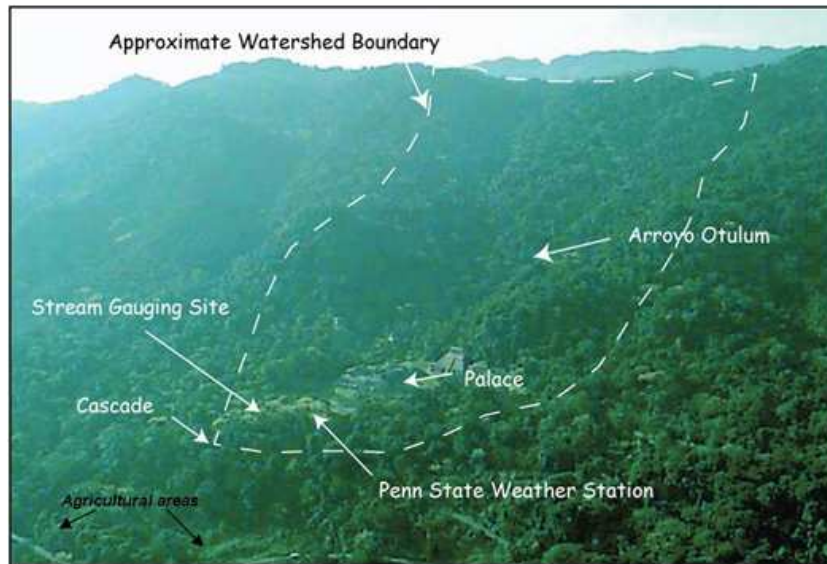


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## **Palenque Hydro-Archaeology Project, 2006-2007 Season Report**



**Research Year:** 2006-2007

**Culture:** Maya

**Chronology:** Classic

**Location:** Chiapas, México

**Site:** Palenque

### **Table of Contents**

[Abstract](#)

[Resumen](#)

[Introduction](#)

[Site Description](#)

[Background](#)

[2006 and 2007 Field Seasons](#)

[Future Work](#)

[Acknowledgements](#)

[List of Figures](#)

[Sources Cited](#)

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## **Abstract**

The cause for the rapid abandonment of the Maya Lowlands has been debated for decades. Theories of warfare, famine, disease, overpopulation, environmental degradation, and most recently drought, have all been presented as either contributing factors or sole causes for the Classic Maya collapse. In A.D 799 Palenque became one of the first cities to collapse in the Maya Lowlands. Palenque, a UNESCO World heritage site located in México's southernmost state of Chiapas, is a prime example of a Maya city of the Classic period. The city was at its height between A.D. 500 and 700, when its influence extended throughout the Usumacinta River Basin, the largest in México. Most great Maya centers, such as Tikal and Caracol, are located in environments that generate a heavy dependency on seasonal rainfall and water storage for human consumption and agricultural practices. Palenque, by contrast, is unique for its water-saturated landscape, where perennial springs, and streams sustain flow through the annual dry season. While the Maya of most other urban centers were concerned with storing water, the Palenqueños were devising methods of managing an abundance of it. If we define meteorological drought as the degree and duration of dryness (water vapor and precipitation) in comparison to normal atmospheric conditions, it is hydrological drought, defined here as extended shortfalls of watershed springflow or runoff, that may explain the different water management activities that took place at Palenque versus those at other Maya sites. It is the difference in watershed hydrology and land use that makes Palenque distinctive and forms the basis for our hydrology-archaeology collaboration.

## **Resumen**

La causa del rápido abandono de las tierras bajas en el mundo maya ha sido debatida durante decenios. Las teorías sobre guerras, hambruna, enfermedades, sobrepoblación, degradación ambiental y, en fechas recientes, sequías, han estado presentes bien sea como factores contribuyentes o como causa exclusiva del colapso de los mayas de la época clásica. En 799 antes de nuestra era, Palenque se convirtió en una de las primeras ciudades en caer en las tierras bajas del mundo maya. Palenque, catalogada como Patrimonio de la Humanidad por la UNESCO, se encuentra localizada en el extremo sur del estado de Chiapas, en México. Es ejemplo por excelencia de una ciudad maya del periodo clásico. La ciudad alcanzó su auge entre 500 y 700 antes de Cristo; durante esa época, su influencia se extendió a lo largo del río Usumacinta, el más grande de México. La mayoría de los grandes centros mayas, como Tikal y Caracol, se localizan en entornos que generan una fuerte dependencia de las lluvias de temporal y del almacenamiento de agua para consumo humano y para la práctica agrícola. En contraste, Palenque es único por su entorno saturado de agua, donde los manantiales perennes y los arroyos mantienen su flujo durante la temporada anual de secas. Así, mientras que los mayas de la mayoría de otros centros urbanos se preocupaban por almacenar agua, los Palenqueños

desarrollaban métodos para administrar la abundancia del líquido vital. Si definimos la sequía meteorológica como el grado y duración de la sequedad (evaporación y precipitación del agua) en comparación con las condiciones atmosféricas normales, es la sequía hidrológica (definida aquí como ausencia prolongada de agua en ríos, arroyos o residuos) la que pudiera explicar las diferentes actividades destinadas a la administración de agua, a diferencia de otros sitios mayas. Y es la diferencia en la hidrología de residuos y en el manejo del uso de la tierra lo que da a Palenque su carácter distintivo y finca las bases de nuestra colaboración hidrológico-arqueológica.



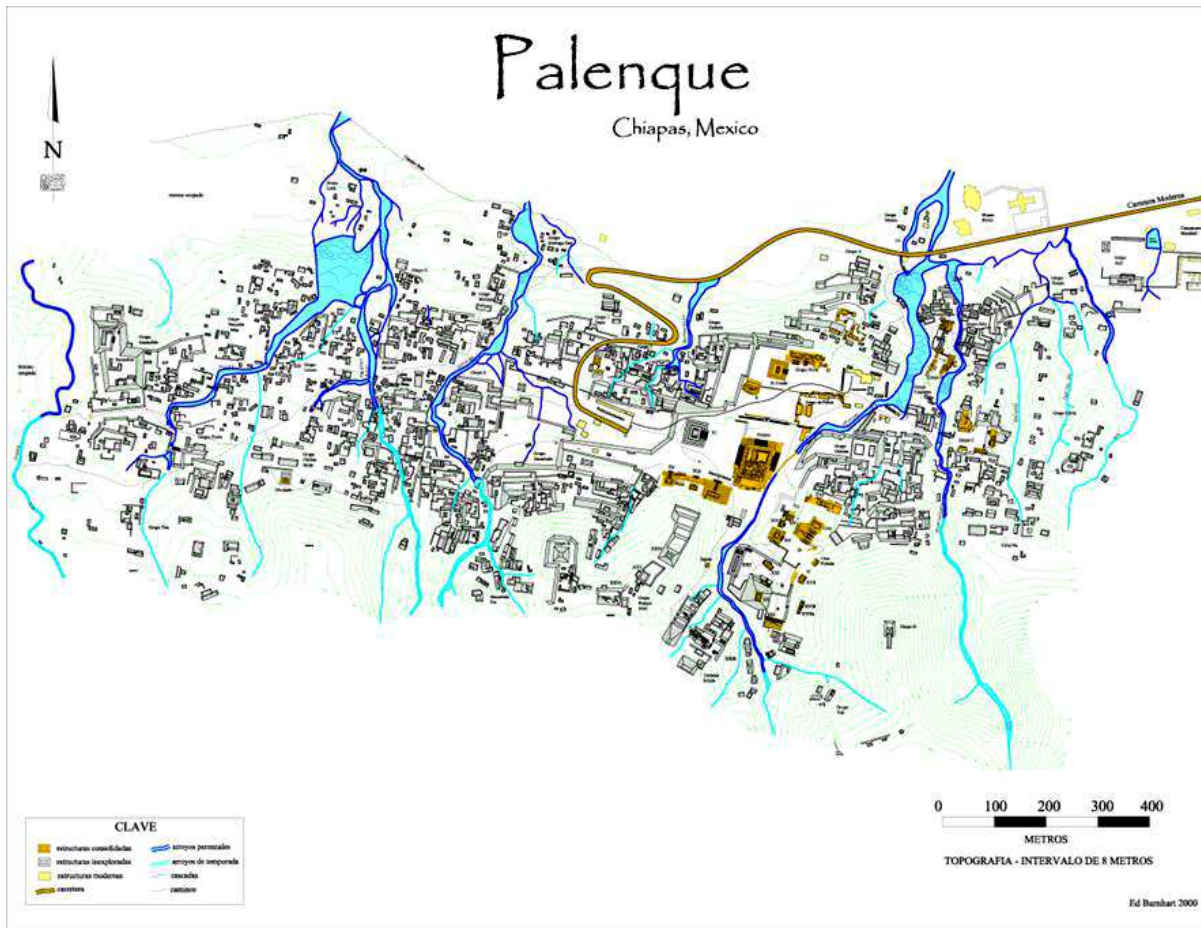
**Figure 1. Location map of the Maya region.**

## **Introduction**

The cause for the rapid abandonment of the Maya Lowlands has been debated for decades. Theories of warfare, famine, disease, overpopulation, environmental degradation, and most recently drought (Gill 2000) have all been presented as either contributing factors or sole causes for the Classic Maya collapse. In A.D. 799 Palenque became one of the first cities to collapse in the Maya Lowlands. Palenque, a UNESCO World heritage site located in México's southernmost state of Chiapas ([Figure 1](#)), is a prime example of a Maya city of the Classic

period. The city was at its height between A.D. 500 and 700, when its influence extended throughout the Usumacinta River Basin, the largest in México. Most great Maya centers, such as Tikal and Caracol ([Figure 1](#)), are located in environments that generate a heavy dependency on seasonal rainfall and water storage for human consumption and agricultural practices (Scarborough and Gallopín 1991). Palenque, by contrast, is unique for its water-saturated landscape, with perennial springs and streams sustaining flow through the annual dry season. While the Maya of most other urban centers were concerned with storing water, the Palenqueños were devising methods of managing an abundance of it (French 2007). If we define meteorological drought as the degree and duration of dryness (water vapor and precipitation) in comparison to normal atmospheric conditions, it is hydrological drought, defined here as extended shortfalls of watershed springflow or runoff, that may explain the different water management activities that took place at Palenque versus those at other Maya sites. It is the difference in watershed hydrology and land use that makes Palenque distinctive and forms the basis for this hydrology-archaeology collaboration.

The problem of identifying sources of water and mechanisms of hydrologic response in watersheds is a function of the atmospheric inputs/outputs, the “pathways” of water, and the physical, chemical, biological, and human processes along the path. The method of hydrograph separation into flow components (Fritz et al. 1976, Sklash et al. 1976, and Rice and Hornberger 1998), and the notion of pathways of water fluxes are conceptually related, but no complete method presently exists capable of resolving the dynamic routes and rates that water takes on the journey from atmosphere to stream. The issues of regolith depth, soil, vegetation properties, the temporal variations/extremes of climate forcing, and the role of human modification (e.g. civic construction, deforestation, agriculture) are central to this research effort. The problem of evaluating watershed response under extreme climate conditions in ungauged tropical watersheds represents a unique scientific and practical challenge, and serves as the focus of this research effort. Quantification of the human-hydroclimatic response to hydroclimatic extremes through simulation of the terrestrial-climate states is the strategy of this research.



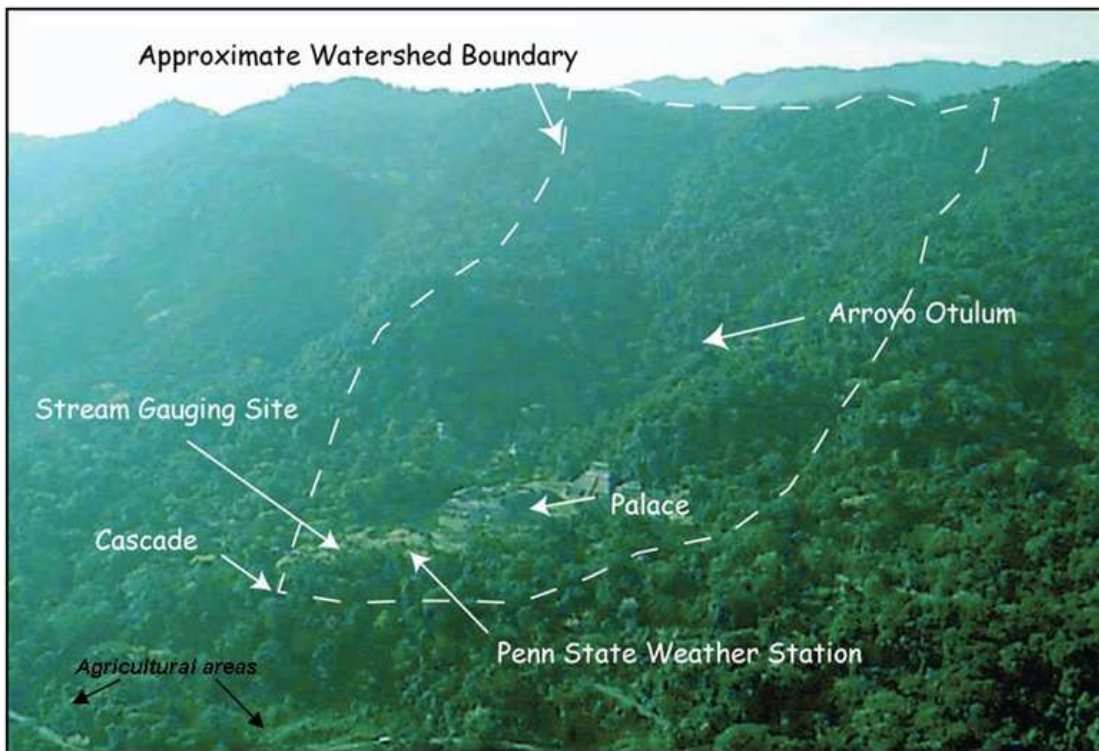
**Figure 2. The Palenque Archeological Map. Palenque’s urban settlement density is the second highest ever recorded for a Classic Maya city. There are 673 stone structures per square kilometer (Barnhart 2001).**

### Site Description

The study site ([Figure 2](#) and [Figure 3](#)) is located along the northern edge of uplifted and folded sedimentary rocks of the Mayan tectonic block in the State of Chiapas. To the south lies the Sierra de Chiapas, a folded and faulted chain of Mesozoic and Tertiary sedimentary rocks with fold axes trending north-west which generally plunge north-westwards beneath the Pliocene and younger sediments of the coastal Tabasco plain and the Gulf of México. During the Cretaceous Period, from 144 to 65 million years ago, most of Chiapas was covered by an ocean. Marine sedimentation from this period is present throughout much of the state. The shallow sea withdrew from the region during the late cretaceous or early tertiary period, approximately at the same time that uplift in the area began (Ferrusquia-Villafranca 1993). The marine sedimentation led to the formation of the Sierra Madre de Chiapas Limestone platform (Morán Zenteno 1994). The region’s geology is further complicated by the extensive

folding and faulting of Mesozoic and Tertiary sedimentary rock layers into a “Northern folded Ranges and Plateaus” region (Ferrusquia-Villafranca 1993, Nencetti et al. 2005, Sedlock et al. 1993). Our study site is located on a gently dipping limestone escarpment overlooking the Plains of Tabasco to the north.

Precipitation in the Maya Lowlands is seasonal, with the lowest rainfall from December to May when it ranges from 90-150 mm/mos, and a rainy season June through October with rainfall in the range of 200-500 mm/mos. September is the wettest month and April the driest. There is a gradient of total annual rainfall from ~1500 mm/yr at the Gulf of México to the north, to nearly 5000 mm/yr in the foothills of the Sierra de Chiapas at Palenque. According to Magana et al. (1999) the annual cycle of precipitation over this part of México exhibits a bimodal distribution with maxima during June and September-October and a relative minimum during July and August, known as the midsummer drought (MSD). The MSD is associated with fluctuations in the intensity and location of the eastern Pacific ITCZ (intertropical convergence zone). Tropical cyclones are a source of heavy precipitation in summer and fall. Convective precipitation and orographic influence are also significant with increasing distance south of the Gulf of México. The average temperature at Palenque ranges from 22.9 °C in Dec-Jan to 28.8 °C in May. The rivers in the region are Usamacinto and Grijalva, which discharge > 30% of the total freshwater flow of México.



**Figure 3. The Palenque watershed showing the Palenque archaeological site, the PSU weather station and proposed stream gauge location.**

## Background

Palenque ([Figure 2](#) and [Figure 3](#)), one of the best known Classic Maya centers, has what is arguably the most unique and intricate system of water management known anywhere in the Maya Lowlands. By the end of the 7<sup>th</sup> century A.D. Palenque had mushroomed into a dense community of 1481 structures (Barnhart 2001)—residences, palaces, and temples—concentrated on a small piece of relatively flat land in an otherwise steep escarpment in Chiapas, México. Years of archaeological research, including intensive mapping since 1997 ([Figure 2](#)), indicated that this settlement had modest beginnings about A.D. 100, and then grew explosively in the 6<sup>th</sup> and 7<sup>th</sup> centuries under a series of powerful rulers. This process of “urban” growth occurred in an environmental setting very different from those found elsewhere in the Maya Lowlands. Large Maya centers typically were rather unconstrained by topographic limits to their development. Buildings of all sorts tend to take advantage of areas of well-drained high relief; so many centers have a kind of dispersed or rambling pattern. The inhabitants of Palenque faced the problem of adapting their growing settlement to a small environment (ca. 2.2 km<sup>2</sup>) and one which, unusually, had an excess of springs and streams. Palenqueños were challenged to increasingly modify their landscape to both take advantage of the hydrological resources, and accommodate their growing city. It was this challenge that resulted in a set of complex engineering adaptations unlike those found anywhere else in the Maya Lowlands, or indeed Mesoamerica. The simultaneous simulation of climate and human activity is essential to understanding their hydrological impact on the watershed.

## 2006 and 2007 Field Seasons

The 2006 field season was composed of three 10-day trips to Palenque in the months of March, May, and November. In May, I was accompanied by Dr. Christopher Duffy, a professor of hydrology in the Civil Engineering Department at Penn State. Aside from downloading meteorological data, the work mainly entailed performing routine maintenance and repairs on the weather station that we installed in July 2005, thanks in part to funding provided by FAMSI. The team also tested the feasibility of measuring stream flow using a handheld SonTek FlowTracker ([Figure 4](#)). The test was a response to the loss of our stream sensors that were installed in 2005.

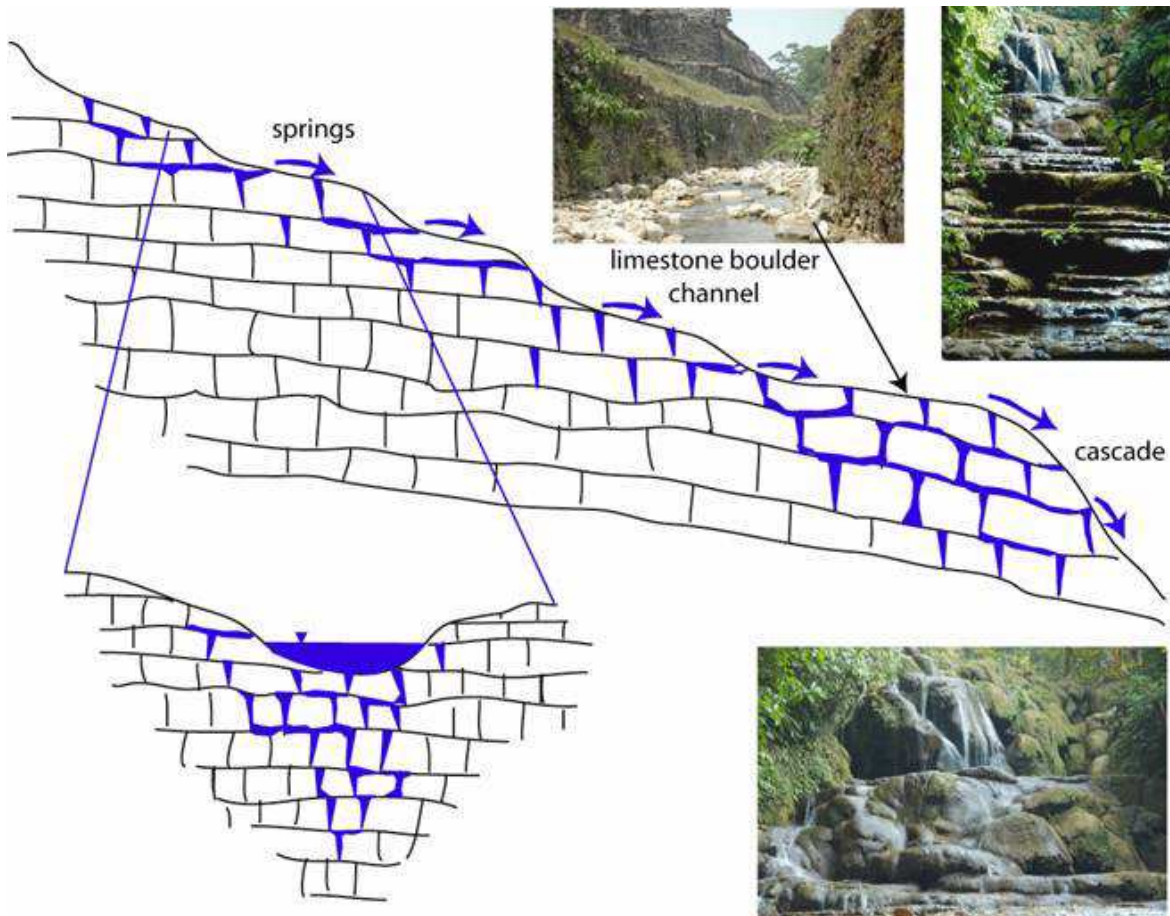


**Figure 4. Dr. Christopher Duffy and Kirk French gauge the Picota Stream with the SonTek FlowTracker.**

The 2007 field season was composed of two 10-day trips in March and October and one three-week trip in July. In January of 2008 I spent four weeks in Palenque, and was again accompanied by Dr. Duffy. In addition to the tasks performed in 2006 (downloading data, routine maintenance and repairs) we hiked the many waterways in Palenque in order to gain a better understanding of the site's geomorphology. We also scouted for new and safer locations for the stream sensors.

The two field seasons yielded almost 1 million meteorological data points and still counting. This data is essential to the next phase of the Palenque Hydro-Archaeology Project (PHAP). Over the last two years Dr. Duffy and I have expanded PHAP's model to take into account the effects of large scale agriculture, deforestation, and climate variability. The generous funding provided by FAMSI has enabled the growth of our hydrology/archaeology collaboration. We have recently submitted a proposal to the National Science Foundation for funding through 2011.

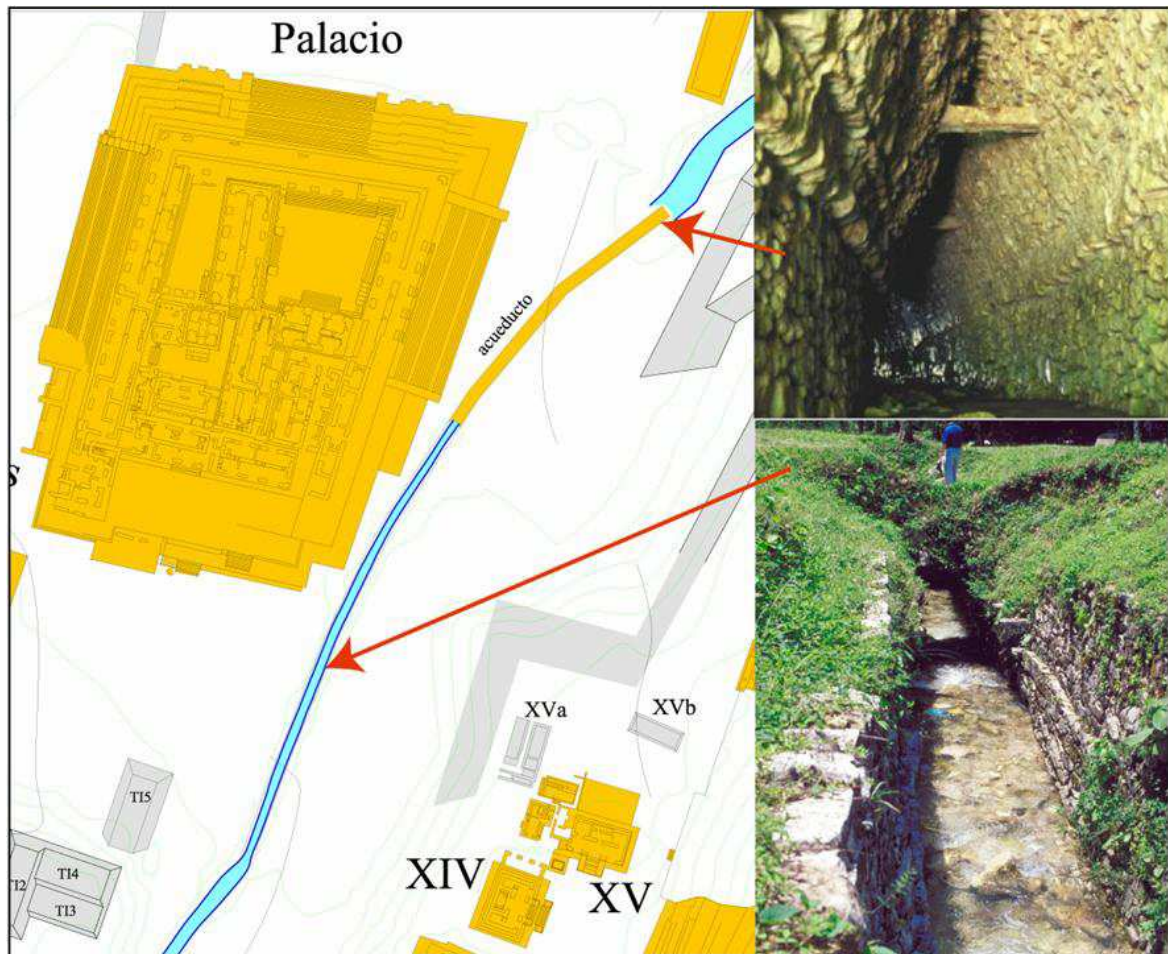




**Figure 5. Hydrologic conceptual model for the Cretaceous limestone watershed at Palenque showing the increased dissolution permeability (karst), especially below the stream channel bed, a boulder channel (top photo) crossing the ruins, and two photos within the groundwater discharge zone showing the pool and ledge cascade and accreting tufa deposits.**

If successful, the approach developed in this study will revolutionize how we understand the water resources of ungauged watersheds in tropical regions by allowing a distributed calculation of the relative “age” and “residence time” of waters contributing at all locations within the watershed storage volume. The hydrodynamic model will be calibrated using geophysics, soil surveys, synoptic and time-intensive isotope sampling. Once the hydrodynamic model is initially “calibrated” then the simulated concept of “relative age” of waters (surface and groundwater) will provide a further means to test the model performance using the observed patterns of stable isotope ratios relative to the seasonal-interannual “signal”. Although we are not able to install piezometers except near the stream itself, the hydrologic conceptual model (HCM) of surface and ground-water seems to be similar to that of Schellekens et al. (2004), where the most active

flow exchange is under the channel with dissolution features and karst development, as illustrated in our conceptual model ([Figure 5](#)). The geophysical survey will be used to examine the plausibility of our HCM at the site. The model, once calibrated using field investigations and stable isotopes, will be applied to evaluating the impact of landuse changes through time at Palenque, the response of flooding from tropical storms, and the impact of long-term drought on the water resources for human consumption and agriculture. The installed stream gauge will also be used for continued testing-improvement in the model performance. From the archaeological perspective, the proposed model developed under modern climate, soil, topographic, and vegetative conditions, will allow us to develop plausible quantitative scenarios for the watershed's response to long term meteorologic drought (Jones and Thornton 2000, and Hunt and Elliot 2005) and its effect on springflow and subsequent agricultural production. For example, did the absence of water storage facilities leave the city vulnerable to long term drought? Plausible scenarios of urban and civic construction will be developed to compare the time scales of human activity with the time scales of hydrologic response. The impact of this research will have ramifications beyond the science proposed. The aerial survey with the bare ground digital terrain product and vegetation height model produced by NCALM (Luzum et al. 2006) for this study will be invaluable to the archaeological community within the unexplored/unsurveyed rain forest in the upper watershed. Simple water balances will be useful to local water management in the fast-growing community and farms. We are working with the Palenque museum on-site to develop a kiosk with real-time weather and streamflow conditions for the public. It is our hope that Palenque will become a long-term experimental observatory for tropical watershed science and hydro-archaeological research.



**Figure 6. The Otulum and the Palace at the Palenque archaeological site. The photos show the aqueduct entrance (upper) and exit near the Palace.**

### **Future Work**

We plan to implement a field experiment using stable isotopes, geophysical surveys, soil, and hydrometric measurements for the purpose of implementing an integrated hydrologic model for the Palenque watershed. Our intention in this proposal is to develop a quantitative interpretation of watershed response to climatic and human change in the ungauged Otulum watershed at Palenque, using a new instrument for rapid and inexpensive stable isotope measurements  $^{18}O/^{16}O$  and  $D/H$ , a newly developed code for integrated watershed modeling (PIHM: The Penn State Integrated Hydrologic Model) (Qu and Duffy 2007), and standard geophysical and soil surveys. The research is focused on the hydraulic and hydrologic urban architecture at one of Mesoamerica's most elaborate and best preserved prehispanic water management systems and the surrounding upland watershed. The research will examine the relation of water management features (Figure 6) constructed by the

Maya on present-day watershed response, including the effects of modern climate patterns, vegetation distributions, soil, and geologic conditions over seasonal to decadal time scales.

Historical climate and vegetation scenarios will be reconstructed to evaluate the potential impact of civic construction, watershed deforestation, maize production, and climate variation for producing scenarios of hydrologic change in this tropical watershed. The experimental strategy is to use synoptic stable isotope sampling (~monthly) of the principal stream in the watershed, as well as time sampling of  $^{18}O / ^{16}O$  and  $D / H$  in precipitation and run-off from the watershed using automated samplers, as a means of parameterizing the model. Implementation of the hydrodynamic model (PIHM) will allow application of a new theory for conjunctive “ageing” of surface and groundwaters in the watershed for evaluation of the full range of time scales contributing to runoff at the site, including the time scales of ecological, climatic, and human disturbances on the water cycle. It is important to mention that the impact of this research goes beyond the specific archaeological and hydrologic science proposed here. It also addresses the potential impact on regional water resources for integrated water budgets, recharge prediction, drought and flood simulations, which are crucial issues for present-day water management. There are presently no quantitative water resource assessments (recharge, discharge, flood/drought response, and water quality) for this humid tropical region of México. Installation of automated sampling instrumentation for stream water and precipitation will take place during the first 12 months of the study. With permission of INAH (Instituto Nacional Antropología e Historia) we will conduct infiltration experiments and limited soil coring over the site to establish the hydraulic properties over the watershed. Isotope laboratory analyses will be conducted continuously over the three years of this research. Ground penetrating radar will be used as a noninvasive evaluation of active subsurface flow, during year one. The NSF laser mapping center, NCALM, has committed to fly the unsurveyed watershed above the ruins in 2008 providing a 1-m resolution digital elevation and a canopy height model (Luzum et al. 2006).

Reconstruction of the last 100 years of daily climate forcing data will be carried out using the tropical weather generator MarkSim (Jones and Thornton 2000) and this period will be used to evaluate the modern watershed response. Statistical climate scenarios over 2000 years BP will be developed using MarkSim, and we will test the role of hydrologic drought as compounding factor in the interpretation of meteorologic drought using the 10k year global climate simulation of the CSIRO Mark 2 model (Hunt and Elliot 2005). Hunt and Elliot (ibid.) indicate that drought episodes in the Yucatán are a consequence of stochastic fluctuations and its location near the ITZ (intertropical convergence zone). Model development and implementation will begin in year one, calibrated/parameterized in year two, and climate/urbanization scenarios will be carried out in year three.

With this research, we will attempt to document the degree and rates of hydrologic change in a watershed subject to urban development and landscape modification over several hundred years, and for which climatic variations (extreme drought and tropical storm flooding) may be factors in the decline of the Maya. We will use known and hypothetical patterns of civic and agricultural construction at Palenque from A.D. 300-800 to evaluate the impact of this development on its water supply and watershed dynamics. Performing a watershed study at a prehistoric urban site which has fully functional water management features will elicit a better understanding of cultural developments in the Maya Lowlands and contribute information to parallel studies in other regions of Mesoamerica where physically-based process models for tropical watershed research might provide a new way of looking at the human-climate-watershed problem.

## **Acknowledgements**

Without the support of FAMSI, INAH, and the Pennsylvania State University this project would not have been possible. Thank you. I would also like to sincerely thank the following people for their personal contributions to the Palenque Hydro-Archaeology Project:

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## **List of Figures**

[Figure 1](#). Location map of the Maya region.

[Figure 2](#). The Palenque Archeological Map. Palenque's urban settlement density is the second highest ever recorded for a Classic Maya city. There are 673 stone structures per square kilometer (Barnhart 2001).

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