983; Gunn and Adams 1981). Many of these early hypotheses are speculative because they rested on untested long-distance associations between the Maya region and Europe, where climate change is better documented (Dahlin 1983; Folan et al. 1983; Gunn and Adams 1981). Given the speculative nature of this early work, it was not widely accepted by Maya archaeologists until Hodell et al. (1995) presented local evidence from cores in Laguna Chichancanab in the northern part of the Yucatán Peninsula for a prolonged episode of severe hydrological droughts (megadroughts) coincident with the collapse of lowland Classic Maya civilization. Gunn and colleagues (Gunn and Folan 2000; Gunn et al. 1995) utilized a combination of paleovolcanism and solar energy output to infer past mean global temperatures. Next, using modern discharge data from three watersheds in the southwestern Maya Lowlands along with the paleoclimate data, they reconstructed the total discharge of the Candelaria River for the last 3,000 years. Their projections of a second-century drought were confirmed by the Chichancanab lake cores (Hodell et al. 2001; Hodell et al. 2005) and more recently by speleothem analysis (Webster et al. 2007). Subsequent work on lake cores in the same general area by Hodell and his colleagues (Hodell et al. 2005; Hodell et al. 2007) has since attributed the abandonment of Mayapan in A.D. 1441 to another spike in aridity.

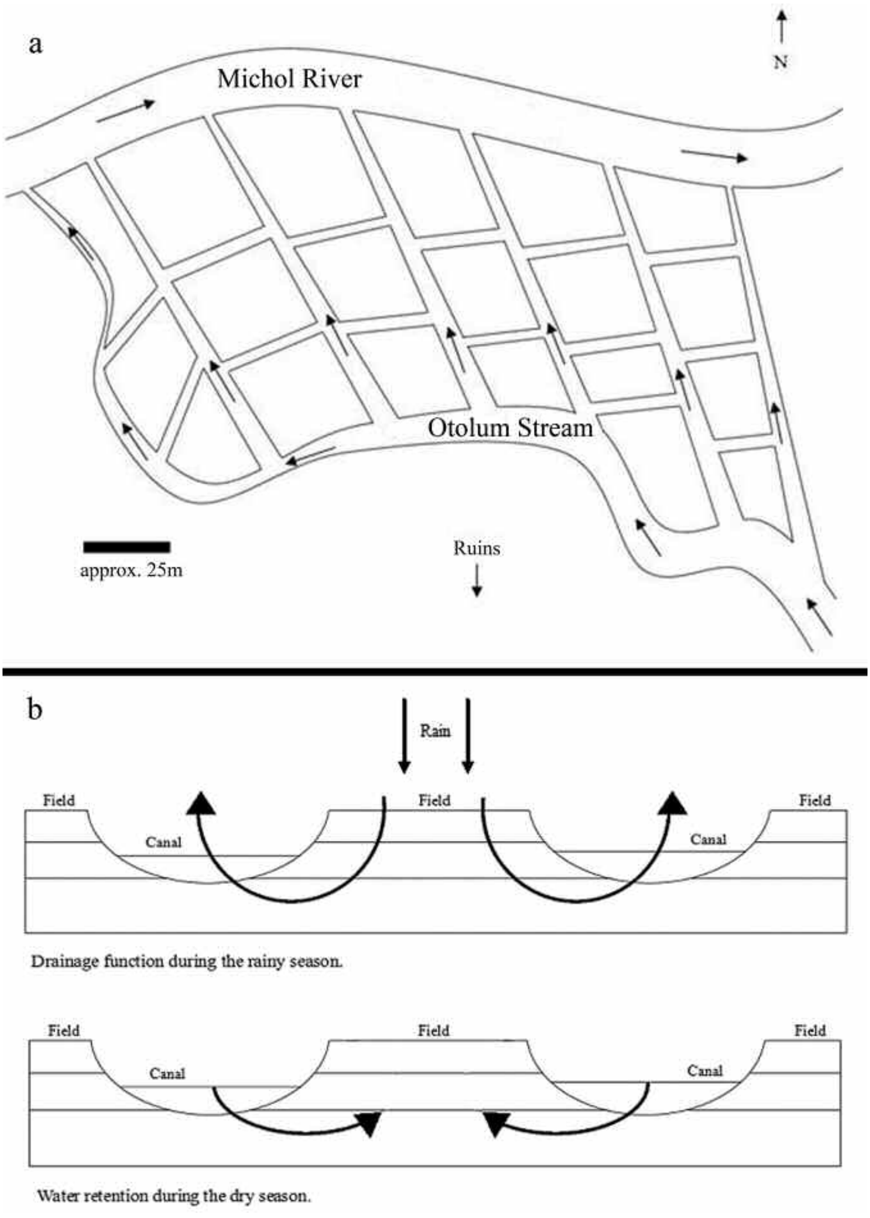

Figure 2. (a) An approximation of Palenque's channelized fields; (b) cross section of Palenque's channelized fields (adapted from Liendo 1999:126–128).

Pollen grains of maize and other indicators of forest clearance in lake cores from the well-watered interior of the peninsula to the south document pioneer colonization of the area by agriculturalists, ca. 2000 B.C. (Pohl et al. 1996). These cores also show pollen evidence for forest regeneration after the collapse and limnological evidence for extreme soil loss in the intervening Late Preclassic and Classic periods, but these environmental perturbations mask most of the climatological data here (e.g., Brenner et al. 2003; Deevey 1978; Deevey et al. 1979; Vaughn et al. 1985). In addition, a massively replicated network of tree-ring chronologies that indicate changes in paleoclimate has been developed for Mexico over the past decade (Villanueva-Díaz et al. 2007; Stahle et al. 2009).

Analogous to tree rings, annual speleothem layers can be counted for excellent age control (Frappier et al. 2002). The physical and geochemical variations in speleothem laminations, moreover, can be more sensitive in recording paleoclimatic changes than lake core stratigraphy because there is little reservoir effect. This means that climatic perturbations that are too small to register in lake sediments, but which might have had marked effects on the human inhabitants of the region, might well be recorded in speleothems (Frappier et al. 2002). Other characteristics of climatic trends potentially can be measured at intra-annual resolutions in speleothems, including the speed of onset and cessation of droughts, as well as differences in seasonality, which can be critically important for agriculturalists (Frappier et al. 2002; Medina-Elizalde et al. 2010; Webster et al. 2007; Zhang et al. 2008).

The recognition of agricultural architecture—terracing and drained fields—led the quest for land-use practices along with pollen analysis for a couple of decades (Fedick 1996; Flannery 1978; Harrison and Turner 1978; Pohl 1985). Intensified agricultural techniques as seen in agricultural architecture were fairly localized, and they ultimately fail to suggest how the most populated sites, such as Tikal and all of the sites in the heavily populated northern peninsula, subsisted. The most informative lake core data on land use in the north come from Lakes Cobá and Sayaucil (Leyden et al. 1998; Whitmore et al. 1996), but these data are very general and have very coarse temporal resolution.

While tremendous strides have been made in reconstructing climates and land-use systems on the Yucatán Peninsula using lake core data, this set of techniques, like all techniques taken in isolation, has built-in uncertainties. Many scholars (e.g., Brenner et al. 2003; Trenberth and Otto-Bliesner 2003) cite the need to integrate more independent climate proxies into a holistic reconstruction of past climates. Moreover, clearer linkages between the characteristics of climate changes and cultural changes, both big and small, are necessary.

Simulating the Paleoclimate at Palenque

Our interest here is in developing a statistically plausible paleoclimatic history for Palenque by simulation, utilizing two climate-generating programs that capture long-range climate variations (≥100 years) and short-range statistics of daily weather. This approach was taken in order to construct realizations of the full range of atmospheric inputs (wet and dry) to the watershed at Palenque, from daily storm events to the annual monsoon to decadal, centennial, and millennial climatic patterns typical of the Palenque area.

MarkSim

MarkSim is a weather generator for crop modeling and risk assessment based on the instrumental record from 9,200 tropical weather stations for Latin America and Africa. The stochastic weather generator uses a third-order Markov process to model daily precipitation, temperature, etc. The daily data provided by the model preserve the statistics of regional data. The climate normals for these stations were assembled into 664 groups using a clustering algorithm. For each of these groups, rainfall model parameters are predicted from monthly means of rainfall, air temperature, diurnal temperature range, station elevation, and latitude. The program identifies the cluster relevant to any required point using interpolated climate surfaces at a resolution of 10 minutes of arc (18 km^2) and evaluates the model parameters for that point (Jones and Thornton 2003). At Palenque the MarkSim weather generator was used to construct a data set of rainfall and temperature over the last 100 years (French 2009:178–183).

Bryson Paleoclimate Model

The second part of our method utilized the Bryson Archeaoclimatology Macrophysical Climate Model (hereafter BMCM), a high-resolution, site-specific, macrophysical climate model. The BMCM was developed in the mid-1990s by Reid A. and Robert U. Bryson as an alternative to general circulation models (GCMs) that could produce results at a spatial and temporal scale useful to a variety of social, natural, and earth sciences. Unlike the wide assortment of GCMs in the literature, the BMCM takes a top-down, rather than bottom-up, approach to model building. The output of the first model was in 200-year averages, but recent revisions and updates to the volcanic record (Bryson et al. 2006) have allowed for 100-year averages in calendar years.

The foundation of the BMCM is the calculated "modules" that provide the location of each of the centers of action for the past 40,000 years, in 100-

year intervals of monthly values. All years in the current models are calculated in calendar years before present (cal B.P.). Each module contains the locations (latitudes) for one center of action at a given longitude. Twenty different modules in four categories are utilized by the BMCM, but only four to six are present in any given model. The breakdown is as follows: temperature modules, highs, intertropical convergence locations, and jet stream locations. The BMCM is, in essence, a heat-budget model predicated on orbital forcing, variations in atmospheric transparency, and the principles of synoptic climatology (Bryson and DeWall 2007). Average monthly rainfall, maximum and minimum temperature, and mean temperature typical of the site under consideration were entered into the BMCM, and a data set of 100-year averages for the last 2,500 years was produced (French 2009:187–189).

Although there is considerable regional variability and site coverage is still sparse in many places, it is clear that significant parts of the U.S. Southwest, northern and central Mexico, and the Yucatán were wetter than presently in the early to mid-Holocene and exhibited a drying trend toward the late Holocene (Whitmore et al. 1996). In contrast, the U.S. Southeast was drier than the present in the early to mid-Holocene and became much wetter in the late Holocene. Ruter et al. (2004) compared the aforementioned observations with simulations of climate for 6,000 years ago, and for the present, made with four different climate models. They conclude that the models showed fair agreement, both with each other and with the proxy record in many locations. The subtropics maintained more similarities, while the tropics differed significantly (Ruter et al. 2004).

Daily-to-Century Climate Scenarios for Watershed Investigation

It is important to restate that the purpose of this analysis was to construct plausible hydrologic inputs to the Palenque watershed that preserve the short-term daily to seasonal statistics of precipitation and temperature while also maintaining the long-term climate variations and patterns in the paleoclimate model. Using the method of proportionality (Intergovernmental Panel on Climate Change 1996), the daily 100-year MarkSim simulations were scaled by the climate trends of the Bryson model to produce 100-year daily scenarios during selected centuries spanning the Maya period. Clearly the approach can only provide an inference or index of past conditions of watershed inputs.

The 2,500-Year Simulation

Two trends of interest arose from the 2,500-year paleoclimate simulation (Figure 3). The first is the consistency of the climate from A.D. 500 to 800. Long periods of predictable climate can often equate with flourishing populations. For Palenque, as for much of the Maya Lowlands, the period of A.D. 500–800 was a period of unparalleled growth and prosperity. Gunn, Folan, and Robichaux (1995) equate this time in Maya history to an optimal balance between seasons. According to Lucero (2006; Lucero et al. 2011) and others (Demarest et al. 2004; Yaeger and Hodell 2008), the Maya collapse most likely occurred during an imbalance between these predictable wet and dry seasons.

Second, according to the simulation, Palenque began to experience a slight cooling (approximately 1 percent) during the ninth century. By the tenth century the site had cooled an additional 1 percent, along with a 1 percent increase in precipitation. Although the changes are small, a cooler and wetter climate during this time period is in opposition to much of the data that support the theory of a great Maya drought (Gill 2000). Recently, however, many scholars have reassessed the role that decreased rainfall played in the transformation of the Maya Lowlands during the ninth and tenth centuries, citing the significant differences from site to site that consistently argue against a single event or catastrophe (Ashmore et al. 2004; LeCount et al. 2002; Lucero 2002; Yaeger and Hodell 2008).

The Palenque Watershed and Hydrologic Setting

The effects of climate change are predicted on (and in many cases have already begun to impact) water resources all over the world. Climatic perturbations also play an important role in changing the ecosystem's structure and function (Westerling et al. 2006). Studies on ecosystem response to relatively short disruptions have indicated that species assemblages often recover

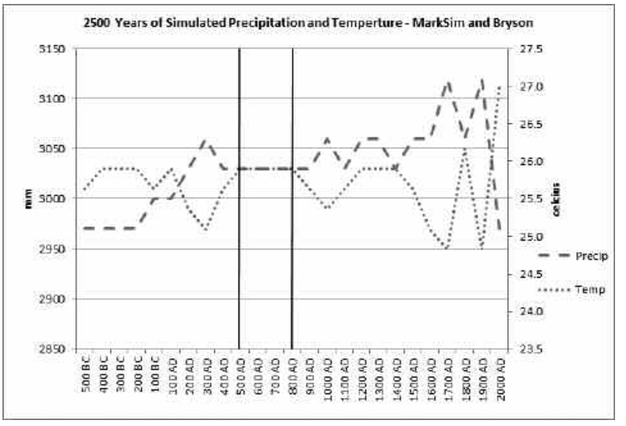

Figure 3. Bryson/MarkSim simulated precipitation and temperature over a 2,500-year span.

rapidly from meteorological drought (Matthews and March-Matthews 2003), but quantitative assessments of ecological impacts from extreme, decades-long wet or dry episodes have revealed more pervasive ecological impacts than previously thought (Gray et al. 2006). A potential strategy available for understanding the cultural and political risks associated with past climate impacts is to obtain a clear definition of past hydrological variability and extremes (National Research Council 2007). Instrumental records of precipitation, temperature, and surface-water flow at many sites throughout Mesoamerica are nonexistent, but long-term estimates of streamflow variability are critical for understanding the impacts of floods and hydrological droughts (Stewart et al. 2004).

Streamflow records can be extended by stochastic approaches to generate synthetic data (Salas 1993). The simulated climatic conditions discussed earlier are incorporated in a stochastic model that produces streamflow sequences that replicate these conditions for a longer period. This stochastic method also generates a long time series of precipitation that is transformed into streamflow using deterministic hydrologic models (Linsley et al. 1982). These approaches assume that existing instrumental data adequately represent the characteristics of streamflow or precipitation well beyond the actual period of observations. This section details a novel method that combines simulated climatic records and watershed modeling to produce estimates of long-term streamflow for the Palenque watershed.

The Palenque upland watershed encompasses 7.21 km^2 and is located approximately 8 km southwest of the modern town of Palenque. The watershed is on the northern edge of uplifted and folded sedimentary rocks of the Mayan tectonic block. To the south lies the Sierra de Chiapas, a folded and faulted chain of Mesozoic and Tertiary sedimentary rocks with fold axes trending northwest, which generally plunge northwestward beneath the Pliocene and younger sediments of the coastal Tabasco Plain and the Gulf of Mexico (Ferrusquia-Villafranca 1993; Nencetti et al. 2005; Sedlock et al. 1993).

Late Cretaceous (99.6–65.5 Ma) limestone covers most of the watershed. The model assumes that the limestone, like the soils, is very permeable. Macropores, which are soil or rock fractures, cracks, root holes, and bioturbation of all kinds, tend to increase the hydraulic conductivity of the soil and rock. The near-surface limestone also weathers along joints and fracture planes as shown in Figure 4.

Palenque is categorized as a "tropical moist forest" according to the Holdridge Life Zone classification scheme (Holdridge et al. 1971). Holdridge defines "tropical moist forest" as a tall, multistratal semideciduous forest with many different species of wide-crowned trees 40–50 m tall. The subcanopy consists of trees up to 30 m tall, mostly with narrow crowns. Palms are generally abundant. The shrub layer is made up of dwarf palms and giant herbs with banana-like leaves. The ground is generally bare except for a few ferns, broad-leafed

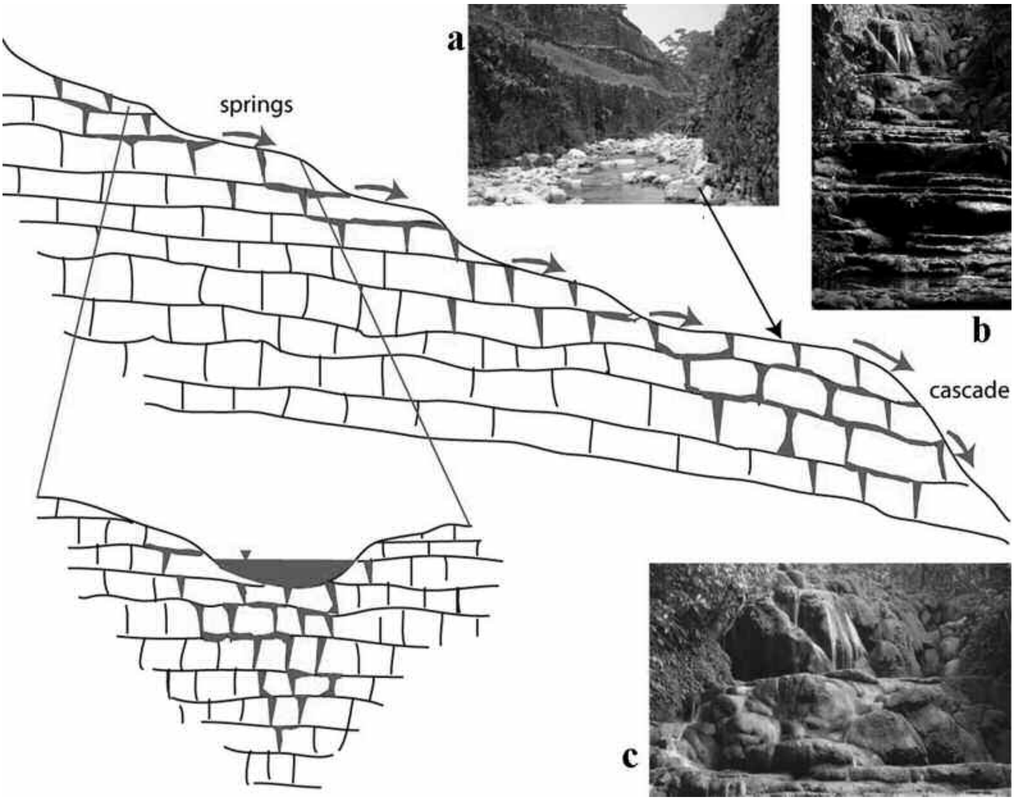

Figure 4. Hydrologic conceptual model for the Cretaceous limestone watershed at Palenque showing the increased dissolution along bedding planes and fractures below the stream channel bed: (a) a boulder channel crossing the ruins; (b) and (c) two view within the groundwater discharge zone showing the pool and ledge cascade and accreting tufa deposits.

herbs, and tree seedlings. Abundant herbaceous vines hang throughout the forest.

The Penn State Integrated Hydrologic Model

Integrated hydrologic models are the latest tools in simulations of the terrestrial water cycle that include all physical processes that affect water (terrain, vegetation, geology, soils, etc.). Traditional approaches are generally spatially lumped and statistically based and generally do not provide anything but input and output. This new generation of terrestrial models is physics-based, with spatially distributed predictions for soil moisture, groundwater, and streamflow "within" the domain of interest. That is, the user not only can simulate the outflow from the watershed but can also simulate the internal dynamics of the river network including groundwater inputs to streams. The hydrologic community is now relying on integrated models that better reflect the physics of water movement through complex geological terrain as called for by the National Research Council (2004, 2005, 2008).

Major hydrological processes within the terrestrial hydrological cycle operate over a wide range of time scales, with interactions among them ranging from uncoupled to strongly coupled. The numerical simulation of coupled nonlinear hydrologic processes provides an efficient and flexible approach to watershed simulation. The Penn State Integrated Hydrologic Model (PIHM) represents a new strategy for watershed modeling in which spatial details of the watershed, including processes of surface flow, groundwater flow, vegetation water, and energy, are accurately represented in the model, and data are derived from national or global spatially explicit data sets (Qu and Duffy 2007). The model equations are numerically solved using the finite volume method (Ferziger and Peric 2002). The model solves the systems of equations on an

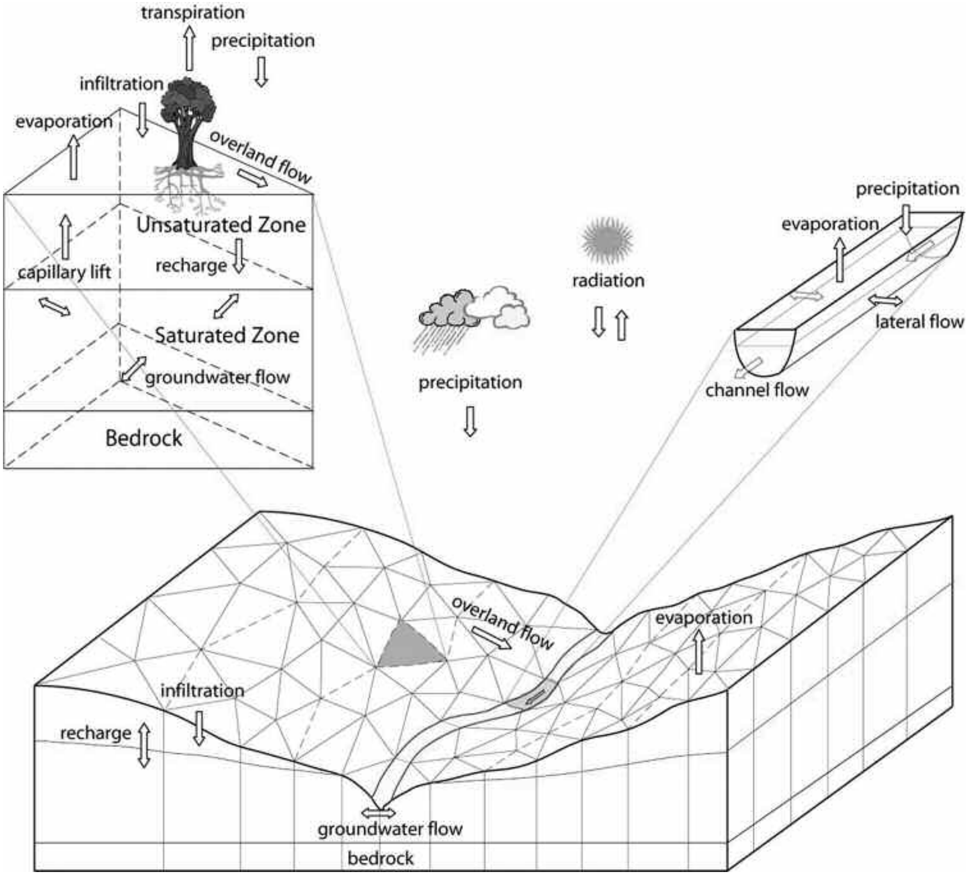

Figure 5. Example of a user-specified discretization of a river-reach with a prismatic finite volume approximation for surface and groundwater flow. The Penn State Integrated Hydrologic Model simulates land surface, subsurface and channels processes. Details are available at http://www.pihm.psu.edu/.

unstructured triangular grid, referred to as a triangular irregular network. The finite volume elements are prisms, projected vertically downward from the triangular surface grid. The grid is generated to follow important features of the model domain, such as the watershed boundary, the stream network, the soils, or the land cover. The model is designed to capture the dynamics of the watershed for surface, groundwater, soil water, and vegetation water use while maintaining the conservation of mass at all grid cells, as guaranteed by the finite volume formulation (Qu and Duffy 2007).

Figure 5 shows typical land surface and channel elements. PIHM and PIHMgis represent a community modeling tool and geographical information system (GIS) tool, respectively, developed under National Science Foundation funding. This application of PIHM serves as a test of the overall modeling strategy for ungauged basins, but where land cover, soil maps, topography, and climate data are available or can be estimated (Qu and Duffy 2007). The important distinction between PIHM and other watershed models is that the physical model and data layers (Figure 5) are explicitly linked (tightly coupled) through a data model and GIS interface.

PIHMgis is an integrated and extensible GIS system with data management, data analysis, mesh generation, and distributed modeling capabilities. This makes it possible to generate a model fairly quickly that can handle the complexity of the different types of data, represent the "built" structures, and produce realistic model simulations. The GIS tool allows visualization of the data and provides algorithms for the hydraulic parameterization of soil and land cover.

PIHMgis was developed using basic Quantam GIS source code (http://www.qgis.org). PIHM is available as open-source code on Source Forge (http://sourceforge.net/projects/pihmmodel/) and on the Penn State Web site (http://www.pihm.psu.edu).

Land Cover at Palenque

Running PIHMgis at Palenque required the input of the 100-year daily climate simulations discussed earlier. The model also required the identification of likely land cover that existed during each epoch. The following three scenarios were constructed to cover a range of climate conditions and plausible land cover during each epoch (Figure 6).

Forested

The U.S. Environmental Protection Agency's "2001 National Land Cover Data" (National Land Cover Database 2001) provides the vegetation and properties for estimating evapotranspiration in the model. The most appropriate category, according to the National Land Cover Database, was "forest/evergreen." It defines "forest/evergreen" as "trees > three meters in height, canopy closure > 35 percent (< 25 percent intermixture with deciduous species), of species that do not seasonally lose leaves" (2001).

Deforested

Evidence suggests that deforestation was common among the Maya, especially those living near urban centers (Webster 2002). In Palenque the deforested areas were composed of the densely populated core and the agricultural fields to the north of the site (Liendo 1999). Although increases in agricultural production caused much deforestation, demand for stucco for monumental stone structures played an even larger role (Abrams and Rue 1988; Hansen et al. 2002; Schreiner 2002). To make stucco limestone must be heated to 900°C, a process called calcination or lime burning, so as to remove the carbon dioxide in a nonreversible chemical reaction. The result is calcium oxide (quicklime), a white, caustic, and alkaline crystalline solid that when mixed with water makes a fine plaster. The Maya used this plaster/stucco to coat all exposed architecture, in

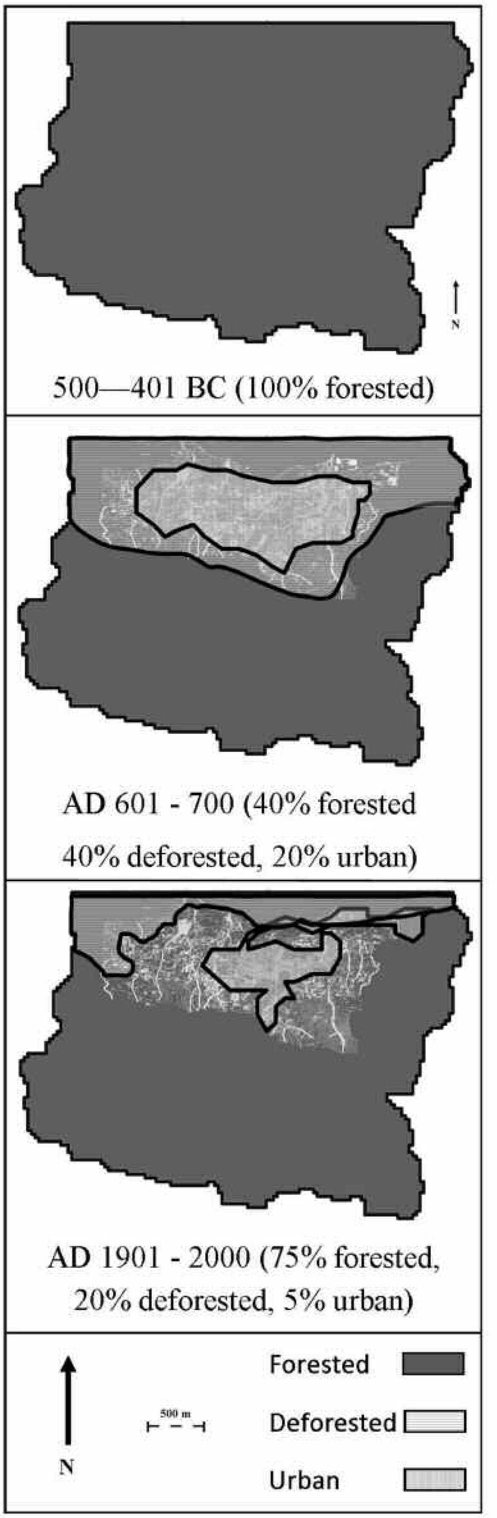

Figure 6. PIHMgis scenarios for the Palenque Watershed.

addition to paving their expansive plaza floors. Because it was a sign of wealth and prestige, the stucco had to be constantly maintained.

Reconstruction of a Maya kiln used for the calcination process determined that 1 ha of forest with trees greater than 5 cm in diameter will provide 444 kg of quicklime (Schreiner 2002). The quicklime contribution to a cubic meter of plaster is 325 kg. Palenque's main plaza would have required approximately 668 m^3 of plaster and pavement (based on 2 cm of thickness). At 325 kg per cubic meter, 217,100 kg of quicklime would have been needed for the surface of the plaza. This equates to 489 ha (4.89 km^2) of forest trees, more than twice the size of the site. Palenque also maintained thick layers (2–10 cm) of stucco in many of its buildings, roof combs, and aqueducts (French and Duffy 2010; Littman 1959; Straight 2007). It must also be noted that some portion of the fuel (trees) used in the production of quicklime would have most likely come from the clearing of land for agricultural production. Based on these arguments we propose that significant deforestation would have occurred locally.

Urban

The urban land-cover scenario was difficult because it is unknown to what extent the Palenque plazas and courtyards were impermeable due to stucco/plaster. In lieu of this information the hydraulic conductivity of the soil within the site boundary was reduced by 50 percent to simulate compaction by urban traffic.

The Hydroclimatic and Land-Cover Scenarios

In the first scenario a 100-year daily climate simulation for 500–401 B.C. included 100 percent primary-forest land cover (Figure 6). Due to an absence of Preclassic pottery and architecture, it is widely accepted that the Palenque shelf was completely unoccupied during this period (Bishop 1994; Rands 1974; Rands and Bishop 1980). There is no evidence of occupation in the area until ca. 100 B.C. The vegetation scenario for 500–401 B.C. simulates pre-settlement conditions during a relatively wet climate period.

The second 100-year scenario, A.D. 601–700, is the plausible height of Palenque's population and urbanization (Figure 6). The land cover developed for this scenario was a mix of forested (40 percent), deforested (40 percent), and urban (20 percent) land-cover types. This time period simulates the maximum effect of human occupation and urbanization on the watershed during a stable climate period.

The third 100-year scenario or the modern period, A.D. 1901–2000, provides the linkage and comparison with the modern tropical climate observations (Figure 6). The land cover for this recent period was a mix of forested (75 percent), deforested (20 percent), and urban (5 percent), to approximate what exists today at Palenque. This span of time is also useful because of the opportunity to compare the scenario with descriptions by local inhabitants of flood and drought events that have taken place in the last 50 years.

Results

Scenarios of land use and climate variability were designed to examine their relative impacts on water supply and flood and drought conditions during three 100-year periods at Palenque. The 100-year climate periods chosen can be classified as wet (500–401 B.C.), average (A.D. 601–700), and dry (A.D. 1901–2000) based on the 2,500-year record. Land-use/land-cover changes represented pre-Maya, peak Maya, and modern for the same 100-year periods, respectively. Perhaps the most interesting result overall is the amplifying effect of land-use change on watershed streamflow response.[1] The results will model net watershed response and will focus on the Otolum channel (Figure 7), which flows through the central plaza, for detailed stream response. The results of the three scenarios are described below.

500–401 B.C.

The results from 500 B.C.–401 B.C. show an average daily discharge of 27,321 m^3/per day with a runoff ratio (runoff/precip) of 47 percent for the entire watershed (Figure 8). The complete forest cover, along with an absence of impermeable surfaces (e.g., plaster/stucco plazas), produced a relatively low runoff ratio and high soil moisture and evapotranspiration rate. It is interesting to note that the climate simulation for average precipitation for 500–401 B.C. was very close to that of A.D. 1901–2000 but 2 percent drier than A.D. 601–700 (Figure 9). As for temperature, the simulations

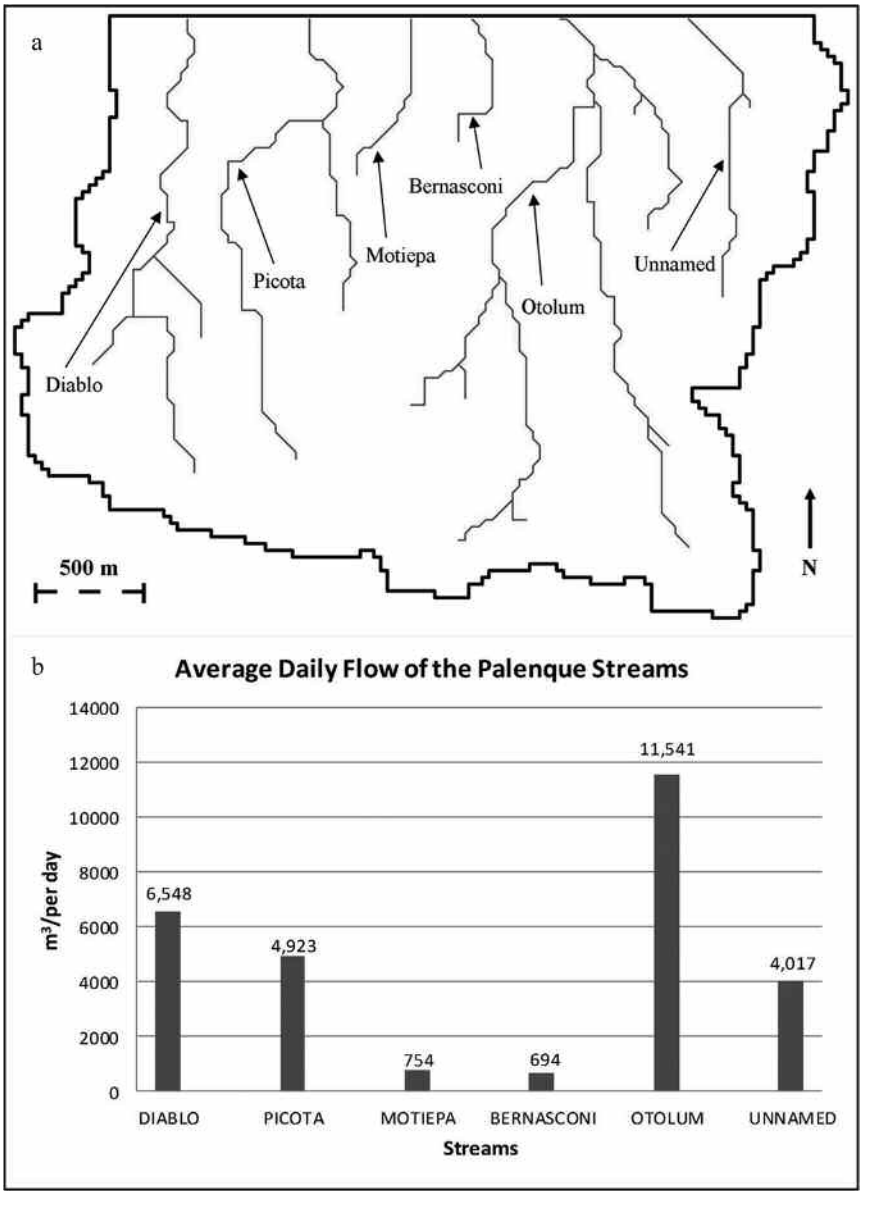

Figure 7. (a) Stream locations within the Palenque watershed; (b) average daily flow for the Palenque streams.

show that the fourth century B.C. was 5 percent cooler than the twentieth century and 1 percent cooler than the sixth (Figure 9).

A.D. 601–700

The results from A.D. 601–700 show the highest average daily discharge of the three time periods, simulated as 31,156 m^3/per day (Figure 8), with a runoff ratio of 52 percent. This results in a greater than 15 percent increase in total runoff when compared with the other two time periods. The deforestation levels along with the presence of urban land cover (i.e., impermeable surfaces) and reduced evapotranspiration from the watershed are the main cause for this increase in runoff in the model simulations. According to the climate simulation, the precipitation for A.D. 601–700 was 2 percent higher than that of the other two scenarios (Figure 9). The temperature experienced a 1 percent increase from that of the fourth century B.C. and

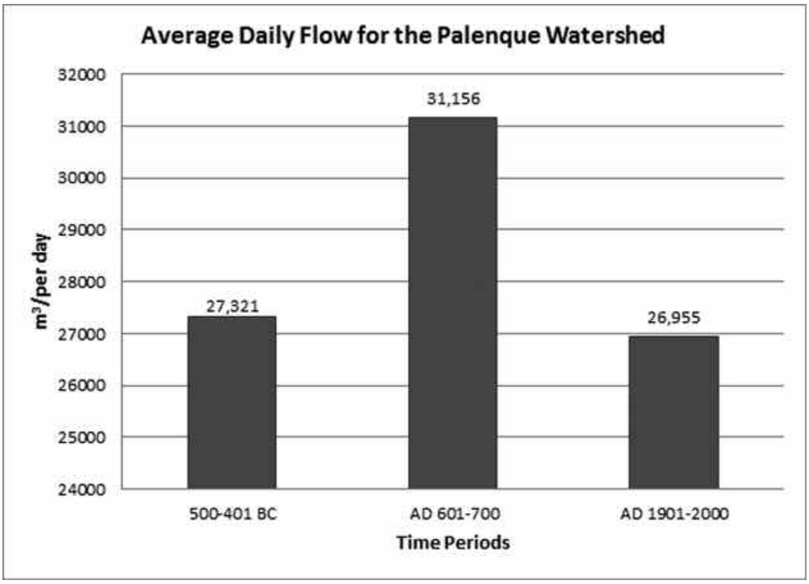

Figure 8. Average total daily discharge for the Palenque Watershed.

was 4 percent cooler than in the twentieth century (Figure 9).

A.D. 1901–2000

The simulations from the last century show the lowest average daily discharge of the three scenarios with 26,955 m^3/per day (Figure 8) and runoff ratio of 46 percent. The precipitation levels during this time period and that of the fourth century B.C. are nearly the same, but the temperature increased by a full 1.4°C (Figure 9). This significant rise in temperature coupled with less forest and an increase in urban cover are the causes for the 2 percent drop in daily flow.

Simulated Flood and Drought Events

The scenarios described above for wet, average, and dry 100-year climate periods with changing land cover make it possible to reconstruct the net hydrologic impacts on the watershed. Taken together, land-use change and climate change can produce an amplification of the basic hydrologic regime, with cooler-wetter conditions and increases in urban land cover equating to much larger runoff and warmer-dryer conditions leading to deeper, longer hydrological drought (lower runoff with longer duration). Details of these analyses can be found in French's 2009 dissertation.

The observed historical climate record is roughly 100 years long. Although earlier data exist, the last 100 years represent the reliable reference period. In order to compare historical simulation scenarios we use the same period as the historical observations. Within 100 years we can expect to find a useful range of variability, providing sufficient numbers of floods and droughts to make the simulations meaningful. Indexes for low- and high-flow conditions are derived from 100-year series of the annual minimum and maximum of the n-day average flow (Hisdal et al. 2004). For example, for $n = 7$, the entry from September 29, 1975, is in fact the average low flow for the period September 23, 1975, to September 29, 1975, inclusively. The derived data can thus be regarded as the outcome of passing a moving average filter of *seven*-day duration through the daily data. Based on the filtered hydrographs, mean annual minimum or maximum seven-day indexes can be derived. In this case, seven-day periods were used for n averages to find the lowest (drought) and highest (flood) flows for 500–401 B.C., A.D. 601–700, and A.D. 1901–2000.

The flood events in Palenque (Figure 10a) are linked to both rainfall and land cover. As mentioned above, the land cover for the fourth century B.C. is 100 percent forest. Forest cover slows the runoff from rainfall. The land cover used for the

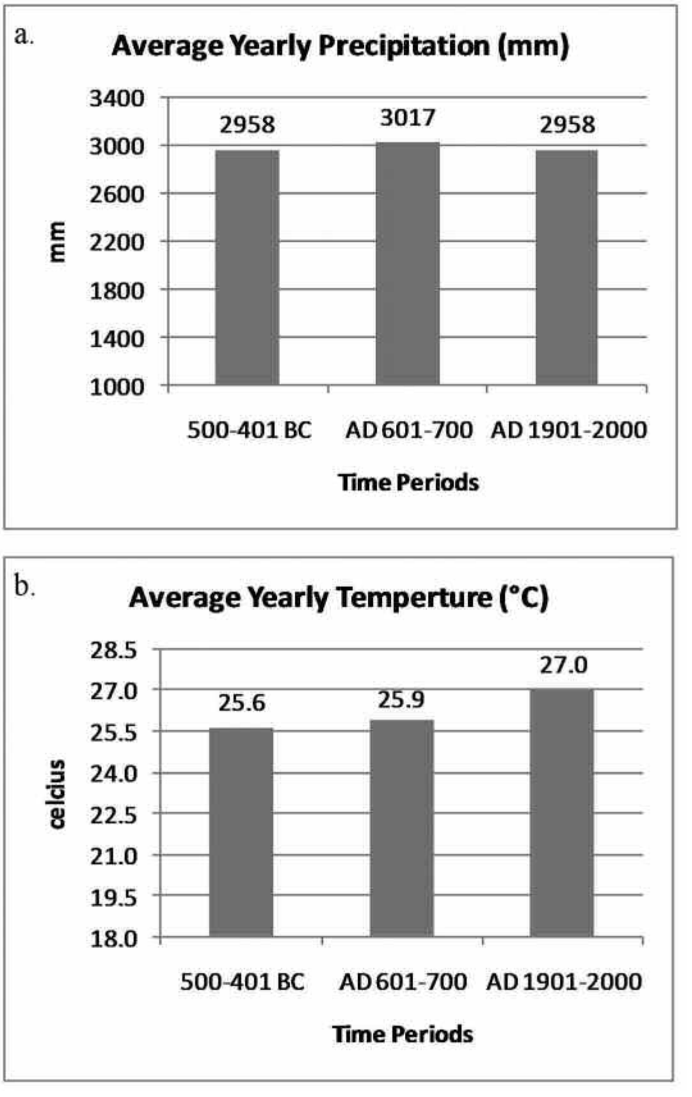

Figure 9. Average yearly precipitation and temperature for three time periods.

time period A.D. 601–700 was a mix of forest, deforested, and urban. Figure 10a shows the amplifying effects that a change in land cover can have on the watershed.

The hydrological droughts in the Palenque watershed (Figure 10b) are not particularly severe even under the worst-case scenario. During the worst seven-day drought of A.D. 601–700 the Otolum was still flowing at 484 m^3/per day. The storing of a mere 25 percent of this daily flow would have provided an ample water supply for a population of more than 17,000 based on 6 liters per person/per day (Back and Lesser 1981). As mentioned earlier, the population of Palenque is estimated at a little over 6,000 at its peak. Furthermore, this seven-day low-flow estimation is based on just one of Palenque's six major waterways, the Otolum (accounting for approximately 40 percent of the site's total flow [Figure 7b]). According to these simulations, Palenque never experienced a hydrological drought severe enough to cause major disruptions in daily life. It is also highly unlikely that Palenque was abandoned ca. A.D. 800 due to drought given that the region's climate remained

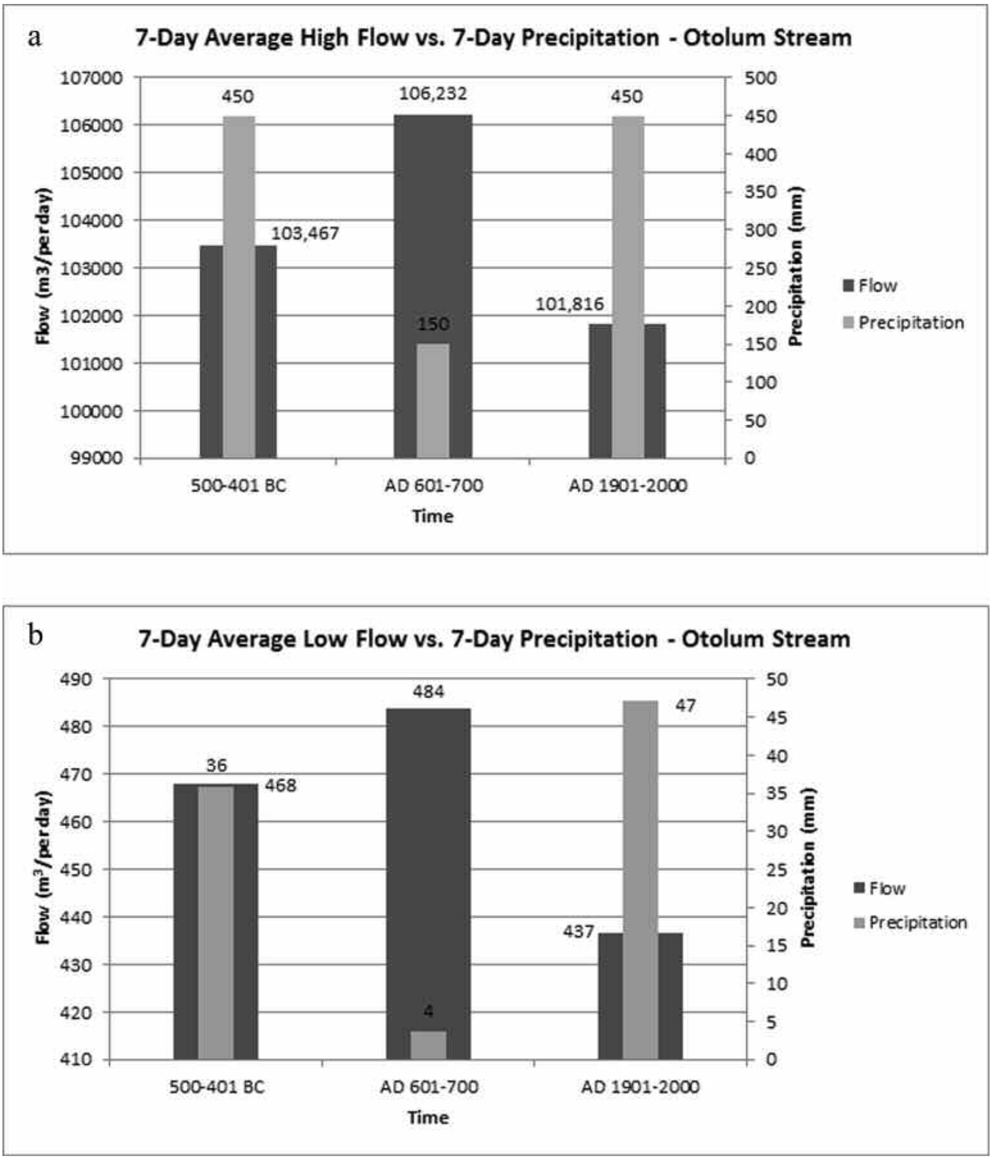

Figure 10. (a) The 7-day average peak flows (flood events) of the Otolum vs. the 7-day precipitation total for all three time periods; (b) the 7-day average low flows (drought events) of the Otolum vs. the 7-day precipitation total for all three time periods.

constant during the 100 years prior (A.D. 700–800) and only became cooler and wetter in the century that followed (A.D. 800–900 [Figure 3]).

In addition, careful analysis of the most severe simulated meteorological and agricultural droughts in Palenque did not reveal a time period that would have catastrophically affected agricultural productivity. Although there were times when the total rainfall during the summer growing season (Table 1) dipped to as low as 650 mm (the average required for maximum production [Food and Agriculture Organizations of the United Nations 2002]), the streams continued to deliver water to the channelized fields in the plains to the north of the site.

Conclusion

The ancient Maya center of Palenque was once a major player in the Usumacinta River Basin and politically significant throughout much of the Maya

Table 1. Estimated Calendar for the Palenque Summer Growing Season for Maize.

Growing Phase		Estimated Dates for Palenque
(0) Establishment		May 1 – May 20
(1) Vegetative		May 21 – June 24
(2) Flowering:	Tassel	June 25 – July 3
	Silk	July 4 – July 12
(3) Yield Formation		July 13 – August 21
(4) Ripening		August 22 – September 4

Lowlands. It was also distinctive for its architecture and for the cleverness its people showed in the manipulation of water. Palenque was remarkably small, both geographically and in population, when compared with other Maya centers with similar influence, such as Tikal, Calakmul, or Caracol.

In order to better understand Palenque's significance we turned to its predominant feature, water. The first step toward researching the water at any site should be to model the watershed. The only way to achieve this goal at Palenque was to first simulate a paleoclimate record. Two programs were used to achieve this end: (1) MarkSim, a daily weather generator; and (2) the Bryson paleoclimate model, a high-resolution, site-specific, macrophysical climate model. The results of the climate simulations for Palenque suggest a relatively stable climate from A.D. 500 to A.D. 800. It was during this period that most of the Maya Lowlands experienced the highest level of development and prosperity. Often, long periods of predictable climate equate with the reproductive, demographic, and political success of a regional population (Demeritt 1991).

The paleoclimatic simulations were used to generate precipitation and atmospheric temperature inputs for the watershed model (PIHM [Qu and Duffy 2007]). The spatial details of the watershed including processes of surface flow, groundwater flow, vegetation water, and energy are accurately represented in the model, and the data are derived from national or global spatially explicit data sets. PIHM modeled the Palenque watershed for three key epochs, each with differing land-cover scenarios: (1) 500–401 B.C., prior to Maya settlers, with a 100 percent primary-forest land cover; (2) A.D. 601–700, the plausible height of Palenque's population and urbanization, with a land cover consisting of 40 percent forested, 40 percent deforested, and 20 percent urban; and (3) A.D. 1901–2000, used as a comparison to the measured record of tropical climate observations, with 75 percent forested, 20 percent deforested, and 5 percent urban. The conclusions from these three scenarios produced drastic distinctions when the percentages of change in climatic conditions are compared with that of the total discharge. The definitive leading factor driving the rise in streamflow is the difference in land cover. The amplification effect of the slight increases or decreases in precipitation or temperature on the watershed from land-cover change is dramatic.

The Palenque watershed's response to the simulated hydrological droughts is contrary to the great "megadrought" theory for the cause of Maya abandonment put forth over the last 15 years (Curtis et al. 1996; Gill 2000; Gill et al. 2007; Haug et al. 2003). According to the scenarios presented here, the Maya of Palenque would never be forced to leave their homes in search of water. The worst simulated droughts repeatedly show more than sufficient levels of freshwater for the population.

Palenque's complete absence of water storage features (French 2007; French et al. 2006) is a result of its annual abundance of freshwater. According to the simulations presented here (and the personal experience of the first author), there are several occasions throughout the seasonal meteorological drought (January–April) when the streamflow is so low that retrieving it with a water jar would prove difficult. However, in times of extreme low flow the outlets of the aqueducts easily could have been dammed to allow for partial filling. The stucco applied on the interior walls of the aqueduct would have drastically reduced seepage. The partial damming (1 m) of OT-A1 (the Palace Aqueduct) could have stored over 225,000 liters of freshwater per day and still allowed enough overflow for crop irrigation in the plains to the north of the site. That is more than 10 times the amount of water necessary to sustain the population of Palenque. If the watershed simulations presented in this article are even remotely accurate, it is safe to say that Palenque was not abandoned because of a lack of water, with regard to either drinking, household use, or food production.

The paleoclimate data from lake cores throughout much of the Maya Lowlands suggest that four major droughts occurred at A.D. 760, 810, 860, and 910 (Gill 2000; Gill et al. 2007; Haug et al. 2003).

This fits neatly into the estimated time of abandonment for many Maya centers. One thing we are certain of is that the Maya left these polities and moved on. There is little evidence of mass starvation, large-scale regional warfare, or disease. It is as if the Maya "disappeared." But it seems more likely that they dispersed into the jungles in small extended-family groups and continued to farm as they became disillusioned with their political system, with its dominant kings who failed to keep chaos at bay and guarantee safety.

It might be overzealous to claim that Palenque was not abandoned because of drought. As we have shown in this article, Palenque was likely never without sufficient supplies of water, even during the worst simulated droughts. Yet the reliable supply of freshwater could still have led to its demise. Because each watershed responds differently to extreme events, Palenque may have been the only center in the region to have a supply of freshwater and productive agriculture during a "megadrought." If this were true, then it would have become a prime target for "drought refugees." When prolonged hydrological drought takes place people are forced to leave. These drought refugees in turn place stress on the communities in which they settle. Examples include the migration from the Great Plains to California in 1936 (Worster 1979), the Horn of Africa in the early 1980s (Myers 1997), and eastern Syria in 2009 (Sands 2009).

The situations mentioned above give one pause in claiming that Palenque was not abandoned because of drought. A significant rise in population due to an influx of drought refugees from neighboring centers would have easily caused a great strain on the political system. Archaeologically, one could look for signs of shanty camps on the periphery, evident by tightly spaced housing with no platform, concentrations of pottery made elsewhere, or human remains with evidence of stress. Although difficult to detect archaeologically, this scenario remains plausible.

Modern Implications

The modern city of Palenque and its 60,000 inhabitants rely heavily on water that is diverted and pumped directly from the Palenque watershed. During early summer 2005 the perennial springs that feed the Otolum Stream ran dangerously low. Although there was still water flowing, the intake pipe was not submerged, causing the pump to fail. Because the town of Palenque lacks the resources to monitor streamflow and rainfall at the site, this minor hydrological drought came without warning. Five days and much panic passed prior to a regenerative rainfall. As the population of modern Palenque grows, the stress on environmental resources will increase. One of the long-term goals of this study is to work with the townspeople and city planners of Palenque with the aim of heading off future problems caused by droughts and creating a knowledge base for water systems in the area through technology transfer and education. This will ultimately help the townspeople understand their water supply and its response to wet and dry climate cycles.

This article proposes that the hydroarchaeological method provides a new way of assessing the degree of human impact on an environment through paleohydrological modeling of a watershed. The strategy could be easily applied to archaeological sites where climate and land-use change impact the surrounding watershed. The possibilities for this noninvasive method are many, including detecting periods of stress within a community, estimating population by developing caps based on the availability of water, and understanding settlement patterns, as well as assisting local populations in areas where monetary resources are lacking. As with most new methods, there will be creative applications by other researchers that we never imagined. In this study, however, land-cover change emerged as the major factor in the magnitude of flood and drought response at Palenque.

Acknowledgments. We would like to thank the following people for their involvement in our research: Joshua A. Balcells, Ed Barnhart, Colin Duffy, Jim Eckhardt, Juan Antonio Ferrer, Elisabeth Flores Torruco, Roberto García Moll, Arnoldo González Cruz, Margarita E. González, Kenneth Hirth, Carol Karasik, Alonso Mendez, Julia Miller, George Milner, Alfonso Morales, Moises Morales, Christopher Powell, Merle Greene Robertson, William T. Sanders, Vernon Scarborough, Kirk Straight, Benito Venegas, and David Webster. We would also like to thank the reviewers of this manuscript for their helpful suggestions. In addition, we would like to thank the following institutions for their support: the Departments of Anthropology and Civil and Environmental Engineering at the Pennsylvania State University; the Foundation for the Advancement of Mesoamerican Studies, Inc.; the National Science Foundation; and most important, the Instituto Nacional de Antropología e Historia.

References Cited

Abrams, Elliot M., and David J. Rue
1988 The Causes and Consequences of Deforestation among the Prehistoric Maya. *Human Ecology* 16:377–395.

Andrews, George
1975 *Maya Cities: Placemaking and Urbanization*. University of Oklahoma Press, Norman.

Ashmore, Wendy, Jason Yaeger, and Cynthia Robin
2004 Commoner Sense: Late and Terminal Classic Social Strategies in the Xunantunich Area. In *The Terminal Classic in the Maya Lowlands: Collapse, Transition, and Transformation*, edited by Arthur A. Demarest, Prudence M. Rice, and Don S. Rice, pp. 302–323. University of Press of Colorado, Boulder.

Back, William, and Juan M. Lesser
1981 Chemical Constraints on Ground-Water Management in the Yucatán Peninsula, Mexico. *Journal of Hydrology* 51(1–4):119–130.

Barnhart, Edwin L.
2001 The Palenque Mapping Project: Settlement and Urbanism at an Ancient Maya City. Unpublished Ph.D. dissertation, Department of Anthropology, University of Texas, Austin.

Bishop, Ronald L.
1994 Pre-Columbian Pottery: Research in the Maya Region. In *Archaeometry of Pre-Columbian Sites and Artifacts*, edited by David A. Scott and Peter Meyers, pp. 15–65. Getty Conservation Institute, Los Angeles.

Brenner, Mark, David A. Hodell, Jason H. Curtis, Michael F. Rosenmeier, Flavio S. Anselmetti, and Daniel Ariztegui
2003 Paleoliminological Approaches for Inferring Past Climate Change in the Maya Region: Recent Advances and Methodological Limitations. In *The Lowland Maya Area: Three Millennia at the Human–Wildland Interface*, edited by Arturo Gomez-Pompa, Michael F. Allen, Scott L. Fedick, and Juan Jiménez-Osornio, pp. 45–75. Food Products Press, New York.

Bryson, Reid A., and Katherine M. DeWall
2007 *A Paleoclimatology Workbook: High Resolution, Site-Specific, Macrophysical Climate Modeling*. Mammoth Site, Hot Springs, South Dakota.

Bryson, Robert U., Reid A. Bryson, and Henry Ruter
2006 A Calibrated Radiocarbon Database of Late Quaternary Volcanic Eruptions. Electronic document, http://www.electronic-earth-discuss.net/1/123/2006/eed-1-123-2006-print.pdf, accessed January 5, 2012.

Curtis, Jason, David A. Hodell, and Mark Brenner
1996 Climate Variability on the Yucatán Peninsula (Mexico) During the Past 3500 Years, and Implications for Maya Cultural Evolution. *Quaternary Research* 46:37–47.

Dahlin, Bruce H.
1983 Climate and Prehistory on the Yucatán Peninsula. *Climatic Change* 5(3):245–263.

Dahlin, Bruce H., Robin Quizar, and Andrea Dahlin
1987 Linguistic Divergence and the Collapse of Late Preclassic Maya Civilization. *American Antiquity* 52(2):367–382.

Deevey, Edward S.
1978 Holocene Forests and Maya Disturbance Near Quexil Lake, Peten, Guatemala. *Polish Archives of Hydrobiology* 25(1/2):117–129.

Deevey, Edward S., Don S. Rice, Prudence M. Rice, H. H. Vaughan, Mark Brenner, and M. S. Flannery
1979 Mayan Urbanism: Impact on a Tropical Karst Environment. *Science* 206:298–306.

Demarest, Arthur A., Prudence M. Rice, and Don S. Rice (editors)
2004 *The Terminal Classic in the Maya Lowlands: Collapse, Transition, and Transformation*. University of Colorado Press, Boulder.

Demeritt, David
1991 Agriculture, Climate, and Cultural Adaptation in the Prehistoric Northeast. *Archaeology of Eastern North America* 19:183–202.

Denevan, William M., and B. L. Turner, II
1985 Calculating Population and Agricultural Intensity Levels from Field Remains: A Comment on Coe's Review of "Maya Subsistence." *American Antiquity* 50:166–169.

Dunning, Nicholas, Timothy Beach, Pat Farrell, and Sheryl Luzzadder-Beach
1998 Prehispanic Agrosystems and Adaptive Regions in the Maya Lowlands. *Culture and Agriculture* 20(2/3):87–101.

Fedick, Scott L.
1996 *The Managed Mosaic: Ancient Maya Agriculture and Resource Use*. University of Utah Press, Salt Lake City.

Ferrusquia-Villafranca, Ismael
1993 Geology of Mexico: A Synopsis. In *Biological Diversity of Mexico: Origins and Distribution*, edited by Antonio Lot, Robert Bye, and Thennilapuram P. Ramamoorthy, pp. 3–107. Oxford University Press, New York.

Ferziger, Joel H., and Milovan Peric
2002 *Computational Methods for Fluid Dynamics*. Springer, New York.

Flannery, Kent V.
1978 *Maya Subsistence: Studies in Memory of Dennis E. Puleston*. Academic Press, New York.

Folan, William J., Joel Gunn, Jack D. Eaton, and Robert W. Patch
1983 Paleoclimatological Patterning in Southern Mesoamerica. *Journal of Field Archaeology* 10:453–468.

Food and Agriculture Organizations of the United Nations
2002 Maize. Electronic document, http://www.fao.org/landandwater/aglw/cropwater/maize.stm#requirements, accessed January 5, 2012.

Frappier, Amy, Dork Sahagian, Luis A. González, and Scott J. Carpenter
2002 El Niño Events Recorded by Stalagmite Carbon Isotopes. *Science* 298(5593):565.

French, Kirk D.
2007 Creating Space Through Water Management at the Classic Maya Site of Palenque, Chiapas, Mexico. In *Palenque: Recent Investigations at the Classic Maya Center*, edited by Damien Marken, pp. 123–132. AltaMira Press, Lanham, Maryland.
2009 The Hydroarchaeological Approach: Understanding the Ancient Maya Impact on the Palenque Watershed. Unpublished Ph.D. dissertation, Department of Anthropology, Pennsylvania State University, University Park.

French, Kirk D., and Christopher J. Duffy
2010 Prehispanic Water Pressure: A New World First. *Journal of Archaeological Science* 37(5):1027–1032.

French, Kirk D., David Stuart, and Alfonso Morales
2006 Archaeological and Epigraphic Evidence for Water Management and Ritual at Palenque. In *Precolumbian Water Management: Ideology, Ritual and Power*, edited by Barbara Fash and Lisa Lucero, pp. 144–152. University of Arizona Press, Tucson.

Gill, Richard B.
2000 *The Great Maya Droughts: Water, Life, and Death*. University of New Mexico Press, Albuquerque.

Gill, Richard B., Paul A. Mayewski, Johan Nyberg, Gerald H. Haug, and Larry C. Peterson
2007 Drought and the Maya Collapse. *Ancient Mesoamerica* 18:283–302.

Gray, Stephen T., Julio L. Betancourt, Stephen T. Jackson, and Robert G. Eddy
2006 Role of Multidecadal Climate Variability in a Range Extension of Pinyon Pine. *Ecology* 87:1124–1130.
Gunn, Joel D., and Richard E. W. Adams
1981 Climatic-Change, Culture, and Civilization in North-America. *World Archaeology* 13(1):87–100.
Gunn, Joel D., and William J. Folan
2000 Three Rivers: Subregional Variations in Earth System Impacts in the Southwestern Maya Lowlands (Candelaria, Usumacinta, and Champoton Watersheds). In *The Way the Wind Blows: Climate, History, and Human Action*, edited by Roderick McIntosh, Joseph A. Tainter, and Susan Keech McIntosh, pp. 263–270. Columbia University Press, New York.
Gunn, Joel D., William J. Folan, and Hubert R. Robichaux
1995 A Landscape Analysis of the Candelaria Watershed in Mexico: Insights into Paleoclimates Affecting Upland Horticulture in the Southern Yucatán Peninsula Semi-Karst. *Geoarchaeology* 10:3–42.
Hansen, Richard D., Steven Bozarth, John Jacob, David Wahl, and Thomas Schreiner
2002 Climatic and Environmental Variability in the Rise of Maya Civilization: A Preliminary Perspective from Northern Petén. *Ancient Mesoamerica* 13:273–295.
Harrison, Peter D., and Billie L. Turner, II
1978 *Pre-Hispanic Maya Agriculture*. University of New Mexico Press, Albuquerque.
Haug, Gerald H., Detlef Günther, Larry C. Peterson, Daniel M. Sigman, Konrad A. Hughen, and Beat Aeschlimann
2003 Climate and the Collapse of Maya Civilization. *Science* 299(5613):1731–1735.
Hisdal, Hege, Lena M. Tallaksen, Bente Clausen, Elizabeth Peters, and A. Gustard
2004 Hydrological Drought Characteristics. In *Developments in Hydrological Drought: Processes and Estimation Methods for Streamflow and Groundwater*, edited by Lena M. Tallaksen and Henny A. J. Van Lanen, pp. 139–198. Developments in Water Science No. 48. Elsevier, Oxford.
Hodell, David A., Mark Brenner, and Jason H. Curtis
2007 Climate and Cultural History of the Northeastern Yucatán Peninsula, Quintana Roo, Mexico. *Climatic Change* 83:215–240.
Hodell, David A., Mark Brenner, Jason H. Curtis, and Thomas P. Guilderson
2001 Solar Forcing of Drought Frequency in the Maya Lowlands. *Science* 292:1367–1370.
Hodell, David A., Mark Brenner, Jason H. Curtis, Roger Medina-Gonzalez, Enrique Ildefonso-Chan Can, Alma Albornaz-Pat, and Thomas P. Guilderson
2005 Climate Change on the Yucatán Peninsula During the Little Ice Age. *Quaternary Research* 63:109–121.
Hodell, David A., Jason H. Curtis, and Mark Brenner
1995 Possible Role of Climate in the Collapse of the Classic Maya Civilization. *Nature* 375:391–394.
Holdridge, Leslie R., W. C. Grenke, W. H. Hatheway, T. Liang, and J. A. Tosi, Jr.
1971 *Forest Environments in Tropical Life Zones: A Pilot Study*. Pergamon Press, Oxford.
Intergovernmental Panel on Climate Change
1996 *Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by John T. Houghton, Gylvan M. Filho, Arie Kattenberg, and Kathy Maskell. Cambridge University Press, Cambridge.
Jones, Peter G., and Philip K. Thornton
2003 The Potential Impacts of Climate Change on Maize Production in Africa and Latin America in 2055. *Global Environmental Change* 13(1):51–59.
LeCount, Lisa J., Jason Yaeger, Richard M. Leventhal, and Wendy Ashmore
2002 Dating the Rise and Fall of Kunantunich, Belize. *Ancient Mesoamerica* 13:41–63.
Leyden, Barbara W., Mark Brenner, and Bruce H. Dahlin
1998 Cultural and Climatic History of Coba, a Lowland Maya City in Quintana Roo, Mexico. *Quaternary Research* 49:111–122.
Liendo, Rodrigo
1999 *The Organization of Agricultural Production at a Maya Center. The Settlement Patterns in the Palenque Region, Chiapas, Mexico*. Instituto Nacional de Antropología e Historia, Mexico City.
Linsley, Ray K., Max Adam Kohler, and Joseph L. H. Paulhus
1982 *Hydrology for Engineers*. 3rd ed. McGraw-Hill, New York.
Littman, Edwin R.
1959 Ancient Mesoamerican Mortars, Plasters, and Stuccos: Palenque, Chiapas. *American Antiquity* 25:264–266.
Lucero, Lisa J.
2002 The Collapse of the Classic Maya: A Case for the Role of Water Control. *American Anthropologist* 104:814–826.
2006 *Water and Ritual: The Rise and Fall of Classic Maya Rulers*. University of Texas Press, Austin.
Lucero, Lisa J., Joel D. Gunn, and Vernon Scarborough
2011 Climate Change and Classic Maya Water Management. *Water* 3:479–494.
Magana, Victor, Jorge A. Amador, and Socorro Medina
1999 The Midsummer Drought Over Mexico and Central America. *Journal of Climate* 12(6):1577–1588.
Matthews, William J., and Edie March-Matthews
2003 Effects of Drought on Fish Across Axes of Space, Time and Ecological Complexity. *Freshwater Biology* 48:1232–1253.
Medina-Elizalde, Martín, Stephen Burns, David W. Lea, Yemane Asmerom, Lucien von Gunten, Vicotor Polyak, Mathias Vuille, and Ambarish Karmalkar
2010 High Resolution Stalagmite Climate Record from the Yucatán Peninsula Spanning the Maya Terminal Classic Period. *Earth and Planetary Science Letters* 298:255–262.
Myers, Norman
1997 Environmental Refugees. *Population Environment* 19(2):167–182.
National Land Cover Database
2001 National Land Cover Database 2001, Multi-Resolution Land Characteristics Consortium. Electronic document, http://www.mrlc.gov/nlcd.php, accessed June 2009.
National Research Council
2004 *Confronting the Nation's Water Problems: The Role of Research*. National Academy Press, Washington, D.C.
2005 *Network Science*. National Academy Press, Washington, D.C.
2007 *Colorado River Basin Water Management: Evaluating and Adjusting to Hydroclimatic Variability*. National Academies Press, Washington, D.C.
2008 *Integrating Multiscale Observations of U.S. Waters*. National Academy Press, Washington, D.C.

Nencetti, A., Franco Tassi, Orlando Vaselli, Jose Luis Macías, Gabriella Magro, Bruno Capaccioni, Angelo Minissale, and Juan C. Mora
2005 Chemical and Isotopic Study of Thermal Springs and Gas Discharges from Sierra de Chiapas, Mexico. *Geofísica Internacional* 44:39–48.
Palmer, Wayne C.
1965 *Meteorological Drought*. Research Paper No. 5. Office of Climatology, U.S. Weather Bureau, Washington, D.C.
Pohl, Mary
1985 *Prehistoric Lowland Maya Environment and Subsistence Economy*. Harvard University Press Peabody Museum Papers, Vol. 77. Cambridge.
Pohl, Mary D., Kevin O. Pope, John G. Jones, John S. Jacob, Dolores R. Piperno, Susan deFrance, David L. Lentz, John A. Gifford, Marie E. Danforth, and J. Kathryn Josserand
1996 Early Agriculture in the Maya Lowlands. *Latin American Antiquity* 7:355–372.
Qu, Yizhong, and Christopher J. Duffy
2007 An Integrated Hydrologic Model for Multi-Process Simulation. *Water Resource Research* 43:1–18.
Rands, Robert L.
1974 The Ceramic Sequence at Palenque, Chiapas. In *Mesoamerican Archaeology: New Approaches*, edited by Norman Hammond, pp. 51–75. Duckworth, London; and University of Pittsburgh Press, Pittsburgh.
Rands, Robert L., and Ronald L. Bishop
1980 Resource Procurement Zones and Patterns of Ceramic Exchange in the Palenque Region, Mexico. In *Models and Methods in Regional Exchange*, edited by Robert Fry, pp. 19–46. Society for American Archaeology Papers 1. Washington, D.C.
Reed, David
1998 Ancient Maya Diet at Copán. Unpublished Ph.D. dissertation, Department of Anthropology, Pennsylvania State University, University Park.
Ruter, Anthony, Jennifer Arzt, Steven Vavrus, Reid A. Bryson, and John E. Kutzbach
2004 Climate and Environment of the Subtropical and Tropical Americas (NH) in the Mid-Holocene: Comparison of Observations with Climate Model Simulations. *Quaternary Science Reviews* 23:663–679.
Salas, Jose D.
1993 Analysis and Modeling of Hydrologic Time Series. In *Handbook of Hydrology*, edited by David R. Maidment, 19.1–19.63. McGraw-Hill, New York.
Sanders, William T., and David Webster
1988 The Mesoamerican Urban Tradition. *American Anthropologist* 90:521–546.
Sands, Phil
2009 Refugees Because the Rains Never Came. *The National*, September 3.
Scarborough, Vernon L.
2003 *The Flow of Power: Ancient Water Systems and Landscapes*. School of American Research, Santa Fe.
2008 Rate and Process of Societal Change in Semitropical Settings: The Ancient Maya and the Living Balinese. *Quaternary International* 184:24–40.
Schreiner, Thomas Paul
2002 Traditional Maya Lime Production: Environmental and Cultural Implications of a Native American Technology. Unpublished Ph.D. dissertation, Department of Architecture, University of California, Berkeley.
Sedlock, Richard L., Fernando Ortega-Gutierrez, and Robert C. Speed
1993 *Technostratigraphic Terranes and Tectonic Evolution in Mexico*. Special Paper 278. Geological Society of America, Boulder.
Siemens, Alfred H., and Dennis E. Puleston
1972 Ridged Fields and Associated Features in Southern Campeche: New Perspectives on the Lowland Maya. *American Antiquity* 37:228–239.
Stahle, David W., Edward R. Cook, Jose Villanueva Diaz, Falko K. Fye, Dorian J. Burnette, R. Daniel Griffin, Rodolfo Acuna Soto, Richard Seager, and Richard R. Heim, Jr.
2009 Early 21st Century Drought in Mexico. *Eos* 90(11):89–90.
Stewart, Iris T., Daniel R. Cayan, and Michael D. Dettinger
2004 Changes in Snowmelt Runoff Timing in Western North America Under a "Business as Usual" Climate Change Scenario. *Climate Change* 62:217–232.
Straight, Kirk D.
2007 Construction, Proportion, and Form at Temple XIX, Palenque. In *Palenque: Recent Investigations at the Classic Maya Center*, edited by Damien Marken, pp. 175–204. AltaMira Press, Lanham, Maryland.
Tallaksen, Lena M., and Henny A. J. van Lanen (editors)
2004 *Hydrological Drought: Processes and Estimation Methods for Streamflow and Groundwater*. Elsevier, Oxford.
Tedlock, Dennis (translator)
1985 *Popol Vuh: The Definitive Edition of the Mayan Book of the Dawn of Life and the Glories of God and Kings*. Simon and Schuster, New York.
Trenberth, Kevin E., and Bette L. Otto-Bliesner
2003 Toward Integrated Reconstruction of Past Climate. *Science* 300:589–591.
Turner, Billie L., II, and Peter D. Harrison
1983 *Pulltrouser Swamp: Ancient Maya Habitat, Agriculture, and Settlement in Northern Belize*. University of Texas Press, Austin.
Vaughn, B. H., C. F. Raymond, L. A. Rasmussen, D. S. Miller, C. A. Michaelson, M. F. Meier, R. M. Krimmel, A. G. Fountain, W. W. Dunlap, and C. S. Brown
1985 Short-Term Velocity Measurements at Columbia Glacier, Alaska: August–September 1984. *U.S. Geological Survey. Open File Report* 29:85–487.
Villanueva-Diaz, Jose, David Stahle, Brian Luckman, Julian Cerano-Paredes, Mathew Therrell, Malcolm Cleaveland, and Eladio Cornejo-Oviedo
2007 Winter–Spring Precipitation Reconstruction from Tree Rings for Northeast Mexico. *Climatic Change* 83:117–131.
Webster, David
2002 *The Fall of the Ancient Maya: Solving the Mystery of the Maya Collapse*. Thames and Hudson, New York.
Webster, James W., George A. Brook, L. Bruce Railsback, Hai Cheng, R. Lawrence Edwards, Clark Alexander, and Philip P. Reeder
2007 Stalagmite Evidence from Belize Indicating Significant Droughts at the Time of Preclassic Abandonment, the Maya Hiatus, and the Classic Maya Collapse. *Palaeogeography, Palaeoclimatology, Palaeoecology* 250(1–4):1–17.
Westerling, Anthony L., Hugo G. Hidalgo, Daniel R. Cayan, and Thomas W. Swetnam
2006 Warming and Earlier Spring Increase Western US Forest Wildfire Activity. *Science* 313:940–943.

Whitmore, Thomas J., Mark Brenner, Jason Curtis, Bruce H. Dahlin, and Barbara Leyden
1996 Holocene Climate and Human Influences on Lakes of the Yucatán Peninsula, Mexico: An Interdisciplinary Paleolimnological Approach. *The Holocene* 6:273–287.

Worster, Donald
1979 *Dust Bowl: The Southern Plains in the 1930's*. Oxford University Press, New York.

Yaeger, Jason, and David A. Hodell
2008 The Collapse of Maya Civilization: Assessing the Interaction of Culture, Climate, and Environment. In *El Niño: Catastrophism and Culture Change in Ancient America*, edited by Daniel H. Sandweiss and Jeffrey Quilter, pp. 187–242. Dumbarton Oaks, Washington, D.C.

Zhang, Pingzhong, Hai Cheng, R. Lawrence Edwards, Fahu Chen, Yongjin Wang, Xunlin Yang, Jian Liu, Ming Tan, Xianfeng Wang, Jinghua Liu, Chunlei An, Zhibo Dai, Jing Zhou, Dexhong Zhang, Jihong Jia, Liya Jin, and Katleen R. Johnson
2008 A Test of Climate, Sun, and Culture Relationships from an 1810-Year Chinese Cave Record. *Science* 322(5903):940–942.

Note

1. All equations and analyses are available from the lead author.

Submitted: July 7, 2010; Revised: October 24, 2011; Accepted: January 18, 2012.