The Pennsylvania State University

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Department of Anthropology

THE HYDROARCHAEOLOGICAL APPROACH: UNDERSTANDING THE ANCIENT MAYA IMPACT ON THE PALENQUE WATERSHED

A Dissertation in

Anthropology

by

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Abstract

Palenque, 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. Years of archaeological research, including intensive mapping between 1997 and 2000, reveal that this major center, situated on a narrow escarpment at the base of a high mountain range in northern Chiapas, Mexico**,** began as a modest settlement about AD 100. Then, during the seventh and eighth centuries, Palenque experienced explosive growth, mushrooming into the second most densely populated Classic Maya center. This process of "urban" growth led to obvious changes in landcover.

In order to better understand the effects that landcover and climate change have on the availability of water for an ancient city a new approach is required. In this dissertation I introduce the hydroarchaeological approach, a new cross-disciplinary method that utilizes simulated daily paleoclimate data, watershed modeling, and traditional archaeology to view the response of the Palenque watershed to varying degrees of ancient human impact. There is great potential for watershed-climate modeling in developing plausible scenarios of water use and supply, and the effect of extreme conditions (flood and drought), all of which cannot be fully represented by atmosphere-based climate and weather projections.

One objective of this dissertation is to test the hypothesis that drought was a major cause for Palenque's collapse. Did the Maya abandon Palenque in search of water? Secondly, evaluate the hydraulic design of the water management features at Palenque against extreme meteorological events. How successful was the hydraulic engineering of the Maya in coping with droughts and floods?

The archaeological implications for this non-invasive "virtual" method are many, including detecting periods of stress within a community, estimating population limits based on the availability of water, understanding settlement patterns, as well as assisting present local populations in understanding the water cycle of Palenque.

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Thanks to Mom, Dad, Mark, Lisa, Chloe, and Hannah for putting up with me.

Laurel Pearson

For Dusty

(2000 – 2008)

Chapter 1

Introduction

The ancient Maya are renowned as great builders, but are rarely regarded as great engineers. Their constructions, though often big and impressive, are generally considered unsophisticated in terms of engineering techniques and knowledge, as we understand them today. Most large Maya constructions required only a simple grasp of building techniques as well as a good supply of unskilled laborers. One major exception to this widely held view relates to water control and manipulation. Many Maya centers exhibit very sophisticated facilities that captured, routed, stored, or otherwise manipulated water for various purposes.

Palenque, 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. Years of archaeological research, including intensive mapping between 1997 and 2000, reveal that this major center, situated on a narrow escarpment at the base of a high mountain range in northern Chiapas, Mexico, began as a modest settlement about AD 100. Then, during the seventh and eighth centuries, Palenque experienced explosive growth, mushrooming into a dense community with an estimated population of 6000 and approximately 1500 structures — residences, palaces, and temples - under a series of powerful rulers (Figure 1.0 and 1.1) (Barnhart, 2001). This process of ―urban" growth led to obvious changes in landcover.

Understanding the effects of landcover on the availability of water for an ancient city required a new approach. The hydroarchaeological approach utilizes simulated daily paleoclimatic data, watershed modeling, and archaeology to explore the response of ancient human impact on a watershed. There is great potential for watershed modeling in developing plausible scenarios of water use and supply, and the effect of extreme conditions (flood and drought), all of which cannot be fully represented by atmosphere-

Figure 1.0 – Location map of Palenque

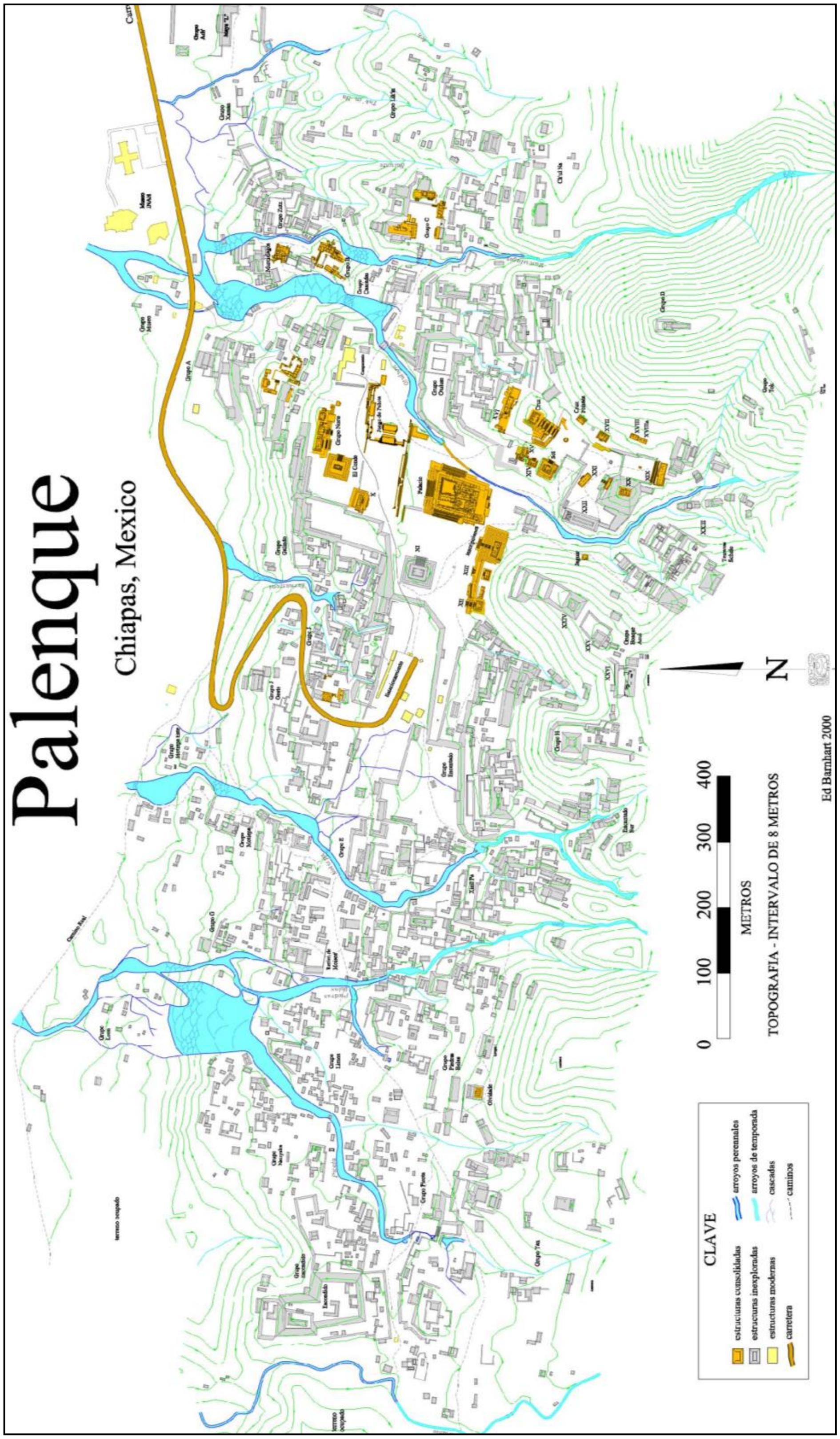


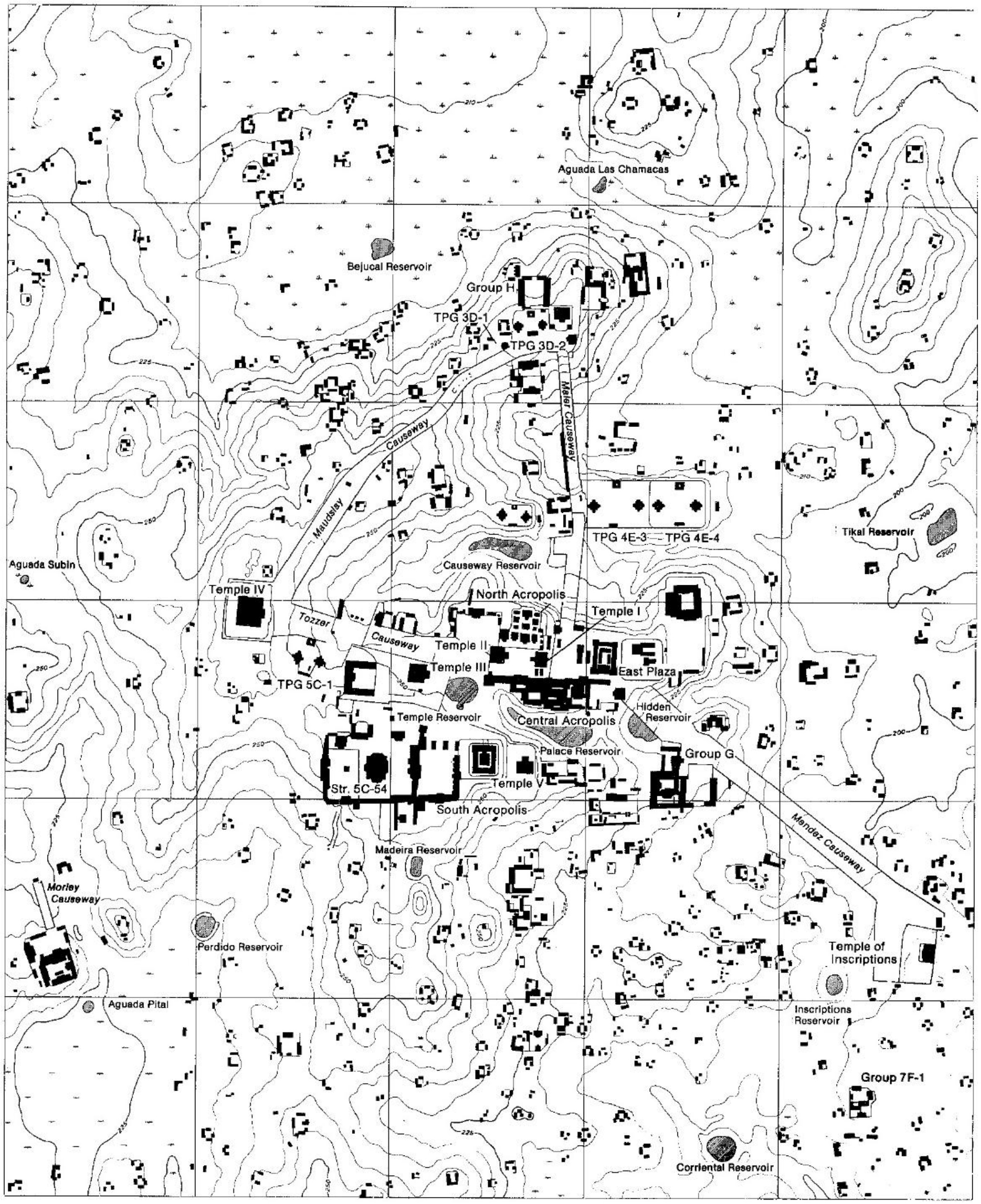
Figure 1.1 - Map of Palenque (French 2002)

based climate and weather projections. One outcome of these simulations is the demonstration that landcover is the ―big actor” in how water behaves.

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 unconstrained by topographic limits (with the exception of broad, flat, depressions, called *bajos*, which hold water during the rainy season). Their builders took advantage of areas of well-drained high relief, and as a result cities such as Tikal and Calakmul grew in a dispersed or rambling pattern (Figures 1.2 and 1.3). The inhabitants of Palenque had to adapt their burgeoning settlement to a small geomorphological space (ca. 2.2 km^2) (Figure 1.4). This confinement created a much more chaotic and crowded layout than that of most other Maya centers.

Contributing to the difficulties of building on Palenque's spatially confined plateau were the spring-fed streams that naturally divided the landscape. 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 simultaneously control flooding, reduce erosion, and bridge the divided areas to expand 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 unique technique expanded the size of their plazas by 23% (French 2002).

The abundance of flowing water was in one sense a blessing, because water was often a scarce resource in the Maya area. On the other hand, Palencanos were challenged to modify their landscape, in order to take advantage of hydrological resources and to 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.



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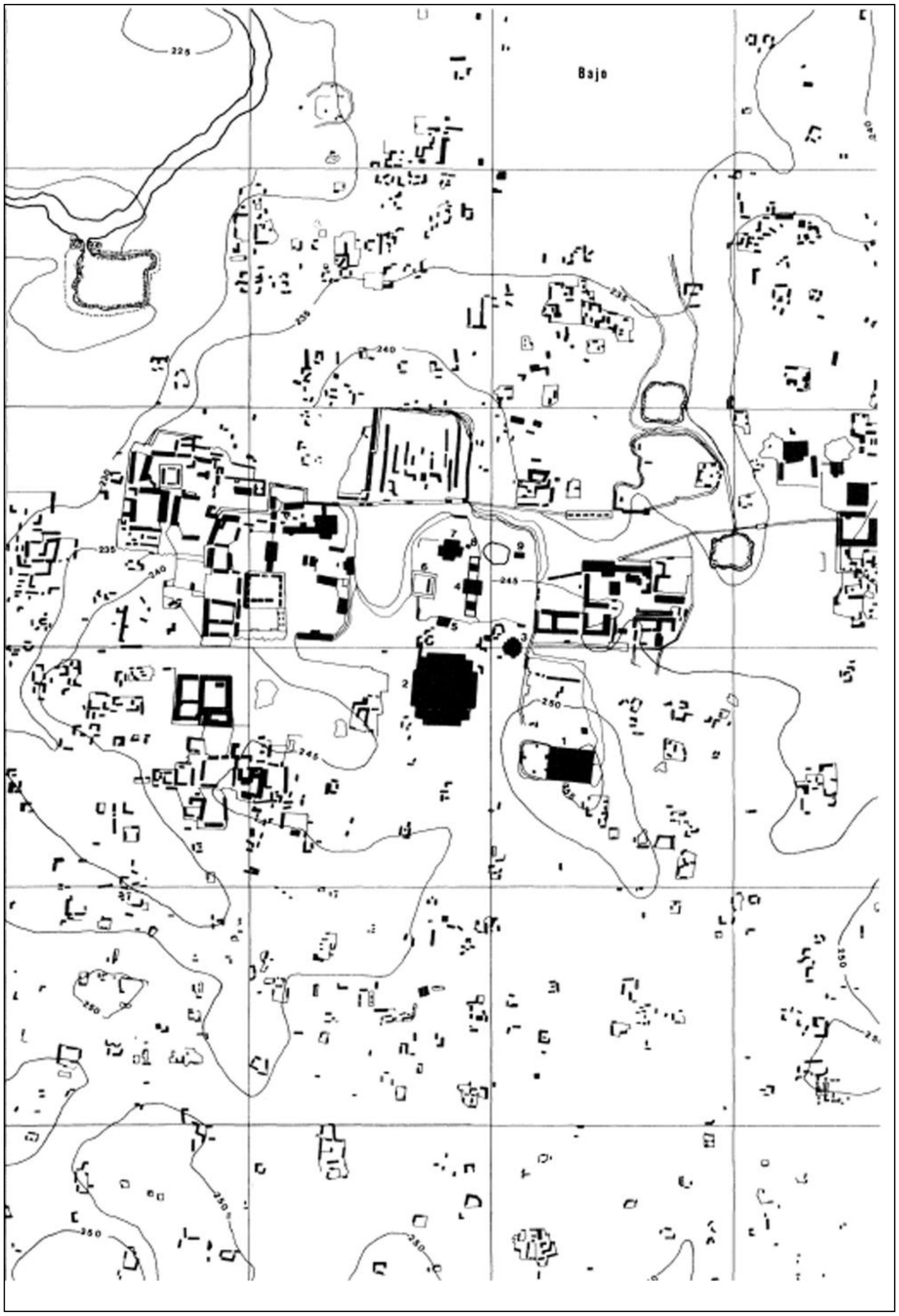

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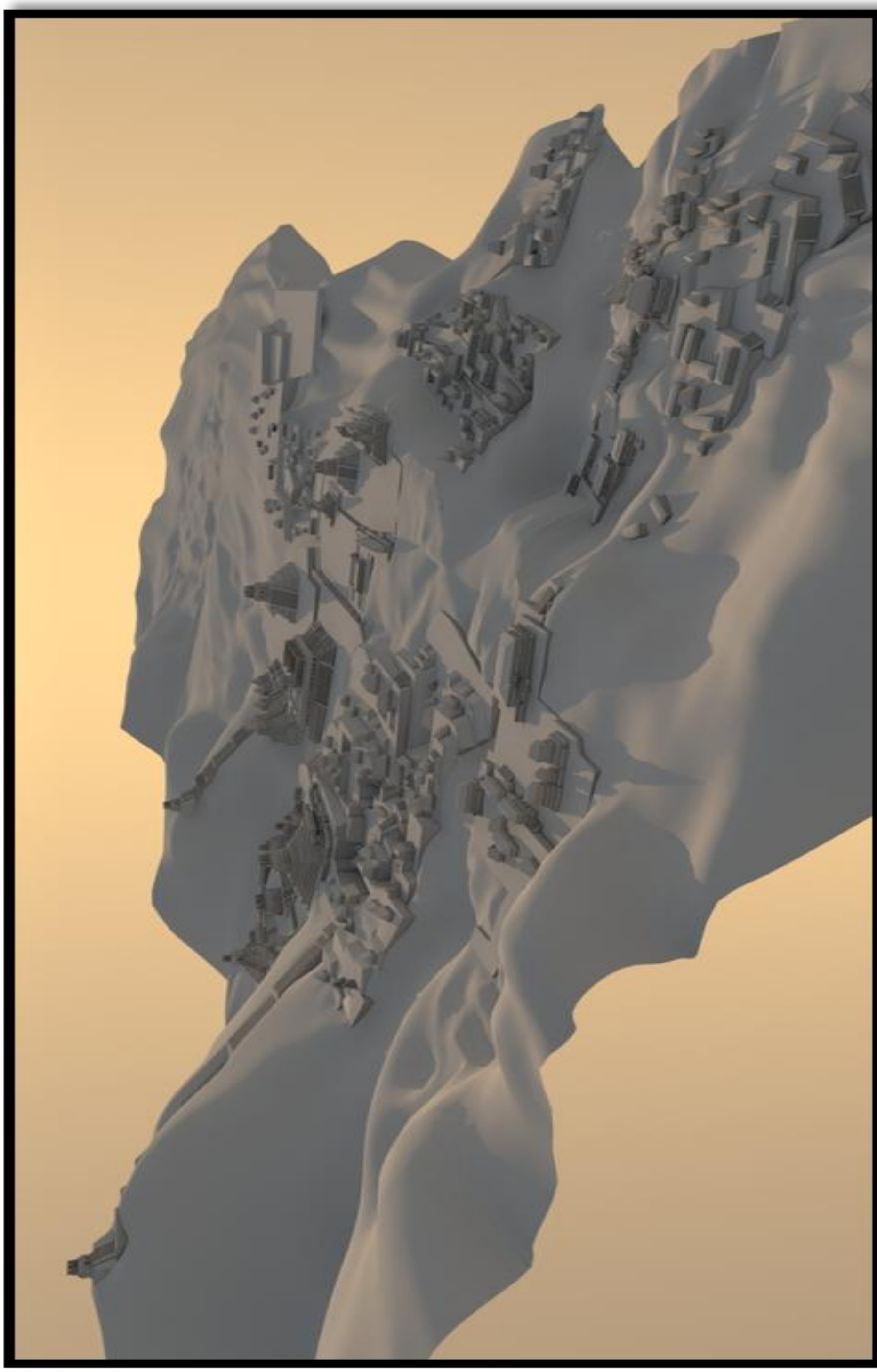


Figure 1.4 – Reconstruction of the Palenque Shelf (Moller 2008)

ENVIRONMENT

Familiarity with environmental conditions in the Palenque region is necessary in order to fully appreciate the hydrological opportunities and problems faced by the community in Classic times.

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 panoramic view Palenque had of the plains below.

An even greater advantage for early settlers was the presence of many natural springs. As with many cultures, water possessed a 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). A landscape such as this must have been emblematic to the ancient settlers of Palenque.

Practically speaking, fresh water, 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 ~1500 mm a year at the Gulf of Mexico to nearly 3200 mm a year in the foothills of the Sierra de Chiapas at Palenque. High as it is, this abundant amount of precipitation falls short of records in such areas as the Maya Mountains in Belize, which can receive a staggering 4000 mm of rainfall per year (Dunning et al. 1998). Of course the amount of rainfall varies throughout the year. 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, a period known as the midsummer drought (MSD). The MSD**,** or ―*canicula*,” is associated with fluctuations in the intensity and location of the eastern Pacific intertropical convergence zone (ITCZ). Tropical cyclones are a source of heavy precipitation in summer and fall. Convective precipitation and *orographic influence* (when moist air encounters a mountain barrier it is forced up over the mountains, the air then cools as it rises, and the moisture condenses and precipitates as rain) are also significant with increasing distance from the Gulf of Mexico. High levels of rainfall naturally bring unbearably high levels of humidity. The average temperature at Palenque ranges from 22.9^{o} C in December and January to 28.8^{o} C in May. Humidity often soars to 100%. The great rivers in the region, the Usumacinta and Grijalva, discharge 30% of the total freshwater flow of Mexico. It is not surprising that important Early Classic (AD 150-350), settlements such as Piedras Negras, Yaxchilan, and Bonampak sprang up in those great lowland riverine environments.

Throughout this dissertation I refer to hydrological, meteorological, and agricultural droughts. A meteorological drought is defined usually on the basis of the atmospheric conditions and the duration of the dry period (or reduced precipitation). 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 effects of periods of precipitation shortfalls on surface or subsurface water supply (i.e., streamflow, reservoir and lake levels, ground water). The frequency and severity of the drought is defined on a watershed or river basin scale. It is the hydrological droughts that cause severe problems for local populations. An agricultural drought links various characteristics of meteorological and hydrological drought to agricultural impacts, focusing on precipitation shortages, differences between actual and potential evapotranspiration, soil water deficits, and reduced ground water. Demand for water depends on the plants 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;

3) Water control to reconfigure and protect the urban landscape.

I will discuss all of these in various following sections of the dissertation.

AGRICULTURAL RESOURCES AT PALENQUE

The alluvial soils found in the plains to the north are where most of Palenque's agricultural production took place (Liendo 1999). The problems of 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 (Figure 1.5).

Channelized fields serve two main functions: drainage and drainage-irrigation (Siemens and Puleston 1972, Turner and Harrison 1983) (Figure 1.6). 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 retaining walls. 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 1988). Based on a 2200-calorie diet each Palencano required 1540 calories from maize per day (Whitmore and Williams 1998). According to Barnhart (2001) an average of 5183

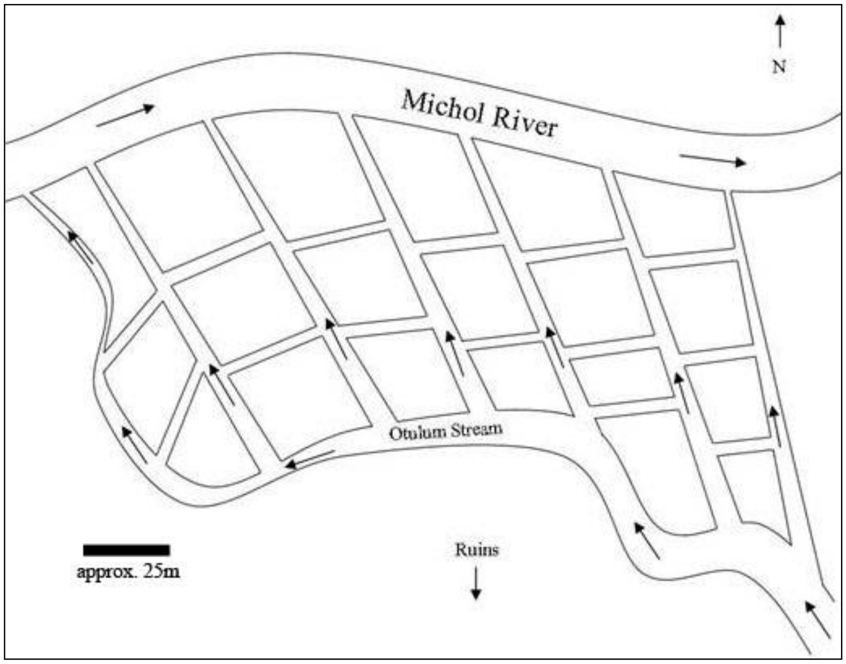


Figure 1.5 - An approximation of Palenque's channelized fields.

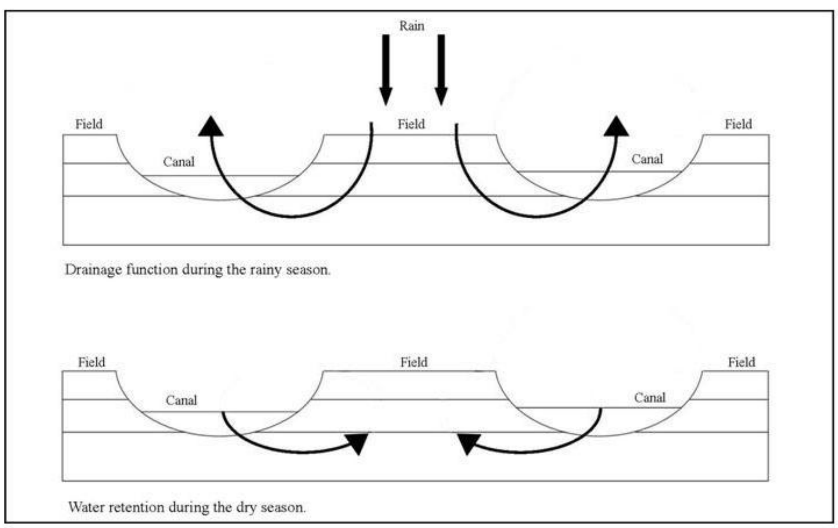


Figure 1.6 - Cross section of Palenque's channelized fields (adapted from Liendo 1999).

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 Figure 1.7 delineates an estimated 3000 ha of agricultural area as well as approximately 500 ha of channelized fields that were excavated by Liendo (1999). A channelized field system that enabled year round use might help explain Palenque's regional dominance and influence. Simultaneous production of all 500 ha of the channelized fields would have produced a enough maize to support a population of approximately 8000. In addition, failure of this system could have contributed to Palenque's abandonment in AD 799, an issue addressed later in this dissertation.

GEOLOGY

The early farmers of Palenque could not know that their site stood upon the northern edge of the uplifted and folded sedimentary rocks of the Maya tectonic block. To the south rose the Sierra de Chiapas, a folded and faulted chain of Mesozoic and Tertiary sedimentary rocks with fold axes trending northwest. These formations generally plunge beneath the Pliocene and younger sediments of the coastal Tabasco plain and the Gulf of Mexico. During the Cretaceous Period, 144 million to 65 million years ago, most of Chiapas lay beneath the 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, about 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).

The region's geologic structure affected the Maya in many ways. The chain of fault lines that riddle the area caused earthquakes. The marine fossils in the rocks found their way into Maya cosmology and art, which portrayed the underworld sea and its creatures. Limestone was used as building material for monumental architecture and

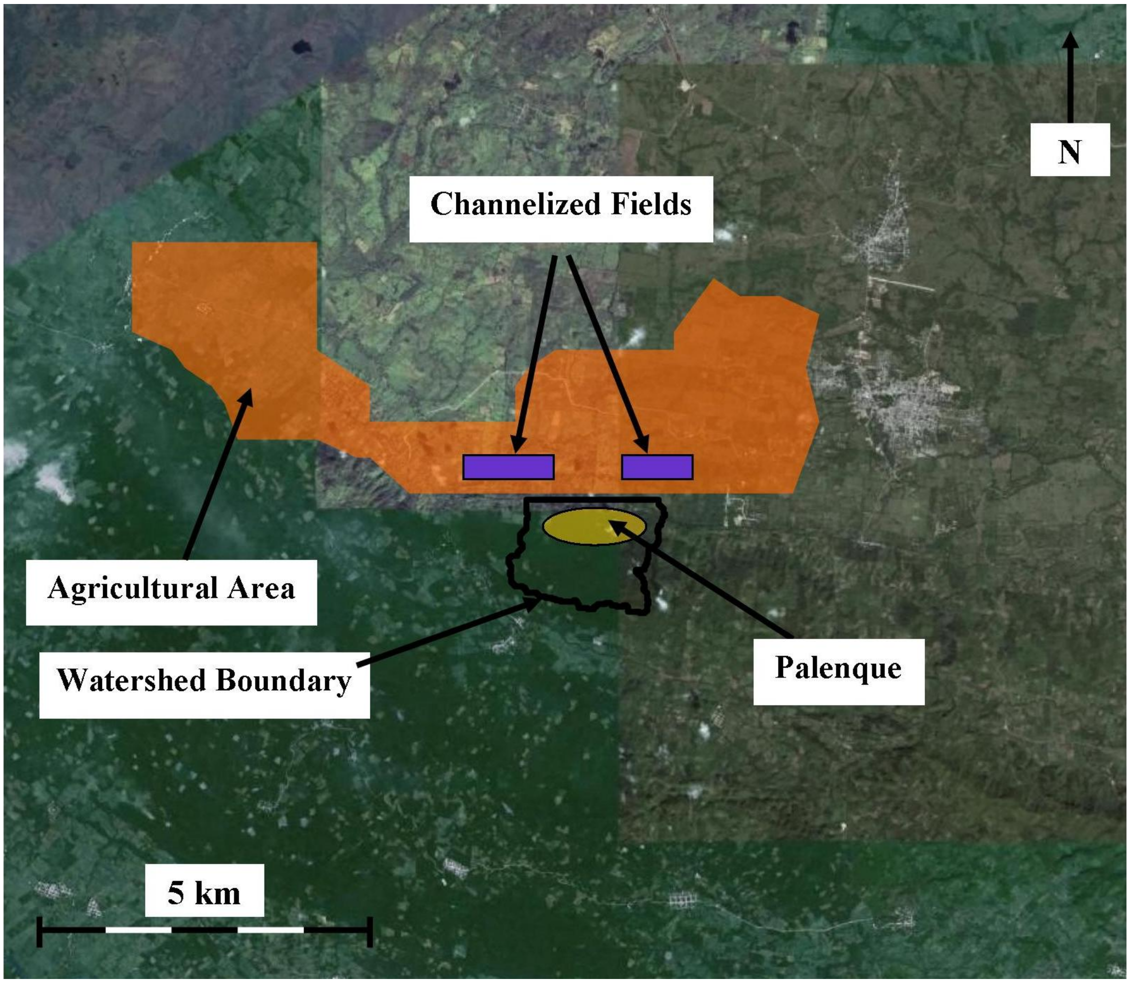


Figure 1.7 – An estimation of Palenque's agricultural land.

stucco facades. Sediments provided the sources for clay. Eventually, the broken remains of ceramic bowls and plates became the main means for archaeologists to date the settlement of Palenque.

RESEARCH OBJECTIVES

My dissertation concerns the testing of the hydroarchaeological approach, a new method of measuring human-environment interplay through paleo-hydrological modeling. This approach is complex and requires a large volume of data, so I limit myself to a few basic issues:

1. What insights can the hydroarchaeological approach provide about the character and culture history of Palenque?
2. Did drought play a role in the abandonment of Palenque?
3. Was hydraulic engineering successful in coping with meteorological events such as droughts and floods?

This dissertation will achieve the following:

1. It demonstrates the usefulness of a new strategy for integrated hydrological modeling devised by Dr. Christopher Duffy, a hydrology professor in Penn State's Department of Civil Engineering, by offering several views of the Palenque Watershed and its responses to varying degrees of human influence;
2. It investigates the process by which the Palencanos adapted their settlement to an abundant, dynamic, and unpredictable set of hydrological resources;
3. It juxtaposes both large and small scale simulated flood and hydrological drought events with Palenque's agricultural production and abandonment; and
4. It examines several large and sophisticated water manipulation features constructed to produce a highly artificial landscape — a considerable feat of civil engineering.

BACKGROUND: THE PALENQUE HYDRO-ARCHAEOLOGY PROJECT

I began working at Palenque in 1998 and was immediately impressed by the remains of the hydrological system, which had long been famous among archaeologists (Maudslay 1889-1902, Andrews 1975, Weaver 1981). I have since spent eleven years trying to better understand this system through survey, documentation, hydrological and meteorological monitoring, as well as watershed modeling. Palenque's abundance of flowing water, unique water management features, and relatively small watershed made it a suitable test case for the hydroarchaeological approach.

While working as a survey assistant to Barnhart on the Palenque Mapping Project, my duties included an initial pedestrian survey to sketch a rough layout of topography and architecture, the operation of the survey instrument (a *GTS-211D* total station), and to record and document all water management features encountered throughout the site. The duration of my fieldwork was approximately 13 months over a three-year period, with the majority taking place between April and August.

2005 Field Season

The Palenque Hydro-Archaeology Project (PHAP) was initiated in late July 2005. The equipment installation started with anchoring two pressure transducers, which measure stream flow, in the bed of the Otolum stream. Pressure transducer 1 (PT-1) was placed in the south at the Otolum's source (OT-S1 and OT-S2) while PT-2 was anchored at the escarpments northern edge (Figures 1.8 and 1.9).

Installation of the Campbell Scientific CR10X full meteorological station revealed a new set of difficulties. The location for the weather station required security from vandalism and a five-meter radius absent of arboreal foliage. The only spot that met these criteria was the backyard of INAH's archaeological camp, on the northern edge of the Palenque escarpment. INAH archaeologist Miguel Angel Vazquez gave invaluable assistance in obtaining swift approval for the installation of the weather station at this ideal location (Figure 1.10).

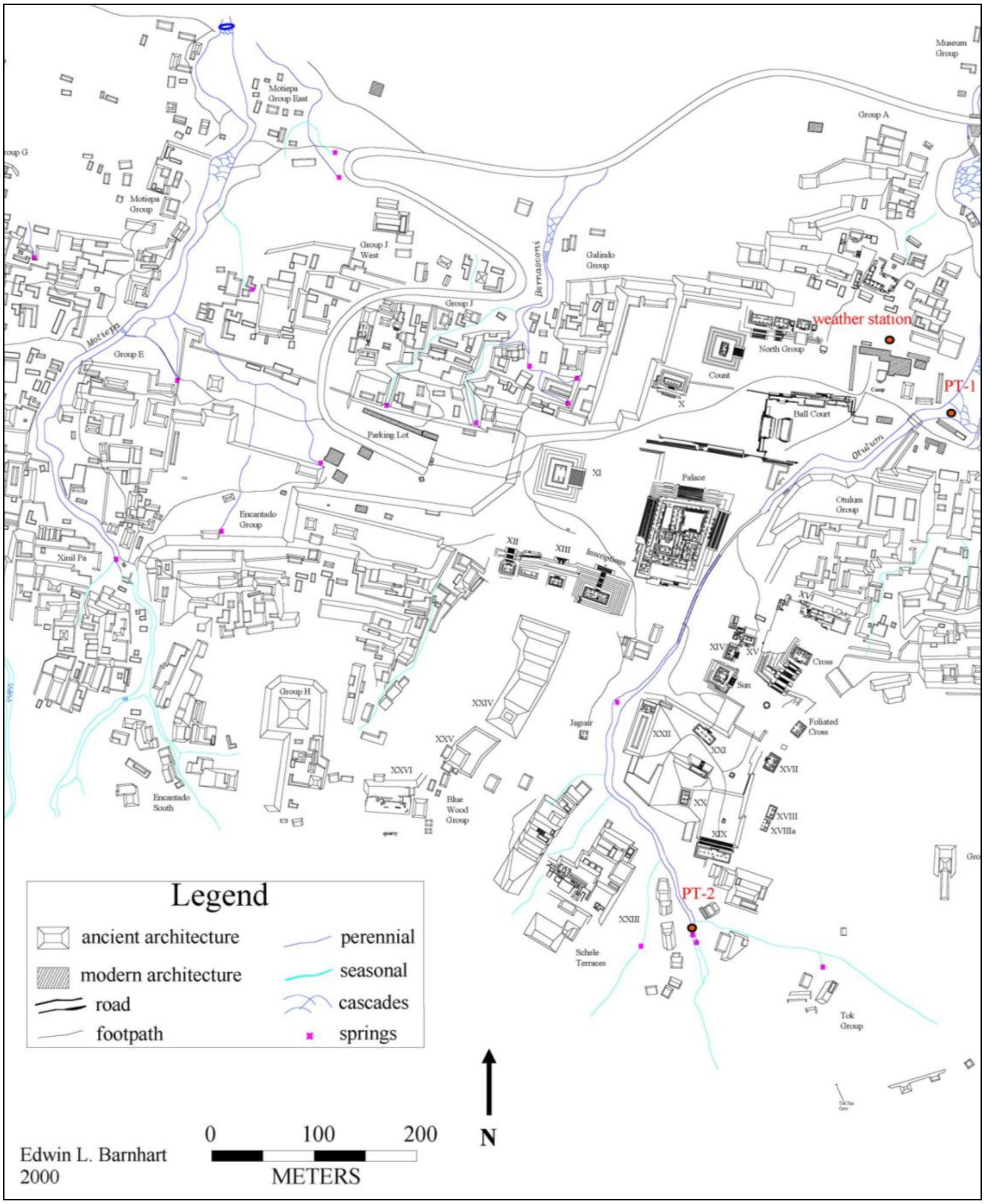


Figure 1.8 – Equipment location map.

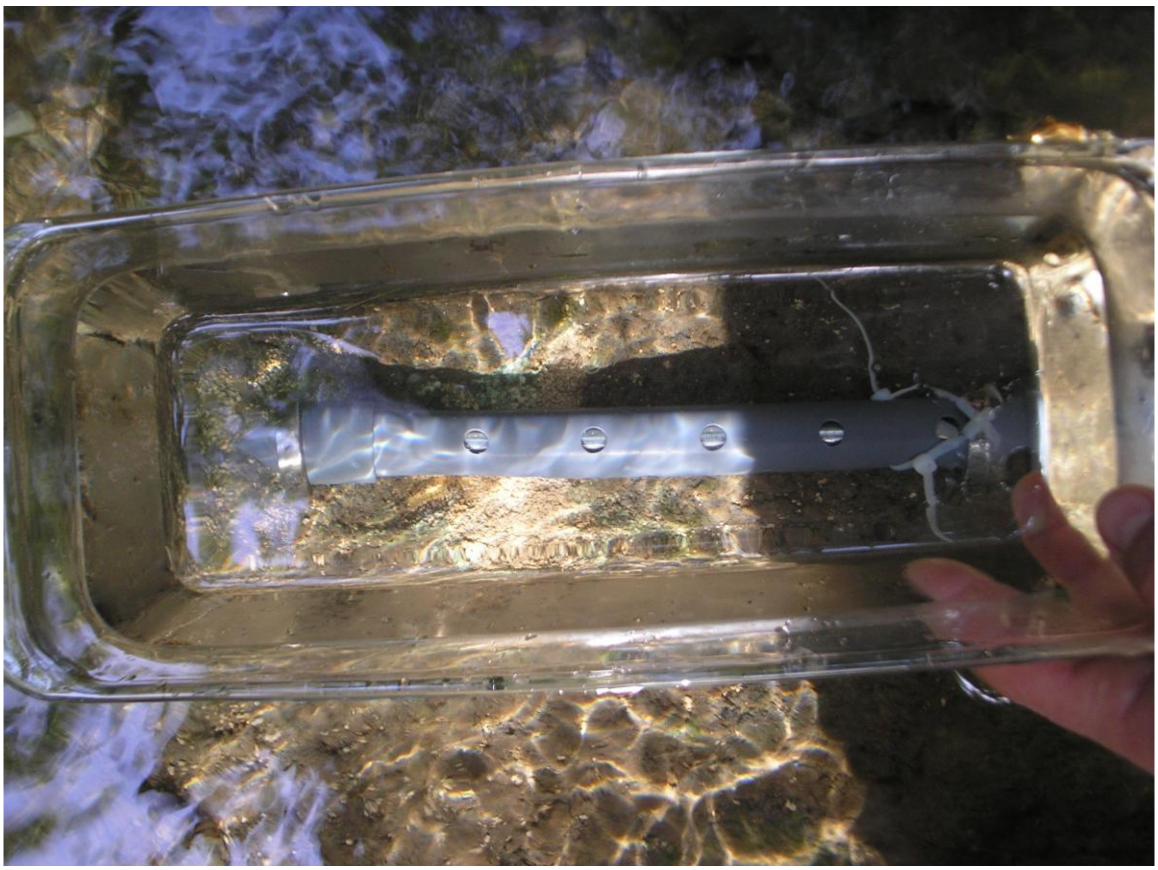


Figure 1.9 – Viewing the anchored pressure transducer through a glass cooking dish

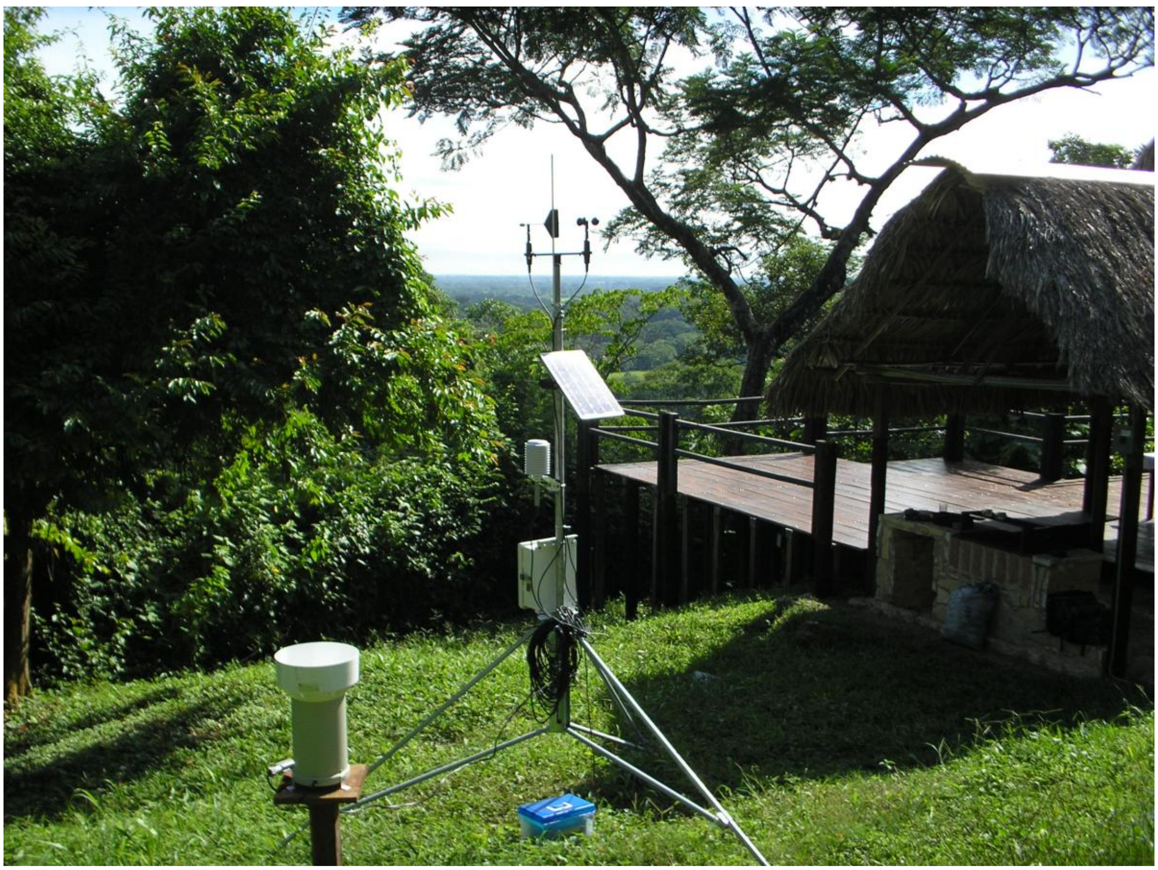


Figure 1.10 – The Campbell Scientific CR10X datalogger and Remote Weather Station

In early August the weather station's three-meter tripod was anchored and all associated instruments were attached and wired to the data-logger (Figure 1.11). The next step was connecting the laptop to the data-logger to insure functionality (Figure 1.12). The cable supplied for this operation was incorrect, and Campbell Scientific informed me it would take several weeks before I would receive the right cable. In addition, the solar panel was not properly recharging the battery. After exhausting all avenues to resolve these issues, and with my teaching assistant duties at Pennsylvania State starting the next week, I was forced to return home.

Five months later, in mid-December, I returned to Palenque with several types of cables, an improved soil sensor, and new battery. I downloaded the stored data from the data-logger and quickly analyzed it for inconsistencies. Luckily all equipment functioned properly during my absence except for an intermittent reading from the rain gauge. Upon closer inspection, my team and I discovered that a nest of ants had made a new home in the tipping bucket of the rain gauge, thus obstructing data recording. This problem was soon remedied with pesticide. Project member Alonso Mendez agreed to return every few weeks to give the rain gauge another dose of ant repellant in hopes of avoiding future problems. When I left Palenque in late December the weather station was operating perfectly and both pressure transducers had survived their first rainy season.

2006 - 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 University. Aside from downloading meteorological data, our work mainly entailed performing routine maintenance and repairs on the weather station. We also tested the feasibility of measuring stream flow using a handheld SonTek Flow Tracker (Figure 1.13). The test was a response to the loss of our stream sensors that were installed in 2005.

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, again

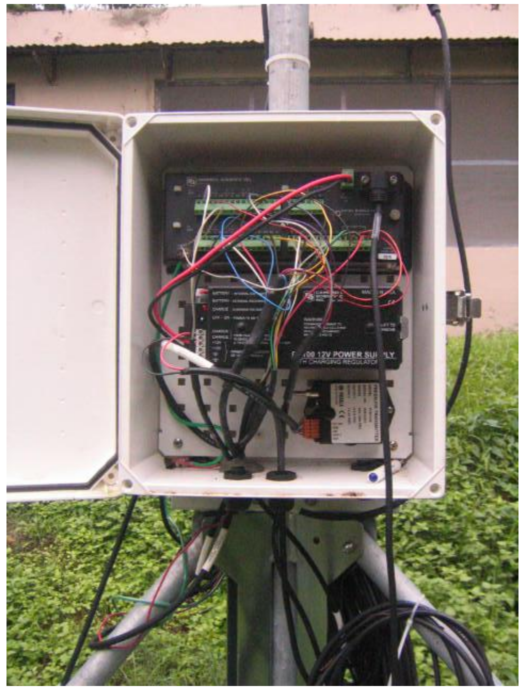


Figure 1.11 – Interior of the CR10X

Figure 1.12 – Kirk French downloading meteorological data from the CR10X.

Figure 1.13 – – Dr. Christopher Duffy and Kirk French gauge the Picota Stream with the SonTek Flow Tracker.

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. This was the final stage of the Palenque Hydro-Archaeology Project due to the expiration of the INAH permit on February 1, 2008.

DISSERTATION ORGANIZATION

Chapter 2 begins the main part of the dissertation with a discussion of non-agricultural water management features found in the Maya Lowlands. This descriptive chapter is necessary due to the absence of agricultural water features within the site boundary (i.e. the 2.2 km^2 center itself). Chapter 3 provides a brief summary of Palenque's early research history and archaeological bias, dynastic sequence, population estimates, and recent projects. Chapter 4 describes the urban landscape of Palenque, and provides an overview of some of my previous research involving the creation of public space through water management. Chapter 5 details the 2,500-year paleoclimate simulations performed for Palenque. Chapter 6 outlines the Palenque watershed and a simulation of its responses to floods and hydrological droughts that might have affected the community. Chapter 7 deals directly with the hydraulic engineering of the OT-A1, Palenque's largest aqueduct. In addition, this feature is evaluated for its response to severe flood, and drought. Chapter 8 describes the hydraulic engineering of a water pressure feature from Palenque. By all accounts, PB-A1 is the New World's earliest form of closed conduit water pressure. Chapter 9 contains my conclusions, thoughts on what I would have done differently, and what the next steps will be.

Chapter 2

Non-Agricultural Water Management

Like all cultures, the Maya used water in a variety of ways. Although their water management methods differed somewhat from these of modern industrialized societies, their purposes are remarkably similar. Generally, when one thinks of water management, the first image that comes to mind is that of a faucet or a simple glass of water. This type of water management is for *household use*, such as drinking, cooking, and bathing. Another image is a swimming pool or hot tub, both of which are essentially *pleasure facilities*. *Symbolism and ritual* imagery might also come to mind, since baptisms and holy water are common for many in American culture. In addition, today's fast-paced society rarely leaves us time to reflect on using water for *transportation*, but billions of tons of cargo are transported by ship domestically and internationally every year. For many people the last concept that comes to mind when thinking of water is *flood control*. Urban life as many of us know it would be impossible without the network of subterranean drains and carefully engineered streets that we use daily, including massive constructions like levees which protect our cities (sometimes not very effectively). The following section will examine non-agricultural hydraulic techniques used by the Lowland Maya during the first millennia AD.

HOUSEHOLD USE

Obtaining water for household use (drinking, cooking, and washing) involves the most common form of water management. It is a necessity for every human every day. The three necessities for sustaining life are oxygen, water, and food. Typically, a person can survive without food for approximately 35 to 40 days; without water for three to five days; and without oxygen about 11 to 15 minutes. Essentially, water is the second most precious resource on our planet. An astonishing 74% of the earth's surface is covered by water, and 97% of which is saline and therefore undrinkable to humans.

In a settled environment under normal living conditions the average person requires a minimum of 2 to 3 l of drinking water a day (White et al. 1972). More specifically, Winzler and Fedick (1995) report that people in the tropics require a minimum of about 1.8 to 3 l of drinking water per day, although this estimate varies with body type, activities, and environmental conditions. In order to insure the existence and availability of potable water on a daily basis, many cultures rely on water storage features. This form of water management was heavily relied upon by the Lowland Maya wherever perennial streams or wetlands did not exist, as was commonly the case. Due to the annual four-month dry season of the region, roughly January through April, water storage was a requisite for survival. Based on a survey of Maya cisterns in southern Yucatán, use of water for drinking and cooking by ancient Maya populations is estimated at about 3.3 l per day (Back and Lesser 1977).

Rain Collection

Rainwater would have been the purest form of water for the Maya. During storms, people probably placed their household water jars outdoors in order to catch as much precipitation as possible, especially roof runoff. Additionally, many of the elite made sure the roofs of their masonry buildings were sloped to maximize rain collection. Sloped roofs also helped protect the structure from sun and rain (Webster and Abrams 1983). The drainage stones found at Structure 9N-8C in the House of the Bacabs at Copan (Figure 2.0) clearly indicate that water was being channeled from the roof (Abrams 1994). The stones prevented water from running down the walls and from falling too close to the vulnerable foundations of the building. It would only make sense to assume this water was also collected, even though the Copan River flowed nearby. The author has noted similar drainage stones at the site of Yaxchilán in Chiapas, Mexico.

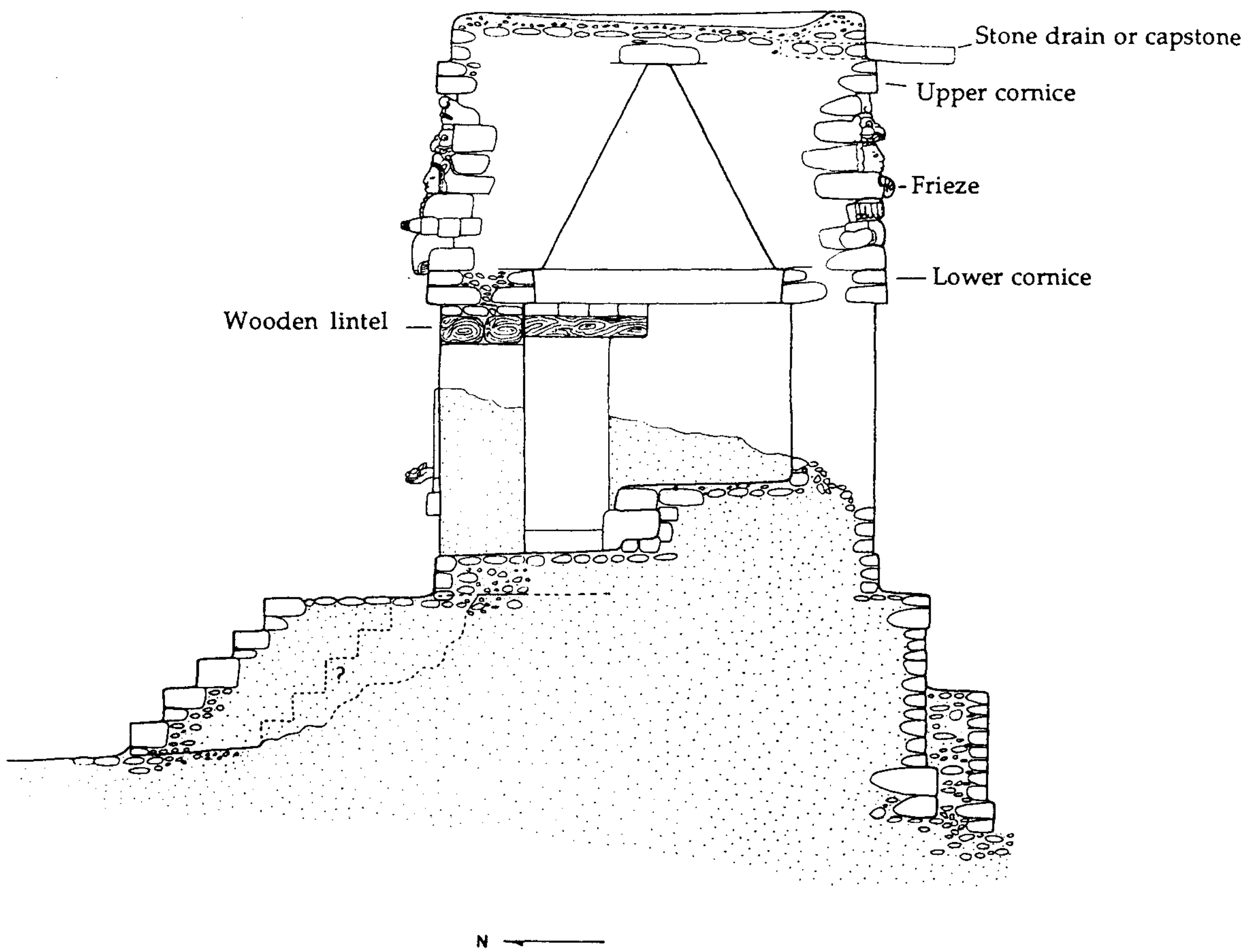


Figure 2.0 - Reconstruction of the cross section of Structure 9N-82 1st and 9N-82 2nd by Rudi Larios (drawing by Stanley Matta) (Fash 1989).

Reservoirs

Reservoirs are water storage features used by many ancient cultures around the globe. At numerous sites the Maya engineered large shallow tanks into the lowland landscape. The water management features most prevalent at Tikal, Guatemala, consist of 1) central precinct reservoirs; 2) *pozos* (small household reservoirs); and 3) *aguadas* (depressions on the edge of a *bajo*—large, seasonally inundated, internally drained swamps) (Scarborough and Gallopin 1991). Varying widely in size, location, and function, these features reflected an elaborate series of water catchment strategies. As Scarborough and Gallopin's analysis demonstrated, the techniques of collecting water at Tikal utilized monumental architecture, causeways, reservoirs, and other types of holding basins. The size of the collection area varied according to the rate of water delivery. For example, monumental, vertical stone structures act as inverted funnels, spreading rainfall to be collected on the paved "catchment" surfaces of plazas and patios. These surfaces, in turn, are sloped to collect the runoff and divert it to one of several collection basins, or reservoirs. An important point should be noted here: the engineering strategies that made water management possible in the central zone of Tikal were handled at the elite level, while the labor that built these public works was provided by society's lowest level. Scarborough (1993) has suggested that control of water for consumption and its conspicuous use might have served the purpose of consolidating power for ancient Maya leaders (see *Dynastic History* in Chapter 3).

There were six major reservoirs in Tikal ranging in size from 6 to 92 ha and could store approximately 900,000 m^3 (900 million liters) collectively based on the low estimate of 1500 mm of annual rainfall (Scarborough and Gallopin 1991). With an estimated population of 60,000 these storage facilities could easily provide the 3 l per person/per day during the 4 month dry season. In addition, there would be approximately 878 million liters of surplus water from these elevated reservoirs to release to the downslope flanks and surrounding bajo margins for irrigation (Adams 1991, Scarborough and Gallopin 1991).

Like Tikal, the city of La Milpa, in northwestern Belize (Guderjan 1991), has a complicated water system at a site with no permanent water source. The central precinct dominates the summit of a hillock with three reservoirs positioned at the beginning of three gently sloping arroyos, naturally draining the site. Survey conducted by Gair Tourtellot indicates that most of the runoff from the main plaza was directed into the northwestern arroyo (Scarborough 1993). A dam approximately 17.5 m long was mapped and test-excavated 200 m down the channel from the plaza edge (Figure 2.1). The dam was U-shaped in longitudinal section, contouring to the eroded channel, but was probably built up considerably when operational. Given the similar gradient on either side of the dam and the breached character of the feature, it does not hold ponded water today. Excavations demonstrate that large, tabular limestone slabs measuring 1.5 m X 1.5 m X 0.4 m were placed on end, one next to the other, spanning the channel and effectively abating the movement of water, thus creating a reservoir. The stones were anchored in a wet marl and rubble fill one meter deep. According to Scarborough (1993), the dam was much higher when originally used; given the care taken to secure the foundation stones and the height of the flanking stone outcrops that constrict this location of the arroyo channel.

The site of Kinal, Peten, 25 km southwest of La Milpa, was intensively occupied during the Terminal Classic Period (Adams 1989). Kinal rests on a ridge dividing two immense *bajos* to the northeast and southwest. In addition, the site had a clear defensive advantage, supplemented by a wall circumscribing the summit central precinct, the paved courtyards and monumental architecture again preserved and directed the runoff into a well-conceived reservoir system (Scarborough et al. 2003).

Unlike the reservoir adaptation seen in the central precinct of La Milpa, where water was collected from the summit catchment and held in sizable tanks for release downslope (Scarborough and Gallopin 1991), the Kinal system was only dependent on the summit catchment for the diversion of runoff. The tanks at Kinal were located downslope from the central precinct, within the residential core but close to presumed field loci. The channel gradient feeding the Kinal reservoirs was steep, in excess of that identified at La Milpa, and the Maya living there had to devise a method to slow the movement of water into the reservoir, thus preventing erosion. To slow runoff, they built check-dams, each consisting of a one-piece diversion stone and pooling area.

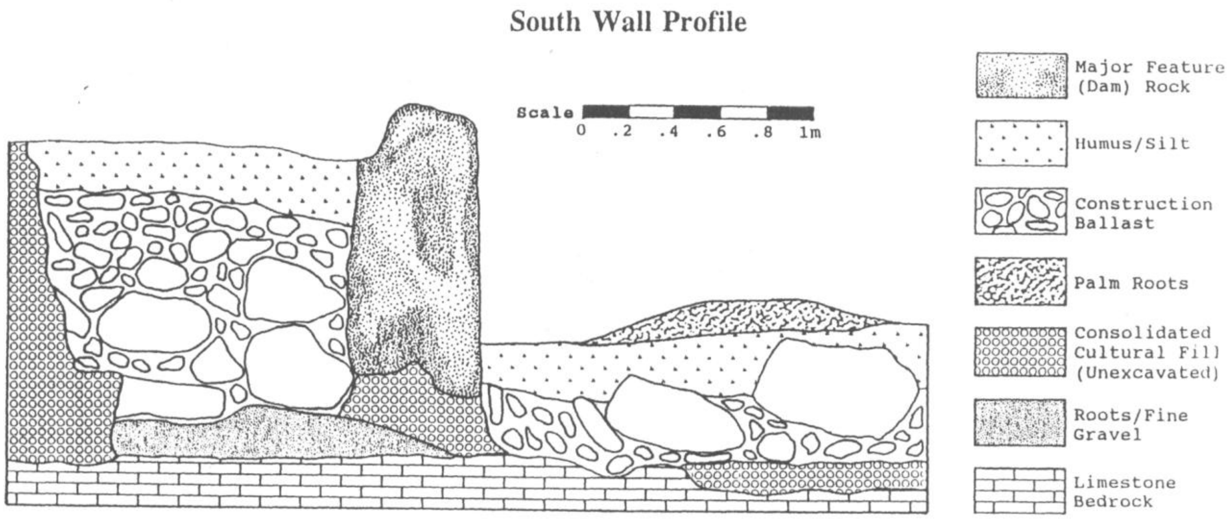


Figure 2.1 – Excavation profile of the tabular limestone dam at La Milpa (Drawing by Beecher 1992) (Scarborough 1993).

The Kinal West Reservoir received focused attention with the exposure of a dam or weir, approximately eight meters long, which directed channel water from the central precinct into a diminutive silting tank before it entered the main body of the reservoir. In addition to preventing large particulate matter from entering the water supply, the reservoir was designed to release water systematically during the dry season. Archaeologists identified a V-shaped outlet positioned at a depth in the reservoir embankment, indicating that the entire volume of the reservoir could be drained (Figure 2.2) (Scarborough et al. 2003).

The Kinal reservoir system represents a less centralized form of water management than the Tikal and La Milpa systems. Nevertheless, Kinal provides hydraulic details about the technology incorporated at all three sites. Reflecting the Lowland Maya's dependency on reservoirs, the care taken to control erosion and sedimentation was pronounced and well defined at Kinal.

The site of Cobá was a major Maya city during the Late Classic period (A.D. 550-1550) (Suhler, et al. 1998), that supported a dense population of up to 60,000 people. (Folan et al. 1983). Two lakes within the site, Lake Cobá and Lake Macanxoc, appear to have been culturally modified. They are ringed by dikes and *sascaberas*—marl mines for plaster and building materials (Klintz 1990). There is no evidence that either lake was modified for agricultural purposes, and sediment studies at Lake Cobá suggest the dikes were constructed around AD 380 to form a reservoir (Leyden et al. 1998).

Edzna is a Late Preclassic site also associated with massive landscape modification for water management. Located in a shallow valley in northwestern Yucatan, the site receives about 1000 mm of rainfall during the rainy season (SARA 1999). The entire storage capacity of the system was approximately 2,000,000 m^3 (Scarborough 1993). Matheny (1976) states that the 20 km of canals, along with the numerous reservoirs, is comparable to the earth-moving expenditures of Teotihuacan's Temples of the Sun and Moon.

Cerros, located on the northern Belizean coast, had a complex system of canals that maintained a storage capacity of 200,000 m^3. The main canal is approximately 1.2 km long, 6 m wide and 2 m deep. Runoff during the rainy season was directed into

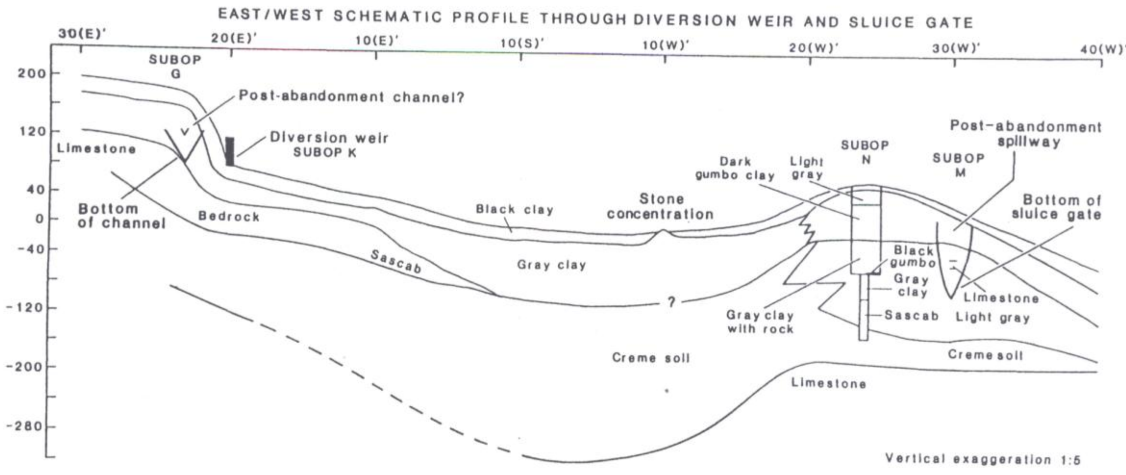


Figure 2.2 – Schematic cross-section of Kinal reservoir (Scarborough 1993).

reservoirs, tanks, and basins throughout the settlement via a system of feeder canals, sills, and dikes (Scarborough 1983, 1991).

Stagnant water inreservoirs was a challenge for the Maya. Standing water can provide prime breeding conditions for insects and parasites, and, more significantly, can result in the buildup of noxious chemicals, especially nitrogen (Burton et al. 1979). A visible sign of clean water is the water lily, *Nymphaea ampla*, a sensitive hydrophytic plant that only grows in shallow (one to three meters), clean, still water that is not too acidic and does not have too much algae or calcium (Lundell 1937). Thus, the presence of water lilies on the surface of *aguadas* and reservoirs is a visible indicator of clean water. In addition, water lilies covering a reservoir slow the evaporation process and thus the loss of a critical resource during the dry season. The water lily was a symbol of royalty in Classic Maya society, as clearly expressed in the distribution of water lily motifs on stelae, monumental architecture, murals, and mobile wealth goods such as polychrome ceramic vessels (Rands 1953).

Wells

Wells are rarely mentioned in discussions of water features in the Maya Lowlands because so few wells have been found at Maya sites. In many places (as at Tikal) the water table is so far beneath the surface that digging wells using preindustrial technology was impossible. The Classic Maya site of Quirigua is located in a water-rich, alluvial, and non-karstic setting on the northern bank of the Motagua River in eastern Guatemala. Despite Quirigua's location on a floodplain, six ceramic-lined wells were unexpectedly encountered there. Discovered by Oliver Ricketson in 1934, the wells through excavations of modern drainage ditches on banana plantations surrounding the 30 ha Quirigua archaeological preserve (Ashmore 1984). Each well system consisted of a column of one to three large ceramic tubes, 0.31-0.45 m in exterior diameter and 0.63-0.93 m long (Figure 2.3). Each column was set in the ground over a flat-bottomed, jar-shaped cistern, 0.67-0.76 m high and 0.55-0.58 m maximum exterior diameter. The compound apparatus provided access to the subterranean water table via five apertures, four (2.1-2.6 cm in diameter) at or near the level of the greatest diameter of the cistern,

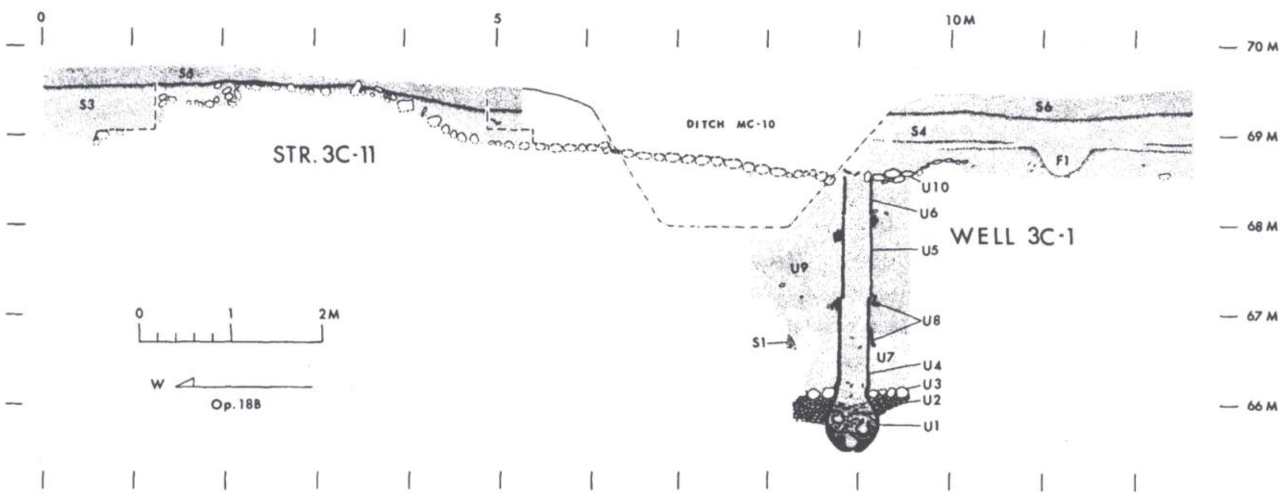


Figure 2.3 – Section drawing of 1978 excavation at Well 3C-1 and Structure 3C-11, Quiriquá (Ashmore 1984).

and one (6.7-8.5 cm diameter) centered in its base (Ashmore 1984.). Entry of water and sediment at the junction of two tubes or between the lowermost tube and the cistern mouth was impeded by packing the outside of these junctures with potsherds, and a gravel matrix around the cistern might have served as a water filter (Ricketson 1935).

Along with the wells, numerous intact vessels were recovered; all but one of them were suitable for retrieving water from the wells. These jars were 15.8-18.2 cm high and maximally 15.5-21.9 cm in diameter. According to Ashmore (1984), the people of Quirigua developed a specialized technology for convenient water procurement during the Late Classic period that may have been both cleaner and more palatable than the nearby river water.

Wells of ancient construction were also found in southern Quintana Roo at the sites of Chacchoben, Margarita Maza de Juarez, and Chicichmuul. Information retrieved at Margarita Maza de Juarez made it possible to measure the present depth of its well and determine some features of the well's construction. The opening was 93 cm in diameter (Figure 2.4). Mortared stones surrounded the shaft in a circular fashion to a depth of 5.4 m, at which point the remainder of the shaft was simply cut through the limestone bedrock (Figure 2.5). Constricting rings occurred at depths of 12.5 m and 17.7 m below ground level and may represent excavation units during construction. The total depth of the well is 22.65 m below ground level and today contains no water (Harrison 1993).

Chultuns

Chambers excavated into bedrock, called *chultuns*, occur in both the southern and northern Lowlands but seem to have served different purposes. While it has been firmly established that *chultuns* served as water catchment and storage chambers in the north (McAnany 1990, Andrews 2004), several alternative functions have been suggested in the south.

The *chultuns* found in the northern Lowlands were typically bell-shaped (Figure 2.6) while the ones in the south resembled the shape of a boot (Figure 2.7). The volumes of the *chultuns* are highly variable, with a continuous distribution ranging from 7000 to 75,000 l at the northern site of Labna (McAnany 1990).

Figure 2.4 – Masonry construction at the top of an ancient well at Margarita Maza de Juárez in southern Quintana Roo, Mexico (Harrison 1993).

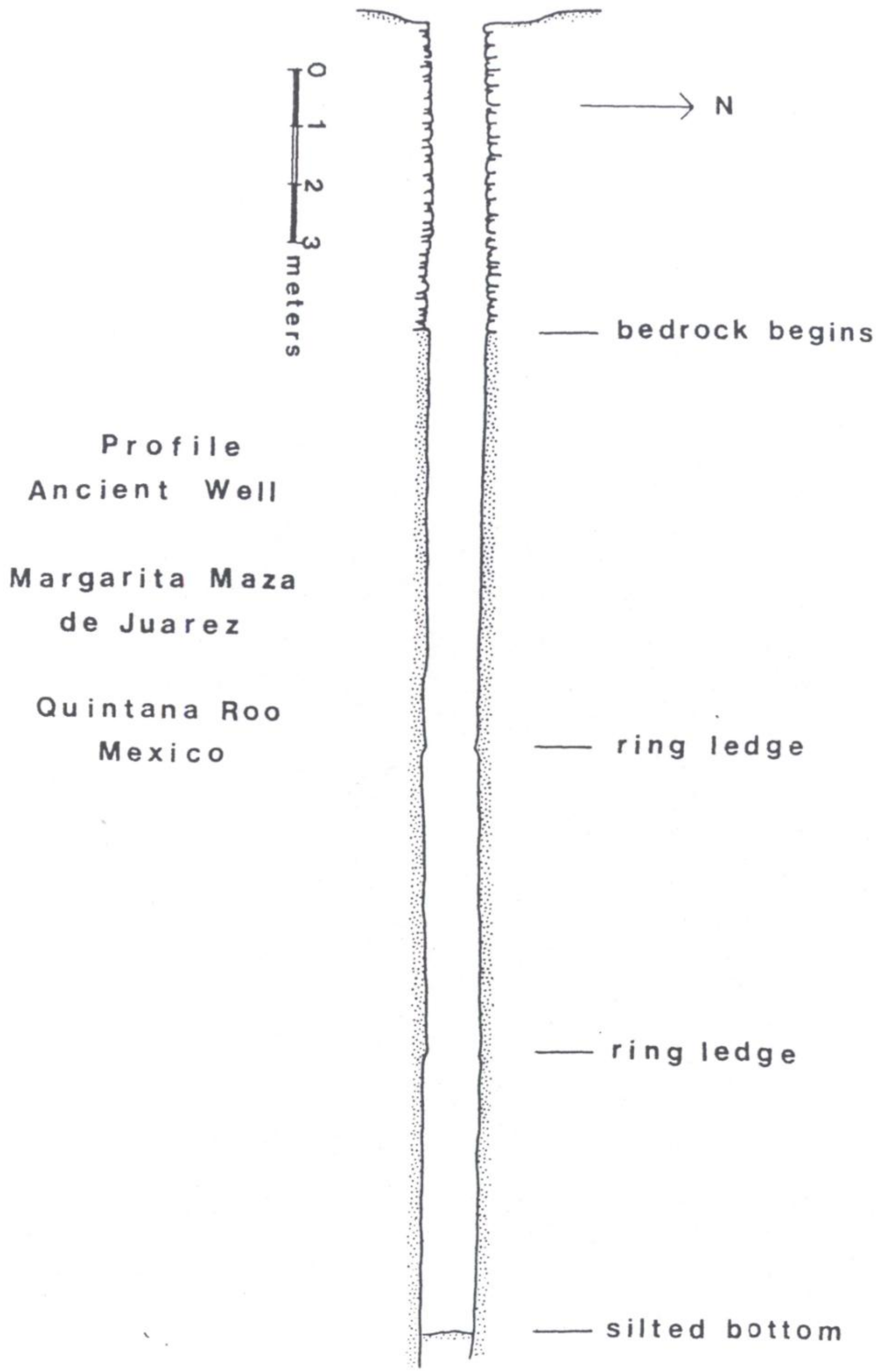


Figure 2.5 – Profile/section of the well at Margarita Maza de Juárez in southern Quintana Roo, Mexico (Harrison 1993).

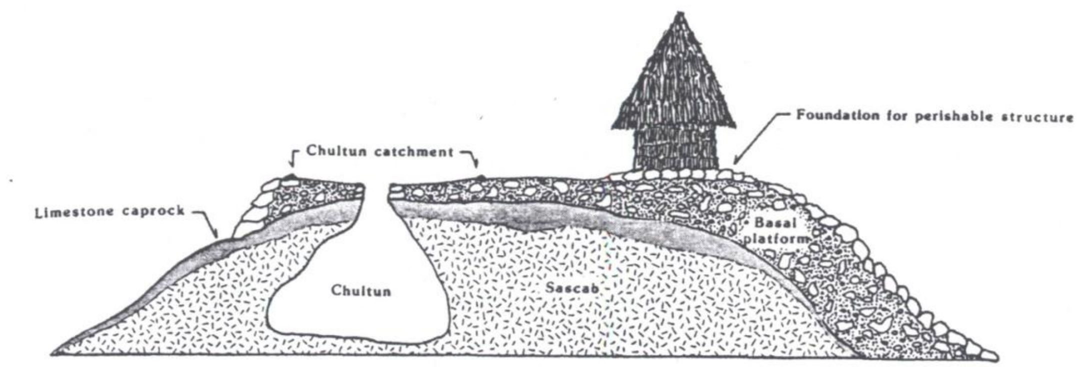


Figure 2.6 – Schematic cross-section of Sayil feature cluster with *chultun* (McAnany 1990).

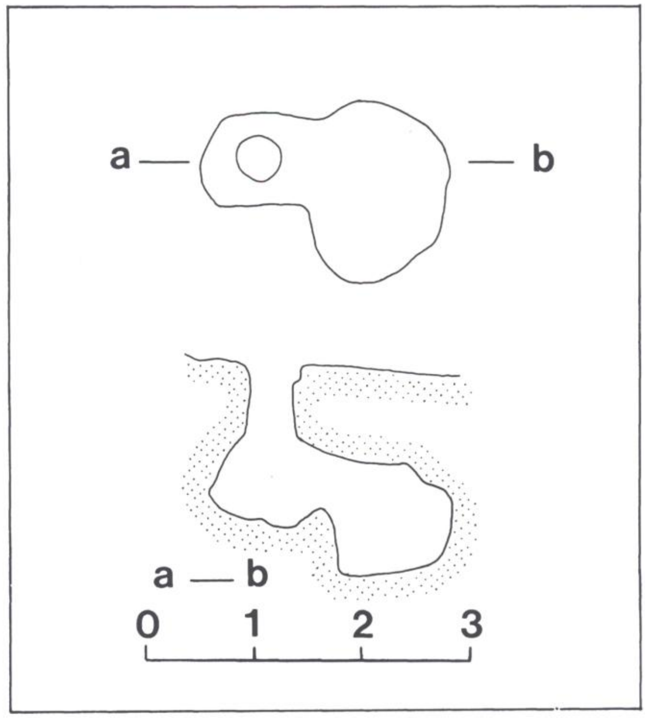


Figure 2.7 – A typical shoe-shaped chultun (Puleston 1971).

As the only significant source of dry-season water in many of the northern sites, the number of *chultunes* in a settlement limited the population size. Both McAnany (1990) and Andrews (2004) used the number of *chultunes* within a catchment area to estimate the population of sites in the Puuc region of northern Yucatan. Their results varied primarily because of differing per capita consumption estimates. While McAnany used 2.4 l of drinking water per day, Andrews chose to use a 6 l estimate based on ethnographic research of a modern Puuc community that included water for cooking, washing, etc. Furthermore, according to Gougoeon (1987), the 6 l a day minimum would not have been sustainable for long without seriously affecting the health of the community.

Puleston (1971) suggested that the southern *chultunes* functioned as chambers for food storage. Experimental studies, however, reveal them to be unsuitable for the storage of most traditional foods, including maize. The only local food crop that appears to be ideally suited for long-term storage under these conditions is the seed of the ramon (*Brosimum alicastrum*, Moraceae).

According to Dahlin and Litzinger (1986), the internal environment of *chultuns* is favorable for fermentation, and they propose that the features were used as places to process, and for limited periods to store, fermented foods such as alcoholic beverages and pickled fruits. Some of the examples of the fermented foods discussed by Dahlin and Litzinger are beer made from the fleshy pulp of fruits, wine from fruits or from sap, as well as pickled preserves from fruits. They also suggest that the distribution of *chultuns* within a site is geared toward a vending economy, principally marketplace vending of alcoholic beverages (Dahlin and Litzinger 1986). This set of interpretations has not been widely accepted, and the various purposes to which the southern *chultunes* were used remain controversial. When abandoned, they often had secondary uses as burial pits or trash pits.

SALT PRODUCTION

Estuarine lagoons and swamps along the northern and northwestern coast of the Yucatán Peninsula have supported salt-making activities since pre-Hispanic times (Andrews 1983). These salt works consist of constructed rectilinear enclosures, or pans, where salt water is trapped at the beginning of the dry season and later evaporates to form thick deposits of salt which are then collected(Andrews 1983). Archaeological evidence of salt-making along the coast of the peninsula may extend back to the early phase of the Late Preclassic period (300-50 B.C.), with evidence for ancient salt pans surviving since the Early Classic period (A.D. 300-600). Andrews (1983) has identified salt pans on the southern coast of Holbox Island, off the north coast of the Yalahua region, that apparently date to recent times.

PLEASURE FACILITIES

Sweat Baths

The earliest descriptions of steam bathing are found in colonial accounts of the Aztec of Central Mexico in the years immediately following the Conquest (Groark 1997). Steam baths were unknown in sixteenth-century Spain (although common in Scandinavia and Russia); in fact, most Europeans of the time considered bathing an unhealthy practice. As a result, the colonial Spaniards were intrigued and horrified by the Aztec enthusiasm for sweat bathing. According to Groark (1997), the practice impressed the historian Clavijero sufficiently that he characterized the sweat bath as "one of the most notable peculiarities" of the Central Valley of Mexico. Throughout Mesoamerica the sweat bath possessed hygienic, therapeutic, and religious significance.

Most ancient Mesoamerican sweat baths encountered archaeologically are those of the elites, and many have been found in the Maya Lowlands (Child 2006). The majority are rectangular structures, typically characterized by a small entrance, raised lateral benches, drains and ventilation holes, and a large adjoining hearth or firebox.

Piedras Negras, located on the Usumacinta River in northwestern Guatemala, is famous for its sweat baths (Figure 2.8). Most of the eight sweat baths recorded within the site core are located near palace structures (Child 2006). Several of the baths have separate antechambers, probably used for undressing or escaping the heat. In addition to a changing room, sweat bath P7 at Piedras Negras had a reservoir atop the structure. When the reservoir was full of water, a plug could be removed from a side drain and those below could enjoy an exhilarating cool shower. The small collection of water could also have been used for the hot stones inside the sweat bath.

The site of Palenque has two elite sweat baths. The first is located on the southern side of the Palace while the second is situated in Group B (Figure 2.9), between the Otolum and Murcielagos streams. Not only was the sweat bath in Group B a water management feature, its location, which required a great deal of landscape alteration, also served to separate the two waterways and thus create more civic terrain (French 2002).

Prior to the construction of Group B and its associated sweat bath, the Otolum and Murcielagos streams probably flowed into each other at the top of the escarpment and then cascaded down as one large stream. Because Palenque had limited civic terrain, several water management techniques were devised for creating additional space. By adding earth to the northern edge of the escarpment and forcing the streams to remain separate, the land once draped in cascades became accessible. This diversion of water allowed for the construction of Group B and the Cascade Group (Figure 2.9).

Pools

Pools are another unique water management feature contributing to the pleasure facilities at Palenque. There are five pools scattered across the site, each built over a perennial spring. Each pool is approximately 6 m X 3 m with a three-meter depth from ground surface. Although the pools receive a constant flow of fresh water, they remain approximately 1.5 m deep because of an appropriately placed overflow drain. The drain directs the excess water to the nearest waterway or stream. No excavations have been conducted in or adjacent to the pools, so their function is unknown (French 2002).

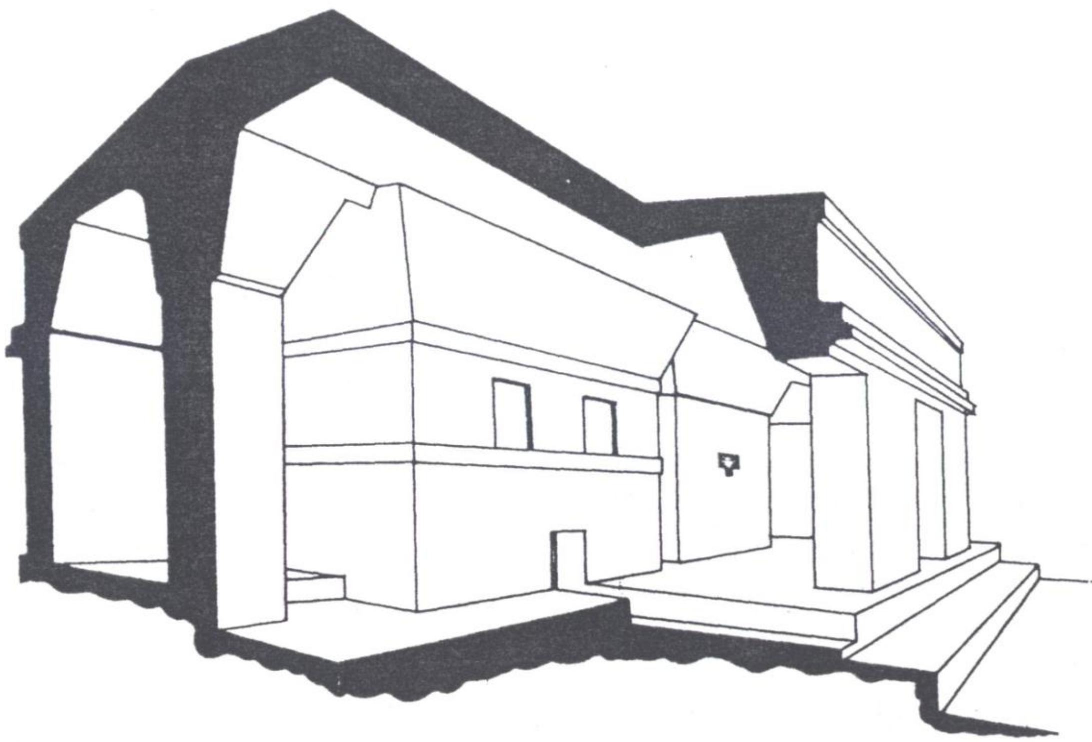


Figure 2.8 – View of sweat bath, Piedras Negras structure P-7-1st-A (Satterthwaite 1952).

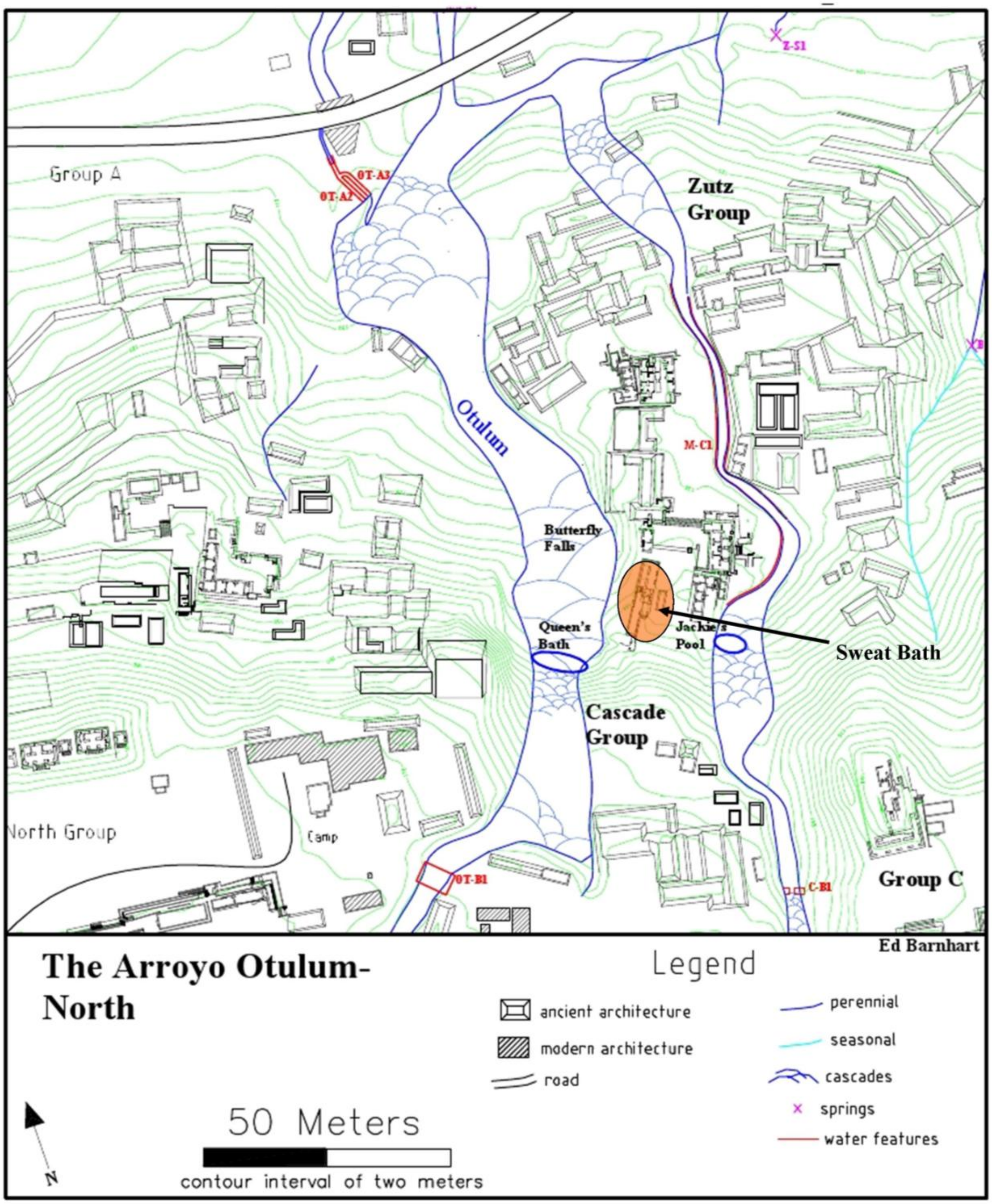


Figure 2.9 – Map of Palenque's Group B and the Cascade Group (French 2002).

SYMBOLISM AND RITUAL

Many ancient Mesoamerican centers and ceremonial precincts can be viewed as architectural replicas of the sacred landscape (Schele & Freidel 1991). The pyramids were mountains that provided an axis of communication with the gods and spirits; the courtyards surrounding them were the valleys and depressions that collected runoff, thereby creating shallow, watery ponds. In some cases, sites contained several large central reservoirs (e.g. Tikal) or were built on islands (e.g. Cozumel's San Gervasio or the ruins of Laguna Miramar in Chiapas) where the temples raised in the center symbolically floated on the primordial waters of creation. Nahuatl terms recorded in 16th century Spanish chronicles reveal that the "water-mountain" concept remained central to architectural programs into the Postclassic period; *altepetl*, a term for polity, translates as "hill place" or "water-hill place" (Miller and Taube 1993, Stark 1999).

For the Maya, water symbolism falls into three broad categories: water on the surface of the earth, water under the earth, and water in the form of rain. Water on the surface of the earth is the domain of the earth god. Water beneath the earth was thought of as an enormous sea that kept the earth afloat. Rain was considered to be the work of the godChaac. Chaac, according to one interpretation, lives in a cave at the horizon from which he hurls lightning to initiate the rain (Bassie-Sweet 1991, 1996). Therefore, much Maya symbolism (as well as most other Mesoamerican cultures) relates to a complex of water/cave/mountain imagery. Thompson (1970) describes a Kekchi and Chol Maya term for the surface of the earth, *Tzultacah*, which means "Mountain-Plain" or "Mountain-Valley." Tzultacah deities may live in or personify springs and rivers, but most importantly they are lords over a particular mountain where they dwell within a cave, protecting maize and controlling thunder and lightning. A corresponding deity reported for the Chuh is *Uitzailic*, who is called *Itacai* among the Chorti Maya. *Thirteen Tzultacah* is a term sometimes used in prayers to embrace the whole body of *Tzultacah* as a single entity. The god of the number thirteen is depicted as a water lily monster sporting a water lily headdress and perhaps representing a *Tzultacah*.

Caves

In addition to providing a reliable source for drinking water during the dry season, the water dripping within a cave is considered extremely sacred and pure. It is collected for the preparation of ritual drinks and healing potions. The symbol for this sacred water is the *cauac* cluster or *tun* sign, which adorns the heads of *witz* monsters at Copán, both on façades and stelae (Fash 1994). The symbol labels the supernatural entity as the embodiment of sacred space. When we see the full- or half-quatrefoil symbol or the *tun* sign on a wall, it is a clue that the space represents a sacred cave or water source. When a royal personage is depicted wearing a water lily headdress, it is a sign that he is acting out the role of a water manager in the guise of *Tzultacah*. Scenes such as this represent rituals performed by a water manager at a water mountain shrine, be it real or symbolic (Fash and Davis-Salazar 2001).

Sweat Baths

Sweat baths played important parts in both Aztec and Maya religion. Groark (1997) states, "When an ailing Aztec entered a sweat bath it was said that he or she was going to see the Yoalticitl, the healer of the night, who could see the secret things and mend that which is disturbed in the bodies of men, fortifying all things tender and delicate". The goddesses associated with the sweat bath possessed strong connections to both the earth and moon and were closely associated with female fertility, pregnancy, childbirth, midwifery, and curing.

Spanish missionaries quickly became aware of the sweat bath's strong religious significance for the Aztecs and immediately began taking steps to eliminate the pagan beliefs and practices. Groark (1997) states that male or female Indians who were not sick and entered a sweat bath faced a penalty of one hundred lashes and two hours tied up and displayed in the public market. Such fierce laws undoubtedly suppressed sweat-bathing rituals but did not destroy them completely. Despite five centuries of Catholicism, the sweat bath remains a sacred structure today in many parts of Mesoamerica.

TRANSPORTATION

Siemens and Puleston (1972) identified several canals along the Rio Candelaria and its tributaries in southern Campeche, Mexico. Using ethnographic analogy to analyze the modern upland settlement of El Chilar and its access canal, they suggested that the canals facilitated transit among settlements, fields, and the river during the dry season. The investigators also suggested that the long canals running parallel to the river course were designed to shorten journeys by avoiding river bends or to aid defensive movements during riverine warfare.

Thompson (1974) disputes the above ideas for two reasons: 1) the cross-cutting canals do not intersect the river and uplands, hence did not provide access; and 2) the parallel canals did not appreciably shorten river journeys. Instead, he uses ethnographic and historic sources to hypothesize that the canals primarily served as fish refuges for pisciculture and only secondarily as means of transportation.

The Maya archaeological site of Chau Hiix, located slightly south and between the sites of Lamanai and Altun Ha in northern Belize, is associated with several canals that were likely used for transportation. Adjacent to Chau Hiix is the Western Lagoon, which was extensively modified with an elaborate system of canals, dams, and dikes. According to Anne Pyburn (2003), the canals connected the site of Chau Hiix to an area of elevated land about one km away on the eastern side of the Western Lagoon. Pyburn describes the canal system but makes little attempt to explain how it functioned. She also fails to supply a map of the canals.

SUMMARY

This chapter provides an overview of the variety of non-agricultural water management techniques used by the Lowland Maya. Although most scholars are acquainted with water practices that are unrelated to food production, many overlook the complexity and importance of humans' daily interaction with water. As humans, our constant reliance on water may in fact be the reason for our unconscious disregard toward water-related research. Water is largely taken for granted because it is a part of everything we do. Just like the Maya, we use water for drinking, cooking, cleaning, swimming, bathing, worshiping, and transporting. The following chapter details my own foray into water management research.

Chapter 3

Palenque: Archaeological History

REDISCOVERY AND EARLY RESEARCH

The first official acknowledgment of the ruins at Palenque appears in a letter written by Ramón Ordoñez y Aguiar to the president of the Real Audiencia of Guatemala in 1773 (Gonzáles 1986). Historical research sheds light on a much earlier discovery by Fray Pedro Lorenzo de la Nada (ibid.). In 1560, Fray Domingo de Azcona invited Fray Pedro to work with the Indians in and around the colonial city of San Cristóbal de las Casas. For six years Fray Pedro worked closely with the Chol and Tzeltal Indians before visiting the Palenque area. During that time, he became fluent in their native languages. When he reached the lowlands, he assisted the Indians by setting up a new town near the Chacamax River, eight km southeast of the ruins. Fray Pedro named this new town Palenque, meaning, according to Spanish dictionaries, "palisade or stockade of wood."

Miguel Angel Fernández, Palenque's head archaeologist during the 1930s, comments in his field reports that "the natives of the area referred to Palenque [ruins] by the name of Otolum" (Gonzáles 1986:5). This name is a word of Chol origin, derived from: <u>otot</u> (house); <u>tul</u> (strong); <u>lum</u> (land), together meaning "strong house land" or "fortified place" (Gonzáles 1986 and Becerra 1980:243). Thus, a strong affinity exists between the words "Palenque" and "Otolum."

Fray Pedro Lorenzo de la Nada is the only person in the early history of Palenque's rediscovery who could have named the town after the ruins. He had a firm enough grasp of the Chol language to search for a similar Spanish translation (Gonzáles 1986). The word Otulum is still used today as the name of the precious stream that flows through the site's center. Palenque was first excavated by Count Frederick Waldeck in 1832. During his two-year stay at the ruins, this eccentric character set up quarters in a temple that was later named in his honor, the Temple of the Count (Trujillo 1974). A lithographer, Waldeck produced beautiful illustrations of the site, although many of his drawings cast the bas-reliefs and stuccos in a Hellenistic light. News of a great Mediterranean civilization, complete with elephants, in the New World sparked enormous interest back in Europe.

In 1840, Patrick Walker and John Caddy journeyed to Palenque. While working in British Honduras (Belize), Walker and Caddy learned of a large-scale scientific investigation of ancient Maya cities that was to be conducted by an American team led by John Lloyd Stephens and Fredrick Catherwood. Britain did not have the resources to support an expedition of such magnitude. "England, despite her reputation for scientific research, was about to become outdone by a representative of that upstart colony to the north" (Pendergast 1967:30). The British knew Stephens and Catherwood were traveling to Copan first and thought it possible to precede them to Palenque. Indeed, Walker and Caddy arrived in Palenque two weeks prior to Stephens and Catherwood. Caddy created a number of remarkable sepia sketches of buildings and sculptures. He published his work promptly in 1840, a full year before Stephens, who also described the site.

During his expedition through Central America in 1890-1891, Alfred P. Maudslay explored the ruins of Palenque. His report on the site occupies the entire fourth and last volume of Biologia Centrali-Americana. "It contains plans of the ruins, photographs and drawings of all the buildings and sculptures known at that time" (Saville 1926:153).

In 1923, the Dirección de Antropología of the Mexican government sent an expedition to Palenque (Blom 1926:168). Frans Blom was asked to develop a rough map to determine the extent of the site's size and density. The data collected from this expedition are still used today by archaeologists. Blom's map was the most thorough survey conducted of Palenque until August 2000.

Before Rodrigo Liendo's (1999) project on agricultural production in the mid-1990s (See Chapter 1), archaeological work included a few regional surveys and test excavations (Rands 1974, Rands and Bishop 1980; Ochoa 1977; Fernandez et al. 1988, Grave Tirado 1999). Without question, the majority of the research at Palenque has focused attention on monumental construction (i.e. temples and palaces) while paying little to no attention to households or the hinterlands. All previous surveying and mapping was similarly limited.

MODERN ARCHAEOLOGICAL RESEARCH AT PALENQUE

Proyecto Grupo de las Cruces and the Palenque Mapping Project

The Proyecto Grupo de las Cruces (PGC), which began in May 1997, was a continuation of archaeological investigations conducted over the last one hundred years. A joint venture of the Pre-Columbian Art Research Institute (PARI), based in San Francisco, California, and Mexico's Instituto Nacional de Antropología e Historia (INAH), the Proyecto Grupo de las Cruces aimed to utilize all available resources to bridge gaps in the archaeological record and to increase understanding of the communal and dynastic histories, as well as the architectural diversity, of Palenque. Under the direction of art historian Merle Greene Robertson and INAH archaeologist Arnoldo Gonzáles Cruz, the PGC made some of the most important finds in the last 30 years. Over a three-year period, archaeologists uncovered the architectural complex of a hitherto unknown king, Ahkal Mo Nahb III, the 14th ruler of Palenque.

A more complete map of Palenque was needed for a better understanding of the site's density and architectural character. In 1998, Edwin Barnhart and team began the task of creating the first complete structural and topographical map of Palenque (Figure 1.1). The Palenque Mapping Project (PMP) was sponsored by Florida's Foundation for the Advancement of Mesoamerican Studies, Inc. (FAMSI). Throughout a three-year period, the PMP mapped a total of 1481 structures within a 2.2 square kilometer area. The earlier map published by Robertson (1983) portrays only 329 structures. The new data generated by the PMP more than quadruples the known size of Palenque, giving it the second highest structure density of all the Classic Maya sites (see population below).

ARCHAEOLOGICAL BIAS AT PALENQUE

Given the beauty of Palenque's central precinct, it is not surprising that most previous investigations have occurred within its boundaries. As a result, archaeological research thus far has presented an unbalanced, elite-heavy picture of Palenque as a community. In other words, archaeologists still lack a basic understanding of Palenque's community as a whole.

The site core was thoroughly documented by the Palenque Mapping Project in 2000 (Barnhart 2002). Barnhart's reconnaissance to the east, north, and south of Palenque's plateau showed that settlement density in those directions dropped off sharply. The last area in question lies to the west. According to topographical maps generated from aerial photos, Palenque's plateau continues approximately one more kilometer to the west as it narrows and becomes increasingly karstic. While settlement density appears to decrease in that direction as well, the area has enough potentially habitable land to merit the continuation of a complete survey out to the plateau's westernmost tip.

Continued survey coupled with the initiation of an excavation testing program is a dire necessity, especially for establishing the chronology of the outer regions. This information could be retrieved through the implementation of a testing program, accomplished with a few test pits in each one of Palenque's outer groups.

An architectural chronology is the next important issue. The validity of the population estimates and settlement densities later discussed in this dissertation are geared to site chronology. While these estimates were appropriately based upon available excavation evidence from multiple sections of the site, too much of Palenque's architecture remains untested to support a more accurate population profile of the site.

We still have only a bare outline of Palenque's community history. The most complete published chronology for Palenque consists of an eleven-period ceramic sequence corresponding to the Middle Formative through Late Classic periods (Rands 1974; 1987; Rands and Bishop 1980; Rands and Bargielski 1992; Bishop 1994). This sequence has been established solely on the basis of a detailed analysis of ceramic paste composition and the comparison of ceramic assemblages to architectural context for which epigraphic records are available (Table 3.0)

According to a recent settlement survey, all the sites within a 37 km^2 radius of Palenque ceramically date to the Late Classic Balunté period (AD 750-820) (Liendo 1999). In fact, many of these sites were occupied as early as AD 350. Palenque is the oldest settlement in the survey area, dating back, according to ceramic finds, to the Late Preclassic phase (300 BC-AD 250) (Mathews 2007). Only Palenque and Chinikihá, in the foothills of the Sierra de Chiapas, show ceramic evidence of settlement during the Early Classic Picota Complex (250-400 AD). Because the largest concentration of Picota assemblages and Preclassic pottery in Palenque come from the Picota Group, it is possible that Palenque's earliest center was located on the western periphery of the site. Since no architectural features at Palenque could be securely assigned to this period, it is assumed that social organization probably was loosely organized at the village level (Bishop 1994:30).

Ceramic Phase	Dates B.C./A.D.
Balunté	c. AD 750 - 820
Murcielagos	c. AD 700 - 750
Otolum	c. AD 620 - 700
Cascada	c. AD 500 - 620
Motiepa	c. AD 400 - 500
Picota	c. AD 250 - 400
Late Preclassic	c. 300 BC - AD 250

Table 3.0 – Palenque Ceramic Phases.

Despite hieroglyphic texts that refer to a lineage founder who came to the throne in AD 431 and an even earlier lord crowned in 967 BC (Martin and Grube 2001), the last 100 years of archaeology have thus far found only structures attributable to the Late Classic Period (AD 650-800). Most of artifact data come from that same Late Classic period. Dr. Robert Rands was one of the few archaeologists in the site's history to find ceramics dating from earlier times.

In sum, much still needs to be learned about Palenque's overall chronology. As it stands we have learned of 18 dynastic rulers from the hieroglyphic texts found mainly within the site center (see Table 3.1). For the details, we must rely on these written records and trust that one day they will be supported by excavations.

DYNASTIC HISTORY OF PALENQUE

Maya dynasties, similar to others throughout Mesoamerica, were patrilineal, meaning descent was mainly traced through males from a founding male ancestor. At times, when the royal family was without a son, rulership was passed to another male relative, often a cousin or uncle. At other times, when a male heir was to accede the throne at a very young age, his mother would serve in his place until he reached appropriate maturity. Another possibility, although very rare, was that a woman inherited the position of ruler. Both Tikal and Palenque witnessed the accession of true queens.

What we know of the dynastic history of Palenque is largely the result of hieroglyphic decipherment rather than archaeological excavations. According to the hieroglyphic inscriptions, several legendary figures, including deities, ruled Palenque millenia before any evidence of human occupation appear at the site. Within the range of historic possibility is the purported founder of the Palenque dynasty, K'uk B'ahlam, who acceded to the throne at the age of 33, on 8.19.15.3.4 - 1 K'an 2 K'ayab (AD March 10, 431).

The second "Ch'a" Ruler was an important individual and reigned for an impressive 52 years. The next two lords of Palenque, Butz'aj Sak Chihk and Ahkal Mo' Nahb I, were most likely brothers, according to Stuart and Stuart (2008).

K'an Joy Chitam assumed the throne in 529 and ruled until his death in 565. Eighty-five days later Ahkal Mo' Nahb II took office, but reigned for only four short years. Kan Bahlam, most likely the younger brother of Ahkal Mo' Nahb II, was subsequently awarded the throne in 572. After Kan Bahlam's death in 583 a rare event

Ruler		Alternate Name(s)	Years of Rule
I	K'uk Bahlam	K'uk' Balam I, Bahlum K'uk	431-435
II	"Ch'a" Ruler II	Casper	435-487
II	Butz'aj Sak Chihk	Manik	487-501
IV	Ahkal Mo' Nahb I	Lord Chaac, Chaacal I	501-524
V	K'an Joy Chitam	K'an Xul I	529-565
VI	Ahkal Mo' Nahb II	Chaacal II, Akul Ah Nab II	565-570
VII	Kan Bahlam	Chan Bahlum I, Kan-Balam I	572-583
VIII	Ix Yohl Ik'nal	Lady Kan, Lady Kanal Ikal	583-604
IX	Ajen Yohl Mat	Aahc-Kan, Ac-Kan, Ah K'an	605-612
X	Janab Pakal	Pacal I	612-612
XI	Muwaan Mat	Lady Beastie	612-615
XII	K'inich Janab Pakal	Lord Shield, Pacal, Pakal, Janaab Pakal, Kinich Janab Pakal II	615-683
XIII	K'inich Kan Bahlam	Snake Jaguar, Chan Bahlum	684-702
XIV	K'inich K'an Joy Chitam	Lord Hok, K'an Xul, K'an Xul II	702-722?
XV	K'inich Ahkal Mo' Nahb	Chaacal III, Ah Kul Ah Nab III	722-?
XVI	Upakal K'inich Janab Pakal	None	?-764?
XVII	K'inich Kan Bahlam II	None	764?
XVIII	K'inich K'uk' Bahlam	Lord K'uk', Bahlum K'uk'	764-?

Table 3.1 – Palenque Dynastic History (Stuart and Stuart 2008).

occurred. Ix Yohl Ik'nal, who is one of only a handful of female rulers known in Maya history, became the queen of Palenque. During her reign on April 23, 599 Palenque suffered a key military defeat by Calakmul, the powerful realm located far to the east. Ix Yohl Ik'nal died in 604 and was replaced with Ajen Yohl Mat in 605. Stuart and Stuart (2008) suggest Ajen Yohl Mat was a "rabble rouser" because he managed to provoke Calakmul during his seven year reign and Palenque was again sacked. The circumstances surrounding the following two rulers, Janab Pakal and Muwaan Mat, are not very clear. Oddly though, Muwaan Mat took his name from an important god-king who fathered the Triad of gods shortly after the creation of the current era. Stuart and Stuart (2008) suggest the parallelism of creation mythology is directly linked to the beginning of a new political order.

K'inich Janab Pakal, was the catalyst who revived Palenque and transformed it into a center of prestige, beauty, and power. On 9.9.2.4.8 - 5 Lamat 1 Mol (July 29, 615), at the age of 12, Pakal acceded to the throne of Palenque. Born on 9.8.9.13.0 - 8 Ahaw 13 Pop (March 26, 603), Pakal was the son of Lady Sak K'uk' and her consort, K'an Hix Mo' (Schele and Mathews 1998, Stuart and Stuart 2008). It is speculated that Pakal's father, K'an Hix Mo', was a foreigner and perhaps that Pakal himself was born elsewhere (Stuart and Stuart 2008). Although succession was normally through the male line, Pakal inherited the throne through his mother, who briefly served as ruler (Schele and Mathews 1998, Stuart and Stuart 2008).

This unprecedented break in the royal line forced Pakal to not only change the historical rules of succession through the father, but to justify it as well. Lady Sak K'uk' was declared the equivalent of the "first mother," or "progenitor deity," (Stuart and Stuart 1998) who, at the beginning of the present creation, gave birth to the three patron gods of Palenque and subsequently became ruler of the city. Pakal then claimed that he had been born on the same calendar date as the goddess, two thousand years before. Pakal and the goddess thus were of the same divine substance. The young king had a right to inherit the throne from his mother because, at the dawn of creation, royal authority had been transmitted through both males and females (Schele and Freidel 1990).

Pakal engaged in warfare during the first thirty-five years of his reign. Several of the wars were motivated by revenge against cities such as Bonampak and Calakmul, which had savaged Palenque prior to Pakal's succession (Schele and Mathews 1998, Stuart and Stuart 2008). The second half of Pakal's reign was devoted to peace and civic expansion. Along with his shift from war to peace, Pakal began a building renaissance that transformed the face of the city. Pakal's dedication to the arts peaked around AD 675, when, at the age of seventy-two, he began construction on his tomb, a task completed by his son and heir. Eight years later, on 9.12.11.5.18 - 6 Etz'nab 11 Yax (August 31, 683), Pakal "took the white road," and his body was placed deep inside the Temple of the Inscriptions (Figure 3.0). The tomb door was sealed and the tunnel that led from the top of the temple was filled with earth and offerings, including several sacrificed servants, who accompanied the king on his underworld journey. Pakal's tomb would remain sealed for the next 1268 years.

Pakal's son, K'inich Kan Bahlam (aka Chan Bahlum), came to the throne in 684. In an attempt to carry on his father's construction legacy, K'inich Kan Bahlam built the Cross Group (Figure 3.0). This expansion east of the Arroyo Otulum (Figure 3.0) probably led to the construction of the Palace aqueduct. The Otolum, flowing through the center of the plaza, naturally divides the site center. In part, the purpose of the aqueduct was to unite the Palace (Figure 3.0) and Temple of the Inscriptions with Chan Bahlum's Cross Group. Without excavation it is difficult to determine the specific dates of the aqueduct's construction.

After K'inich Kan Bahlam's death, his younger brother K'inich K'an Joy Chitam became king and ruled for about 20 years. The throne was then passed to the nephew of the two brothers, K'inich Ahkal Mo' Nahb in 722. Much political art concerning his legitimacy through close kinship to K'inich Janab Pakal was discovered during the excavations of Temple XIX in 1999 and 2000. The following 80-100 years saw the rise and fall of three more kings, but little is known. Inscribed on a modest pot is the name of the last ruler of Palenque, Wak Kimi Janahb' Pakal, who acceded to the throne on 9.18.9.4.4 - 7 K'an 17 Muwan (November 17, 799). This is the latest dated text found at

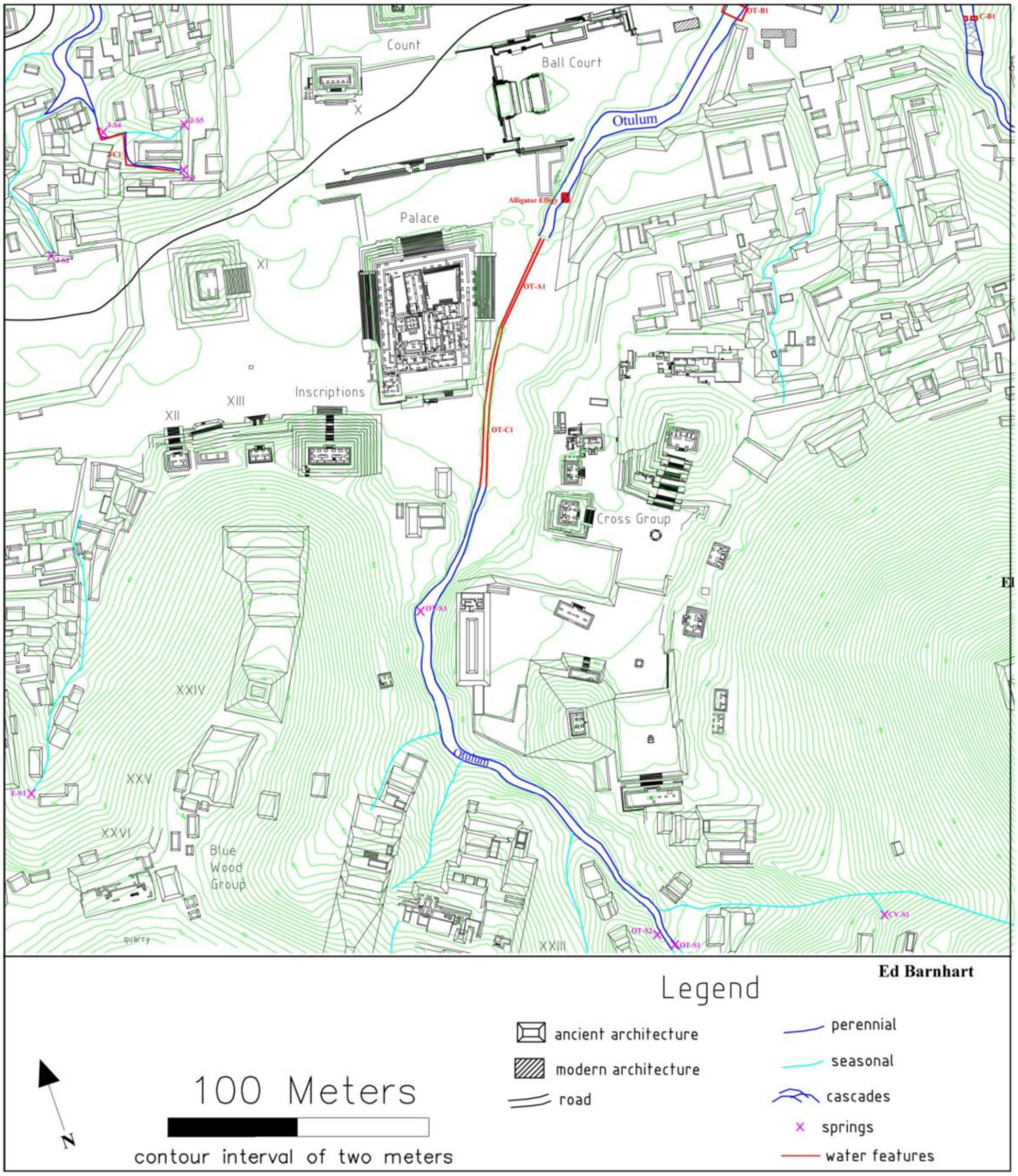


Figure 3.0 – Map of Palenque's central core.

the site. Like other Classic Maya centers, Palenque was abandoned for reasons not fully understood, and the pacing of its abandonment is poorly dated and obscure.

POPULATION

Beyond the ceremonial center and the compounds of nobles dwelled the common people. The peripheral settlement of Palenque (i.e., that within a minimum of 40 km^2 and presumably under the sway of Palenque's kings), to the extent it exists, lies on different landforms than Palenque's plateau-top core. In order to properly assess Palenque's periphery, surveys are needed of the mountains above and the plains below. The plains were sampled in the 1990s and found to have extremely sparse settlement. Liendo's (1999) detailed survey of 37 km^2 extending east of Palenque's center to the bank of the Chacamax River and west along the Michol located around ten habitation sites from the Otolum phase, and more than 80 habitation sites with Balunté pottery (Table 3.0) as well as many agricultural canals. Surveys of the mountainsides around the plateau have yet to be conducted. Based on current evidence and informal reconnaissance, a very low settlement density for the immediately adjacent mountainsides is also predicted (Barnhart 2001). At the substantial distance of 10 km to the east and west of Palenque appear the small satellite sites of Nunutun and Santa Isabel.

According to Barnhart's (2001) documentation of 1481 structures over a 2.2 km^2 area, Palenque's urban core has an average of 673 structures per sq km. As Table 3.2 illustrates, Palenque's urban settlement density is the second highest ever recorded for a Classic Maya city. If we include the Postclassic sites, Palenque's rank drops to third overall, behind Mayapan (986 structures/km^2) and Copan. Given Palenque's geographical limitations, such a high settlement density is not entirely unexpected.

In almost every population estimate put forth for an ancient Maya city the researcher has altered the results by calculating a percentage from the standard count of 5.6 persons per structure. Some would have the raw numbers reduced, based on the accepted fact that not all peripheral mounds could be residential. Haviland's (1965) studies at Tikal led him to suggest that 16.5% were non-residential. For Copan, Webster

Site	Core Area (km^2)	Structures / km^2
Copan	0.6	1449
Palenque	***2.2***	***673***
Dzibilchaltun	19.0	442
Caracol	2.2	300
Siebal	1.6	275
Tikal	9.0	235
Becan	3.0	222
Sayil	2.4	220
Quirigua	3.0	128
Belize Valley	5.0	118
Uaxactun	2.0	112
Nohmul	4.0	58

Table 3.2 - Core area urban settlement densities at selected Classic Maya sites (Adapted from Sharer 1994, Rice and Culbert 1990, and Barnhart 2001).

and Freter (1990) suggested 20-30%.

On the other hand, there are those who would have the raw numbers increased, based on the undetectable presence of perishable structures. For the sites of Santa Rita (D. Chase 1990) and Tayasal (A. Chase 1990), the population estimates factored in perishable and undetected structures, raising the surveyed structure count by 37-50%. Studies at Nohmul also factored in for hidden structures (Pyburn 1990). In the case of Palenque, with its extremely high building density, it is hard to imagine adding much more space for perishable structures. Palenque's lack of data on small mound excavations further begs conservative estimates. Percentage reductions also have to be factored in for gaps in the chronological data. Given these limitations, Palenque's estimate presented by Barnhart (2001) utilizes the figures compiled by Rice and Culbert (1990): a flat 30% reduction from the raw structure count.

Palenque contains 1481 structures spread over a 2.2 km^2 area. Estimating four to six persons per structure, we arrive at a population of 4147-6220 people. That translates to a population density of 1885-2827 people per sq km. Tables 3.2 and 3.3 show those figures compared to the core areas of other Classic period Maya sites. These population estimates clearly suggest that a very elaborate center along with a durable and politically active Maya kingdom could have a core population of well below 10,000.

Based on current archaeological evidence, the "site" of Palenque is, effectively, the "polity" of Palenque in demographic terms. Sites such as Tikal or Calakmul had relatively flat topography that allowed for expansive distribution of population and architectural growth well beyond their centers, while the site of Palenque was so confined geographically (Figure 1.4) that the site and its polity are essentially one in the same. In the following chapter I suggest it is this difference in geographical space that led to the unusual urban landscape of Palenque and the degree to which the manipulation of water was essential to its growth and maintenance.

Site	Core Area (km^2)	Peak Population	Population/km^2
Copan	1.0	5797 – 9464	5797 – 9464
Sayil	3.4	8,148 – 9,900	2,396 – 2,912
Palenque	***2.2***	***4,147 – 6,220***	***1885 – 2827***
Komchen	2.0	2,500 – 3,000	1250 – 1500
Siebal	1.6	1,644	1028
Santa Rita	5.0	4,958 – 8,722	992 – 1744
Tikal	9.0	8,300	922
Tayasal	8.0	6,861 – 10,400	858 – 1,300
Caracol	2.2	1,200 – 1,600	545 – 727

Table 3.3 - Comparison of population estimates in the Maya region (Adapted from Sharer 1994, Rice and Culbert 1990, and Barnhart 2001).

Chapter 4

The Urban Landscape

The criteria used to determine the presence of urbanism in Mesoamerica has varied among researchers. Mesoamerican urbanism has been evaluated against a checklist with a variety of characteristics that comprises mainly of four components: 1) population size; 2) nucleation; 3) social diversity; and 4) economic complexity. All four have been demonstrated to have existed within ancient Maya communities. Populations in the thousands have been estimated at most sites for which settlement pattern data exists. In addition, many centers had populations in the tens of thousands. Nucleation appears to have been present within the majority of Maya centers; the core area being much more densely settled than its periphery. But social diversity has been the most debated of the three criteria for the Maya. Compared to the evidence from Central Mexico, and especially Teotihuacan, Sanders and Webster (1988) suggested the Maya did not reach a level of social diversity sufficient enough to be classified as urban.

Today scholars continue to argue the urban nature of Classic Maya centers. The majority of the debate seems to have turned toward defining the degree of urbanism these centers achieved. In their 1988 paper "The Mesoamerican Urban Tradition", Sanders and Webster applied an urban classification system developed by Fox (1977) to Mesoamerican cities. Fox's model defines three types of pre-industrial cities: 1*) regal-ritual*, 2) *administrative*, and 3) *mercantile*. Sanders and Webster categorized most Classic Maya centers as "regal-ritual". The criteria cited to support their assertion were; obtrusive ideological functions, comparatively low populations, consumption-based economies, kinship based, inherited power, and only minor social differences between city core and peripheral inhabitants.

Sanders and Webster concluded that most centers in Mesoamerica were of the "*regal-ritual*" type. That is, generally having a low population, being consumption based and focused primarily on ritual activities taking place in the central precincts. They claimed that the ancient Maya were a “low energy” culture group due to their dependence on manpower for transport.

According to Barnhart (2001), Palenque was “one of the most highly urbanized centers of the Maya Classic Period” because of 1) a high settlement density (see Chapter 3); 2) monumental public works (see Flood Control and Erosion below); and 3) public activity zones, such as plazas (see Creating Space below).

Whether or not Palenque conforms to some particular definition of urbanism is not as important as the unusual character of the site’s architectural landscape. The dilemma of having limited geographic space for civic and household construction was exacerbated by the many waterways that cut through the site. The engineers of Palenque designed several subterranean aqueducts to aid the inhabitants of this urban environment.

PUBLIC WORKS AND THE URBAN LANDSCAPE AT PALENQUE

Flood Control

In the semi-tropical land of the Maya the searing dry season is followed by an intense period of precipitation. The rainy season would not have been such a problem for most Maya cities were it not for the vast amount of impermeable civic construction. Many of the large plazas and courtyards were blanketed with thick layers of stucco, resembling our all too familiar concrete and “asphalt jungles.” Because the precipitation could not penetrate the stucco floors the surfaces had to be carefully engineered with a slight slope to allow for runoff. In addition, numerous drains had to cope with the massive overflow during tropical storms.

Flood control was another function performed by the aqueducts at Palenque. The four-month rainy season causes mountain streams to expand significantly in size as they rush downhill toward the level shelf where plazas and associated structures lie. The abrupt change in declination causes the streams to slow, subsequently forcing the water level to rise and flood the plazas and residential compounds, at least for large precipitation events. When Maudslay (1889-1902) visited Palenque during the dry season of 1895, prior to the refurbishment of the Palace aqueduct (OT-A1), he observed that the Main Plaza completely flooded three times during his stay. His fieldwork was conducted between February and April, when the average rainfall reaches only 78.4mm (Figure 4.0). Prior to 1950 the entrance to the Palace aqueduct was completely collapsed, causing the Otolum to flow a few meters to the east in a new streambed (Figure 4.1). Maudslay's account, along with the damaged entrance, provides a view of how the Main Plaza would function during heavy rains without the assistance of the aqueduct. By forcing the flowing water of the streams below the surface of the plaza, city planners were able to decrease the risks of plaza and residential flooding provided that the hydraulic capacity of the aqueduct was designed to have sufficient size and slope.

Erosion Control

As mentioned earlier, a serious problem Palenque's city planners must have faced, along with seasonal flooding, was erosion. Without proper water control features in place, erosion and damage to the built environment would have been severe, not just for the elite but also for the large number of urban residents living near the city's center. In order to minimize land loss and residential disruption from erosion, a partial canalization of all nine waterways was implemented. Construction of these walled channels or aqueducts outside of the center constitutes suggests what Barnhart (2001) refers to as "public works." These public works encompass all monumental constructions that served the needs of the community at large. The sophistication of the water management features is demonstrated by the fact that the majority of them remain intact and functional after more than 1200 rainy seasons.

Creating Space

Palenque's control of nine separate waterways generated from 56 recorded springs provided an ample supply of water for an expanding community. With this great quantity of water came an unforgiving landscape consisting of steep hills, sheer cliffs, and deep arroyos that posed challenges for city growth. The obstacle for the city planners of Palenque was not water insufficiency, but rather a paucity of habitable terrain. This

Palenque Rainfall & Temp A Simulated 100-year Average		
Month	**Rainfall mm**	**Temp °C**
January	247.7	21.5
February	111.2	24.5
March	84.8	25.4
April	39.4	26.4
May	150.1	28.7
June	302.5	27.8
July	303.8	27.1
August	335.3	26.8
September	476.9	26.6
October	546.5	25.2
November	241.7	24.3
December	194	22.9
Total/Avg.	**3033.9**	**25.6**

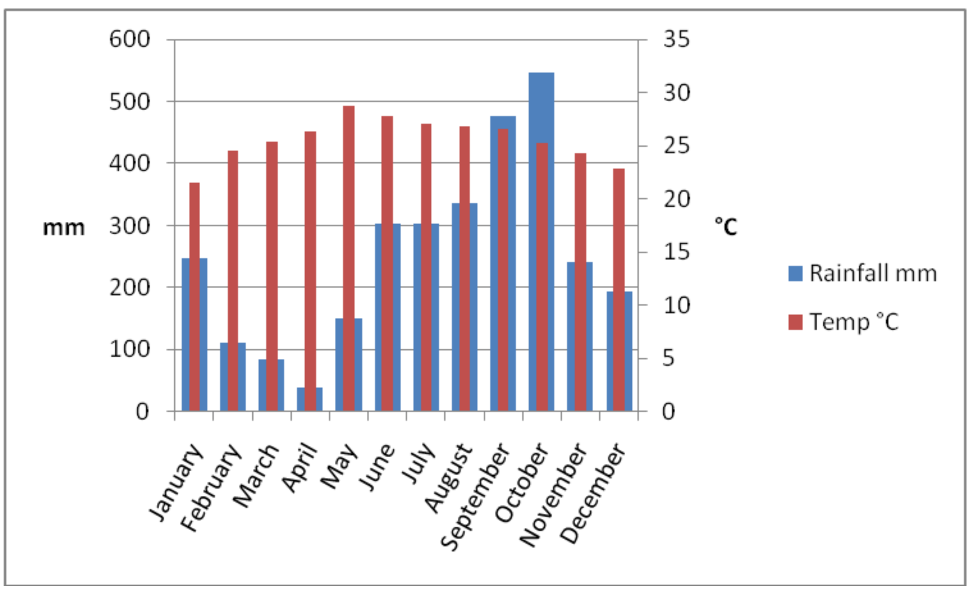


Figure 4.0 – Palenque's annual rainfall charts based on simulation (see Chapter 5). The 100-year rainfall estimate (1901-2000) was based on an interpolation of tropical weather stations by MarkSim (Jones and Thorton 2000).

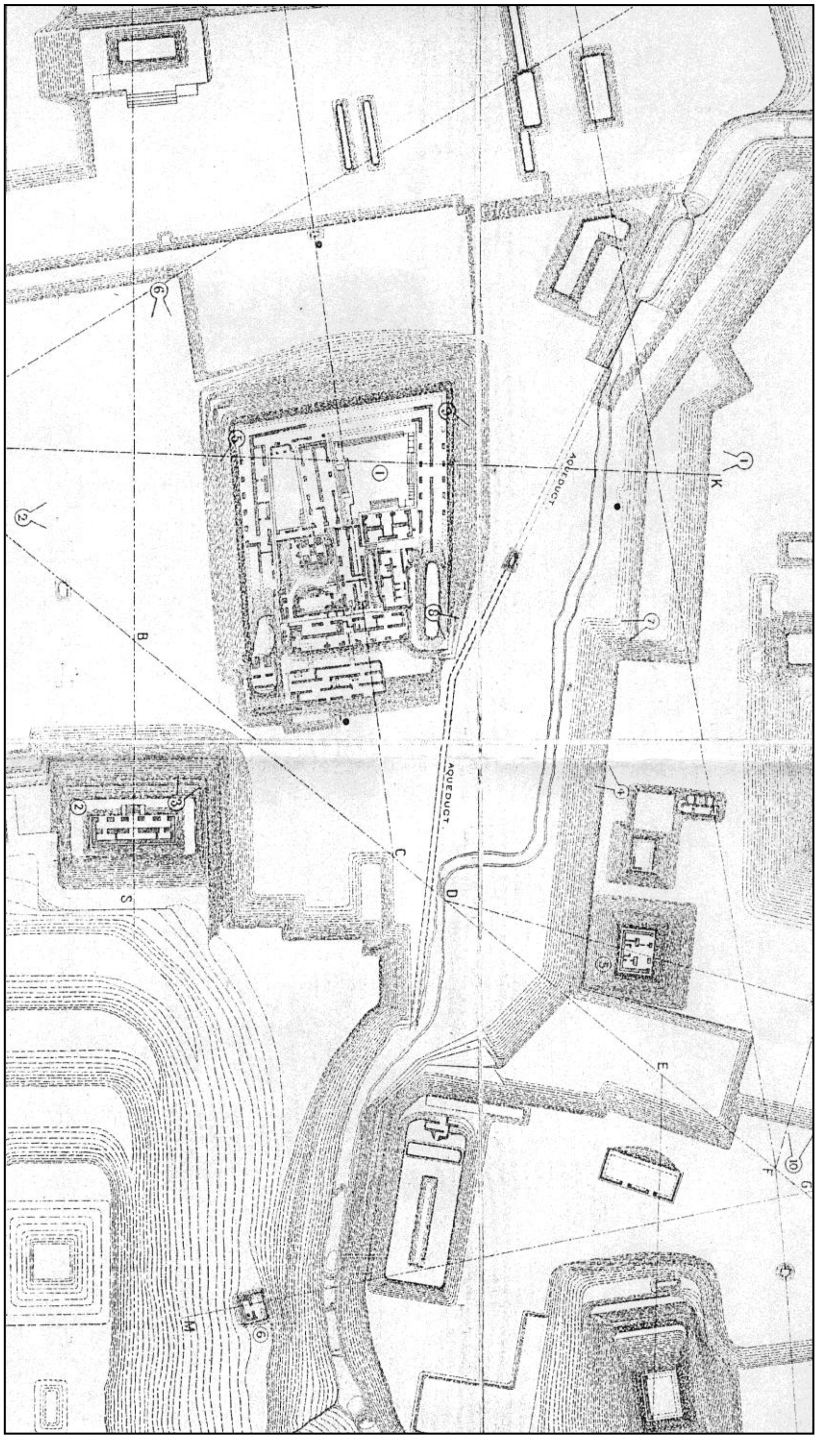


Figure 4.1 - Map of Palenque in 1891. Notice the stream bypassing and flowing parallel to the aqueduct (Maudslay 1889-1902).

challenge led the ancient Palencanos to develop the second most densely populated city in the Maya region (Barnhart 2001) in tandem with a phenomenal subterranean aqueduct system.

Although many of the site's residential groups were constructed on terraced hillsides, the plazas and public centers were created atop a narrow limestone escarpment measuring approximately 1700 m east-west by 260 m north-south. While the escarpment does continue further to the west, evidence of prehispanic settlement declines abruptly. The constricted limestone shelf provided limited space for such occasions as religious or political ceremonies, public markets, or simple habitation.

Civic activities in Mesoamerica typically occurred in large, level, open spaces located within the city's center--plazas. These areas were designed for public use and provided a setting for everyday urban life where daily interactions, economic exchange and informal conversations occurred, and created socially meaningful space within the city (Low 2000). These communal interplays are thought to be the threads that create the natural "human whole" (Arensberg 1961; Redfield 1955) that serves as a society's principal unit of biological and cultural reproduction (Yaeger and Canuto 2000). Murdock (1949) also strongly emphasized the importance of interaction among community members, claiming it as a necessary condition of the community's existence.

The modern Latin American plaza can provide insight into the Precolumbian plaza via ethnoarchaeology (Low 2000). Many scholars share the belief that the grid-plan town with a central plaza found throughout Latin America is a European creation, but Low (2000) presents suggestive evidence that counters this assumption. She explains that the redesign of Spanish cities in grid-plan during the mid-16th century under the rule of Philip II was in part stimulated by the urban-design experiments of the New World. By overlooking the Precolumbian architectural and archaeological record, many historians have constructed a Eurocentric view of the evolution of the New World urban form. Town centers of European cities such as Córdoba and Madrid, rebuilt many years after the colonization process began, mimic the design of the newly created plazas of the Spanish-American New World. Low's implication that the colonial plaza and grid-plan design found in Latin America was more an indigenous than Spanish creation only adds validity to the ethnographic research of plazas as ethnoarchaeological data.

Today, throughout Latin America, plazas are locations within cities where communal activities take place. The church as well as the government offices of a city are typically found on the borders of the plaza, where the majority of public religious and political gatherings occur. The design of most Mesoamerican plazas exhibits a similar layout, where the grandest of temples coupled with a palace or elite residential structure characteristically create the borders of the plaza.

At Palenque, the spring-fed streams that naturally dissected the landscape contributed to the dilemma of building on its confined plateau. George Andrews (1975) claimed that this irregular natural terrain caused many problems for the city's builders, who were forced to do a considerable amount of reshaping of the existing ground form to maintain a semblance of visual order in the over-all layout of the city. To simultaneously control flooding and erosion and also bridge the divided areas to expand civic space, the Maya of Palenque covered portions of the preexisting streams by constructing elaborate subterranean aqueducts that guided the stream beneath plaza floors. The two plazas of concern here are the Picota Plaza (Figures 4.2 & 4.3) and the Main Plaza (Figures 4.4 & 4.5).

The Picota Plaza, located one km due west of the site center, contains approximately 1477 m^2 of surface and the Picota stream passes beneath its floor. In order to estimate how much surface space was gained by channeling the stream underground, I calculated the average width of the Picota arroyo by systematically measuring its width where canalization was absent; an average width of 7.23 m. This figure was then multiplied by 47 m, the length of the Picota aqueduct (P-A1), to arrive at an estimate of 340 m^2 of surface area created by covering the stream (Table 4.0). The construction of P-A1 allowed the Maya of Palenque to increase their plaza size by 23% (Figures 4.2 & 4.3). Apart from plaza expansion, the absence of the aqueduct would have prevented the construction of the structure and staircase built on the south side.

Main plazas are one of the most important elements of a Maya center. The counterweight to mass is void, and the Maya valued the plazas as much as the structures

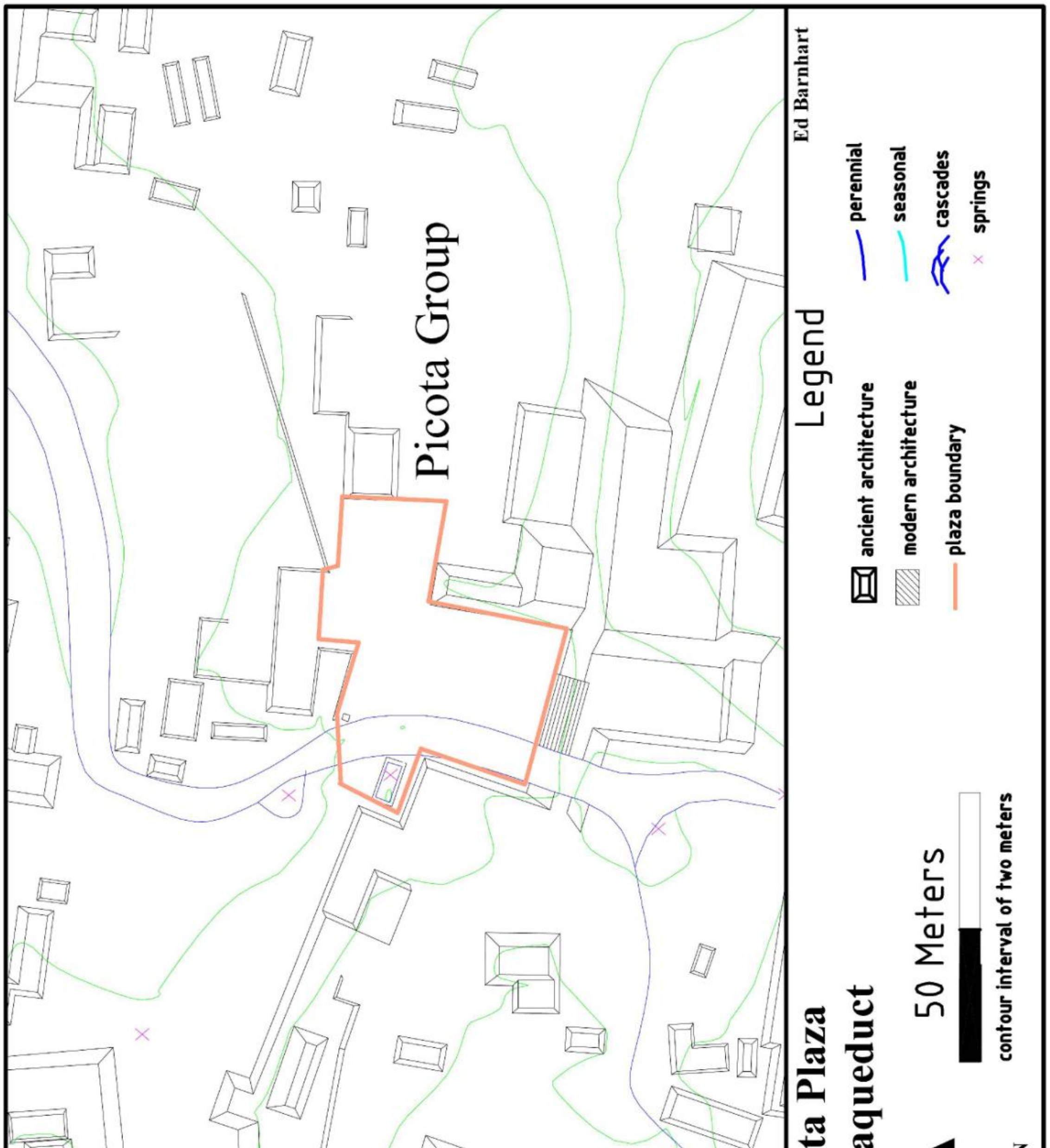


Figure 4.2 – The Picota Plaza without the aqueduct (French 2002).

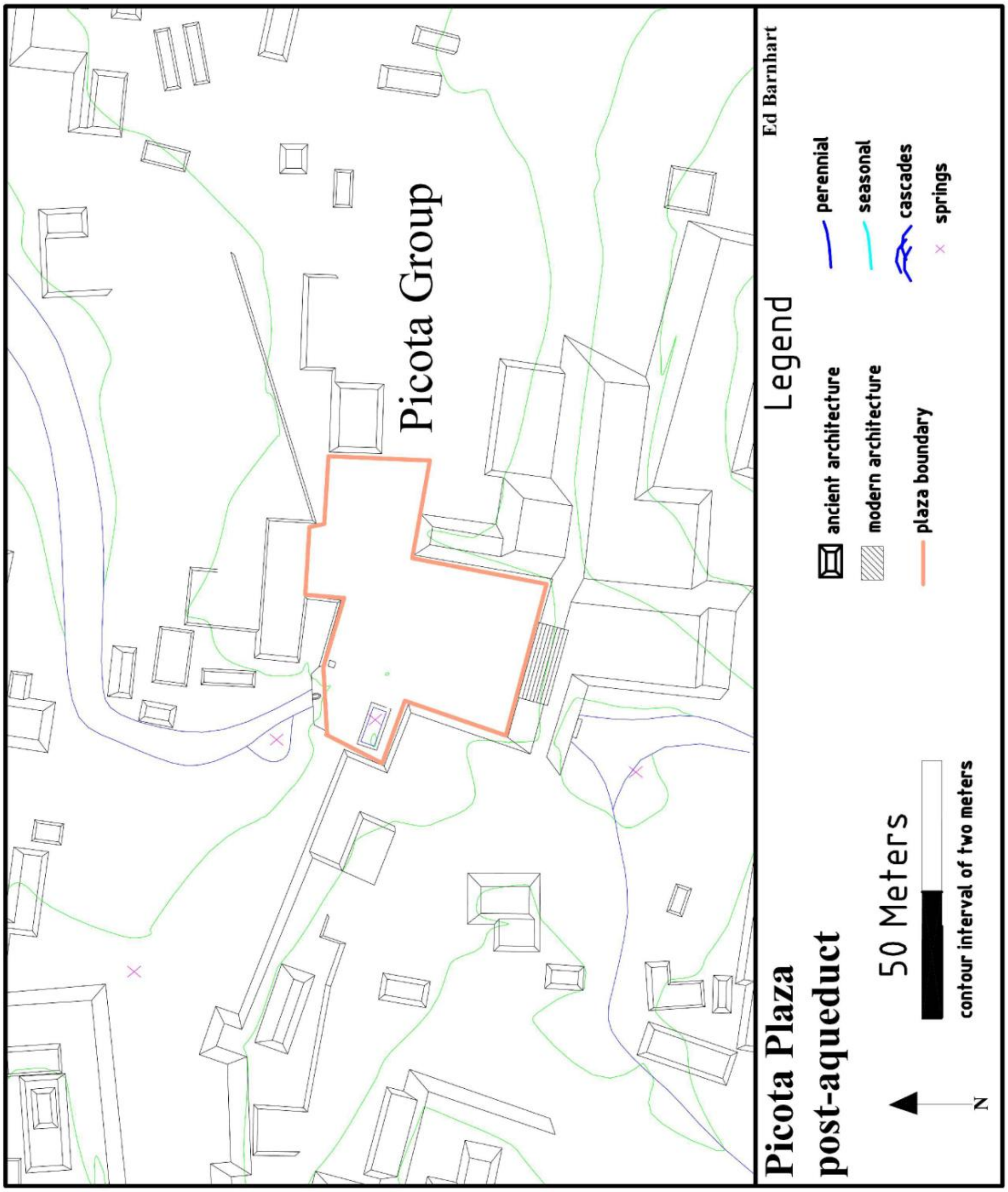


Figure 4.3 – The Picota Plaza with the aqueduct (French 2002).

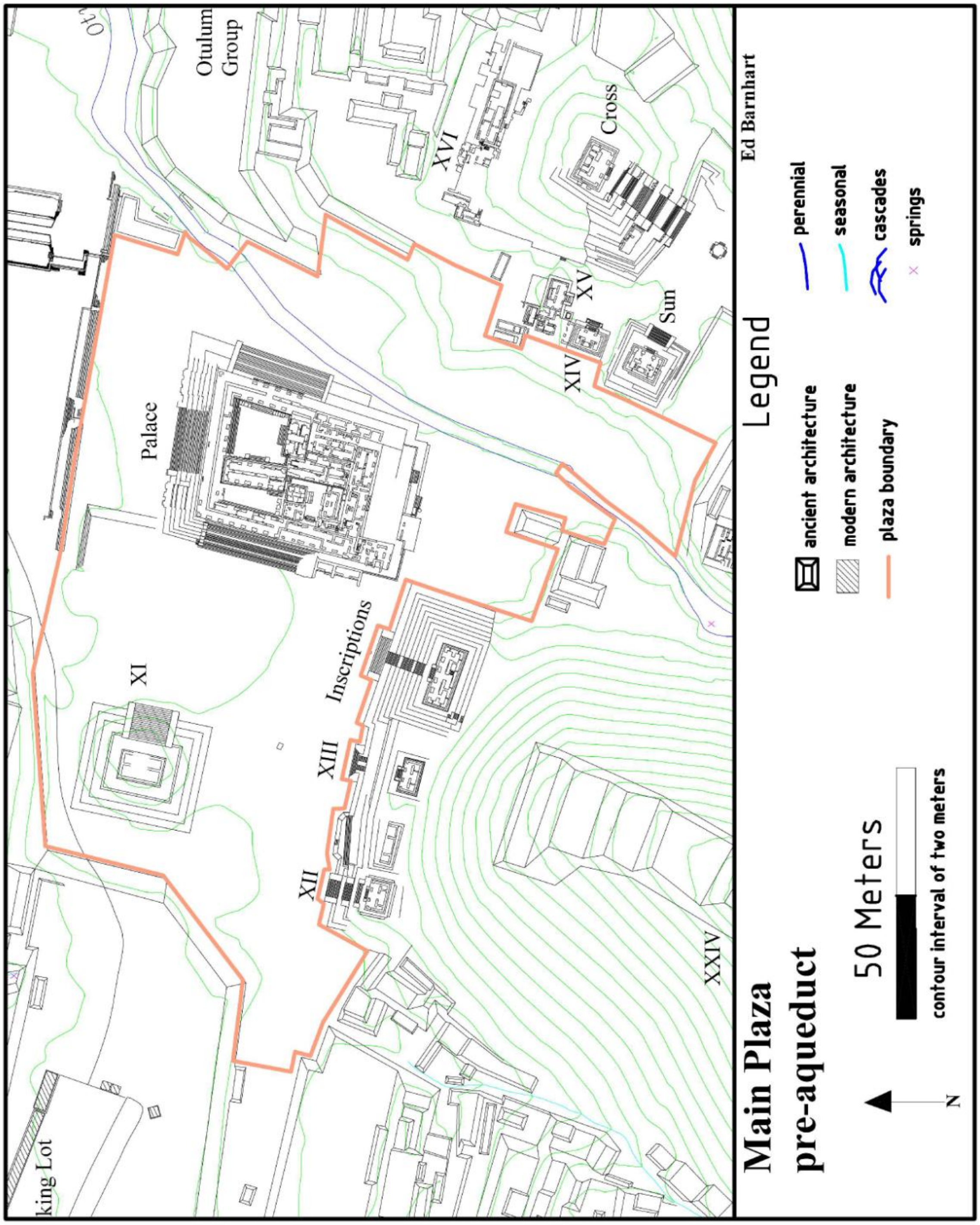


Figure 4.4 – The Main Plaza without the aqueduct (French 2002).

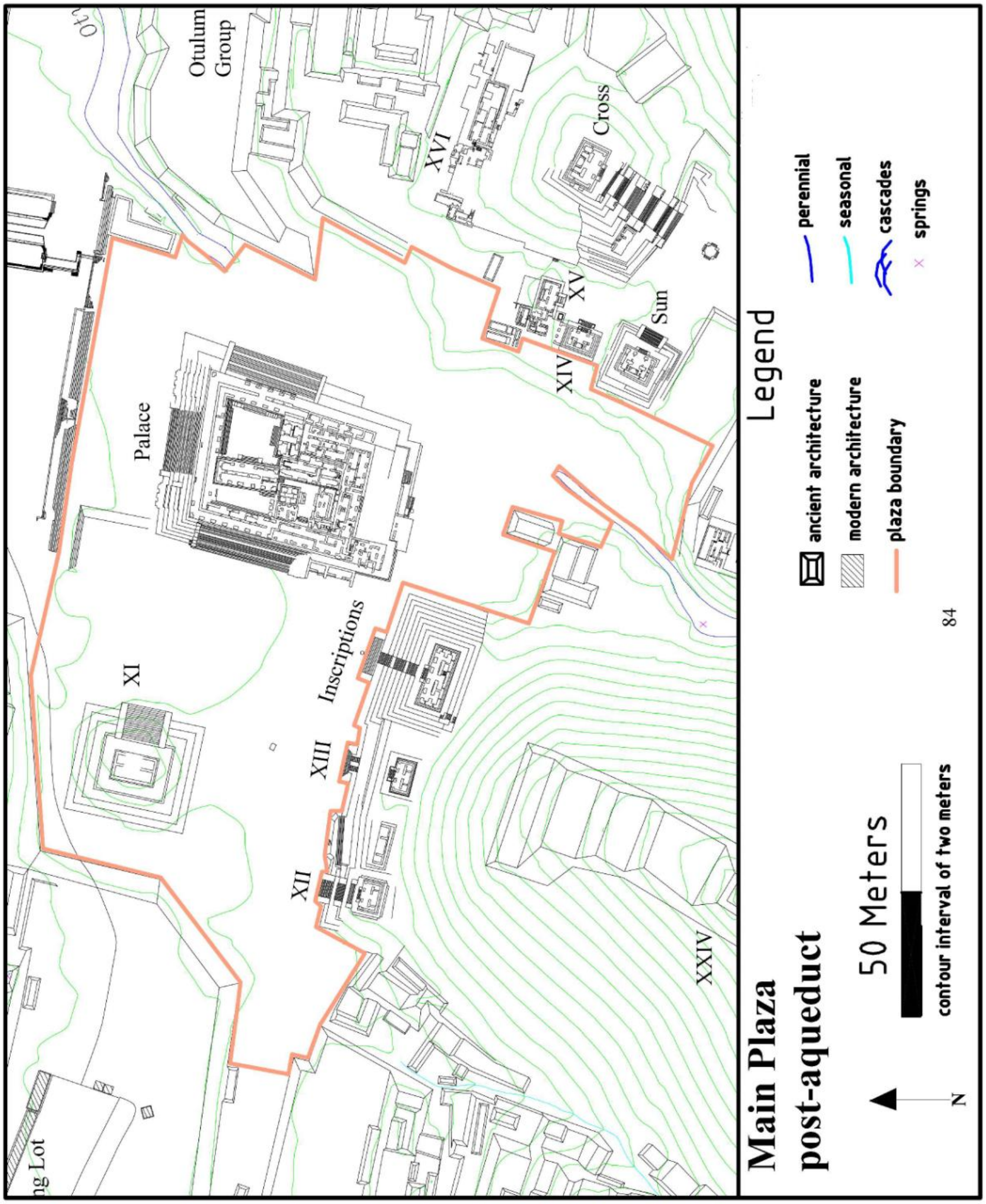


Figure 4.5 – The Main Plaza with the aqueduct (French 2002).

Feature	Plaza Size	Average Arroyo Width	Aqueduct Length	Land Generated	Increase	Land Gained Opposite Streamside	Total Gained
Picota Plaza	$1477m^2$	7.23m	47m	$340m^2$	23%	na	23%
Main Plaza	$33421m^2$	6.27m	154m	$971m^2$	3%	$6547m^2$	23%

Table 4.0 – Plaza expansion calculations

that surrounded them (Miller 1999). Larger buildings demand larger plazas, so the plazas required expansion as a city grew and buildings became larger. Due to the irregularities of Palenque's topography, expansion required innovation.

The Palace was constructed on the banks of the Otolum stream in order to utilize the open space on its west side. On the east side, the city planners constructed a subterranean aqueduct beneath the plaza floor. Due to variations in materials and architectural styles, the aqueduct appears to have been implemented in four separate stages, with each stage creating more space to the south side of the plaza (Figures 4.4 & 4.5).

By covering 155 m of the Otolum, only 971 m^2 of surface area was actually created, which is a mere 3% of the total plaza size. But, 6547 m^2 of surface area was gained by bridging together the area to the east of the Otolum. The land produced by the aqueduct, along with the level terrain east of the Otolum, increased the size of the Main Plaza by 23%. Today, Palenque's Main Plaza is partially divided by the Otolum Stream due to the collapse of the Palace aqueduct's southern portion.

The strongest evidence for urbanism in Palenque is the investment in public works. Significant resources were expended outside the central precinct of the site. Great amounts of labor were spent on the construction of 16 non-contiguous km of architectural terracing (Figure 4.6) and significant canalization of each stream. These major projects appear to have opened habitable land for construction. The existence of these public works makes Palenque different from most other major Maya Classic cities. Construction of permanent flow conveyance structures at Palenque required understanding of local material properties and flow design capacities, given the extreme flooding events known to occur at Palenque. The simulated paleoclimate data presented

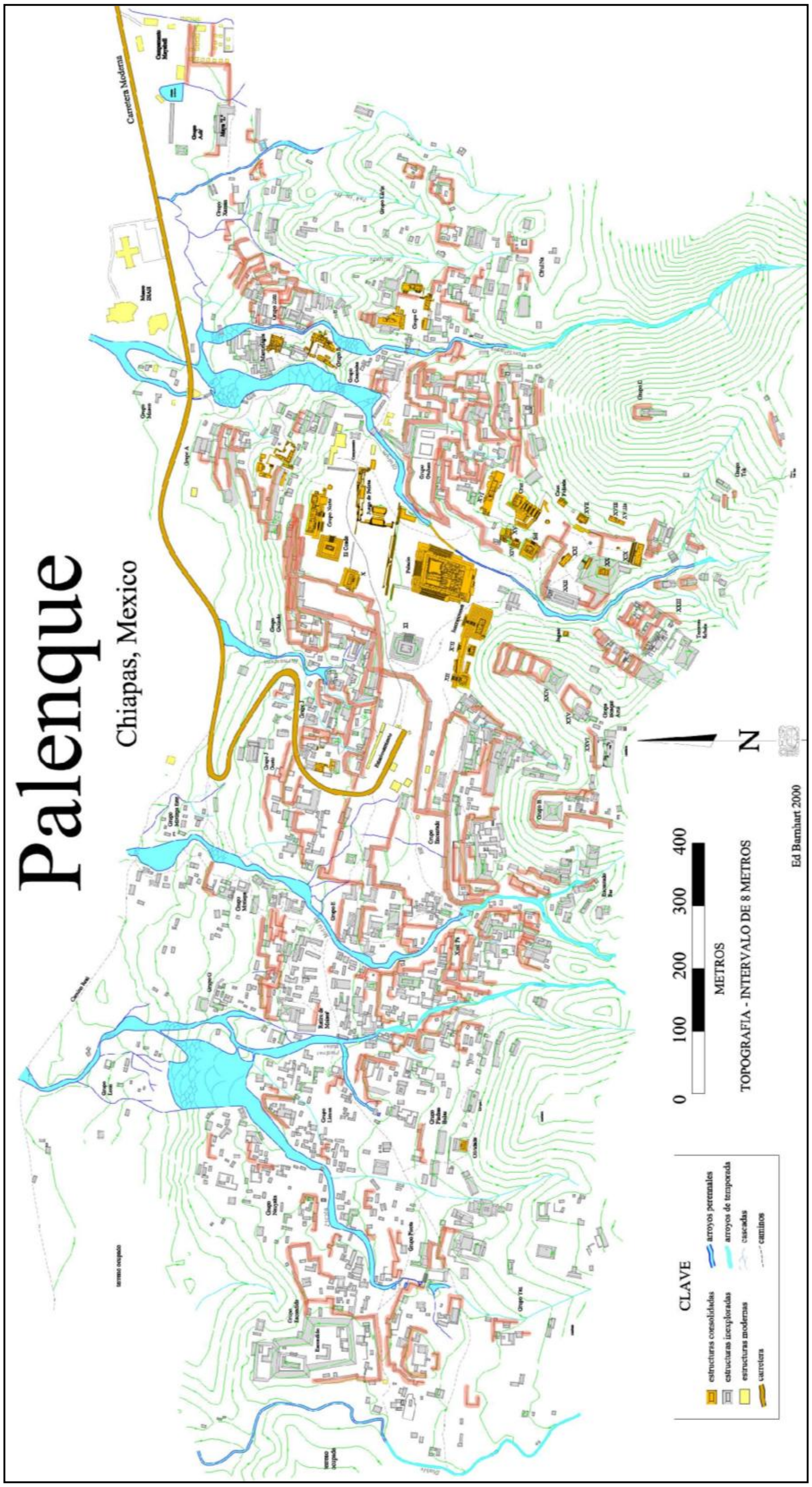


Figure 4.6 – Map of Palenque with terraces delineated in rose.

in Chapter 5 are the first step toward understanding the effects of flooding on the Palenque Shelf.

Chapter 5

The Paleoclimate of Palenque

We can learn much from the study of past climates, both globally and locally. In fact, if we are to understand how and why climates change now and in the future, we must be able to understand the climates of the past. Fortunately, we are able to simulate present and past climates through a variety of programs that rely on input data from around the world. In order to better understand the Palenque Watershed and simulate stream flow (see Chapter 6) a paleoclimate record was needed.

PALEOCLIMATE

Climate involves interactions among the atmosphere, the oceans, the land surface and its vegetation and hydrology, and the cyrosphere. It naturally varies on time scales ranging from annual (seasonal), inter-annual (El Nino) to millennia or longer. The meteorological record of the last one hundred years or so is clearly inadequate to help us understand long-range processes, but it does provide important information on the statistical properties and correlation with proxy variables (Trenberth and Otto-Bliesners, 2003).

Paleoclimate reconstructions fill this void. Made up of estimates of climate variables at times long before the instrumental record, they are based on proxy indicators known to be sensitive to climate. Examples include cores from long-lived trees, ice sheets in Greenland and Antarctica, glaciers at high elevations in the tropics, sediments, corals, and now speleothems (cave formations). Ingenious use of these proxies provides information about past climates, natural variability, and global climate change.

The reconstruction of a time series of temperature or precipitation at a single location is no mean achievement. To synthesize results from previous reconstructions is even more difficult and has only recently been credibly achieved after considerable work, especially in statistical analysis (Mann et al. 1999). It is becoming clear, however, that a synthesis of data with more physical credibility requires collaboration between paleoclimate and climate dynamics experts (including modelers).

The best estimate of global surface temperature change is a 0.6 °C increase since the late 19th century with a 95% confidence interval of 0.4 to 0.8 °C. The increase in temperature of 0.15°C compared to that assessed in the Intergovernmental Panel on Climate Change – Working Group I (IPCC WGI) Second Assessment Report (IPCC, 1996) is partly due to the additional data for the last five years. It is likely that there have been real differences between the rate of warming in the troposphere and the surface over the last twenty years, which are not fully understood. New paleoclimate analyses for the last 1,000 years over the northern hemisphere indicate that the magnitude of 20th century warming is likely to have been the largest of any century during this period (Mann and Jones 2003). In addition, the 1990s are likely to have been the warmest decade of the millennium. New analyses indicate that the global ocean has warmed significantly since the late 1940s: more than half of the increase in heat content has occurred in the ocean's upper 300 m, mainly since the late 1950s. The warming is superimposed on strong global decadal variability. Night minimum temperatures are continuing to increase, lengthening the freeze-free season in many mid- and high latitude regions. There has been a reduction in the frequency of extreme low temperatures, without an equivalent increase in the frequency of extreme high temperatures. Over the last twenty-five years, it is likely that atmospheric water vapor has increased over the northern hemisphere in many regions. There has been a widespread reduction in daily and other sub-monthly time-scales of temperature variability during the 20th century. On seasonal time scales new evidence shows a decline in Arctic sea-ice extent, particularly in spring and summer. Consistent with this finding are analyses showing a near 40% decrease in the average thickness of summer Arctic sea ice over approximately the last thirty years, though uncertainties remain and the influence of multi-decadal variability cannot yet be assessed. Widespread increases are likely to have occurred in the proportion of total precipitation derived from heavy and extreme precipitation events over land in the mid- and high latitudes of the Northern Hemisphere (Mann and Jones 2003).

The drastic and rapid change in global climate discussed above is the catalyst for much of the research being pursued by numerous scholars in a variety of disciplines.

Scientists, such as Penn State's Michael Mann, strive to predict the direction and severity of climate change in hopes of preparing today's global community. While utilizing the same technology and methods, other scientists are attempting to understand the impact of past climate shifts on ancient cultures. As an archaeologist and proud participant in this climatological trend, I follow in the footsteps of researchers who have begun the arduous task of piecing together the environmental changes experienced by the Maya.

Maya archaeologists and paleoecologists have long hypothesized an intimate relationship between climate change and ancient lowland Maya cultural dynamics (e.g., Gunn and Adams 1981; Folan et al. 1983; Dahlin 1983; Dahlin et al. 1987; Gunn et al. 1995; Gill 2000). 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 (Gunn and Adams 1981; Folan et al. 1983; Dahlin 1983). 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 Yucatan peninsula for a prolonged episode of severe hydrological droughts (megadroughts) coincident with the collapse of lowland Classic Maya civilization. Subsequent work on lake cores in the same general area by Hodell and his colleagues have since attributed the abandonment of Mayapan in 1441 AD to another spike in aridity (Hodell et al. 2005).

Pollen and sedimentary analyses of lake cores from the well-watered interior of the peninsula to the south have also provided a tiny window into ancient Maya land use practices, starting with the first pollen grains of maize and other indicators of forest clearance during pioneer colonization of the area by agriculturalists, ca. 2000 BC (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 intervenening Late Preclassic and Classic periods, but these environmental perturbations mask most of the climatological data here (e.g., Deevey 1978; Deevey et al. 1979; Vaughn et al. 1985; Brenner et al. 2003).

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 (Flannery 1978; Harrison and Turner 1978; Pohl 1985; Fedick 1996). Intensified agricultural techniques as seen in agricultural architecture were fairly localized and they ultimately fail to suggest how the most populated sites, like 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 comes from Lakes Coba 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 Yucatan peninsula using lake core data, this set of techniques, like all techniques taken in isolation, have their own built-in problems and uncertainties (see Brenner et al. 2003). According to many (Brenner et al. 2003; Trenberth and Otto-Bliesner 2003), more independent climate proxies to integrate into a holistic reconstruction of past climates are needed. Moreover, clearer linkages between the characteristics of climate changes and cultural changes, both big and small, are necessary. Without more and different proxies, paleclimatologists run the age-old risk of confusing correlation with causation and indulging in a most simplistic environmental determinism; the megadrought explanation for the Classis Maya collapse is already developing into one of the world's best known examples of this scientific fallacy (e.g. Dahlin 2002).

It is critical to note that the evidence for megadroughts in Yucatán comes from only a few lake cores, principally Punta Laguna and Laguna Chichancanab. Cores from lakes in the southern Maya Lowlands, for example Peten Itza (Curtis et al., 1996) and Salpeten (Rosenmeier et al., 2002), do not contain compelling evidence for Terminal Classic megadroughts, nor evidence of lesser droughts during the Late Preclassic and Classic periods. Not even all of the lake cores from the northern Maya area contain a consistent climate record. For example, there is little evidence for Terminal Classic megadroughts at Lake Coba (Leyden et al., 1998), located less than 50 km south of Punta Laguna, nor at Aguada X'caamal in NW Yucatán where these signals appear to be strong. Furthermore, cores from Aguada X'caamal contain evidence for a severe hydrological drought at 1400-1500 AD (Hodell et al., 2005), which does not appear in the records of Punta Laguna or Laguna Chichancanab. Similarly, close comparison of short climate intervals between Punta Laguna and Laguna Chichancanab cores show considerable discrepancies. In sum, little is known about the spatial variability of climate change across the Yucatán Peninsula and, as a result, critical questions arise as to whether the spatial variability of the Classic Maya collapse is due to different cultural responses to hydrological drought (e.g., Dahlin, 2002) or spatial variability in drought severity**.**

Although several climate indicators were used in the lake cores (e.g., pollen, diatoms, limnology and mineralogy), the principal evidence for climate change in the Yucatán Peninsula has been oxygen isotope variability in microorganisms and lenses of gypsum found in lake sediments. In closed lake systems these are well-known proxies for evaporation/precipitation ratios and hence excellent indicators of hydrological drought. Great care was taken (studies cited above) in choosing Yucatán lakes that approximate a closed system, but the karst hydrology of the region makes this difficult. Many Yucatán lakes are connected to regional groundwater systems that receive input from variable sources (e.g., Perry et al., 2002) which can complicate the interpretation of oxygen isotope data and gypsum precipitation. This potential problem is enhanced by the fact that lake-groundwater connections can change over time so the current lake hydrology is not necessarily indicative of past conditions. It seems likely that the variability of water sources inflicts limitations on interpreting regional complexities in the oxygen isotope data insofar as these complexities could, in part, reflect regional differences in groundwater systems and their response to climate change (Perry et al, 2002).

SIMULATING PALENQUE'S PALEOCLIMATE

I developed a statistically plausible paleoclimatic history for Palenque by simulation, utilizing two climate-generating programs that capture long range (≥100 year) climate variations and short range statistics of daily weather. This approach was necessary in order to simulate realizations of the full range of atmospheric inputs to the watershed at Palenque, from daily storm events to the annual monsoon, to decadal, centennial and millennial climatic trends that occur in the Palenque area.

MarkSim

The weather generator MarkSim is a computer tool used to generate statistically reasonable weather data for crop modeling and risk assessment based on the instrumental record from tropical weather stations, latitude, and elevation. This software package generates daily weather data for user specified locations for Latin America and Africa. The stochastic weather generator uses a third-order Markov process to model daily precipitation, temperature, etc. The model has been fitted to data from more than 9200 tropical stations with long runs of daily data throughout the world. The daily data provided by this large array of stations preserves 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 min or arc (18 km^2) and evaluates the model parameters for that point (Jones and Thornton 2000). The coordinates and elevation of Palenque were entered into the MarkSim program and a 100-year data set of rainfall and temperature was generated (Appendix A).

A German NGO (non-governmental organization) recently utilized MarkSim to assist small-scale drybean farmers in Nicaragua (Nieto et al 2006). The study was used to establish a system of weather insurance that would provide a safety net for the farmers in the event of a meteorological drought. The final report shows that the MarkSim's simulations were comparable to the observed data collected by the Nicaragua Ministerio Agropecuario y Forestal (MAGFOR).

Bryson Paleoclimate Model

The second computer tool utilized was 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 (R. U. 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 BP). 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 (ITC), 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 (Figure 5.0) (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 dataset of 100-year averages for the last 2,500 years was produced (Appendix B).

Although there is considerable regional variability and site coverage is still sparse in many places, it is clear that significant parts of the US southwest, northern and central Mexico, and the Yucatan were wetter than present in the early to mid-Holocene and in addition, exhibited a drying trend toward the late Holocene (Whitmore et al. 1996). In contrast, the USA 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 forementioned observations to simulations of climate for 6000 years ago, and for the present, made with four different climate models. They concluded that the models showed fair agreement both with each other and with the proxy record in many locations, particularly in the subtropics, although significant differences were also noted, especially in the tropics (Ruter et al. 2004).

Properties of the Bryson Macrophysical Climate Model (BMCM)

- High resolution: models variations in climate at a resolution of single centuries (100-year averages by month)

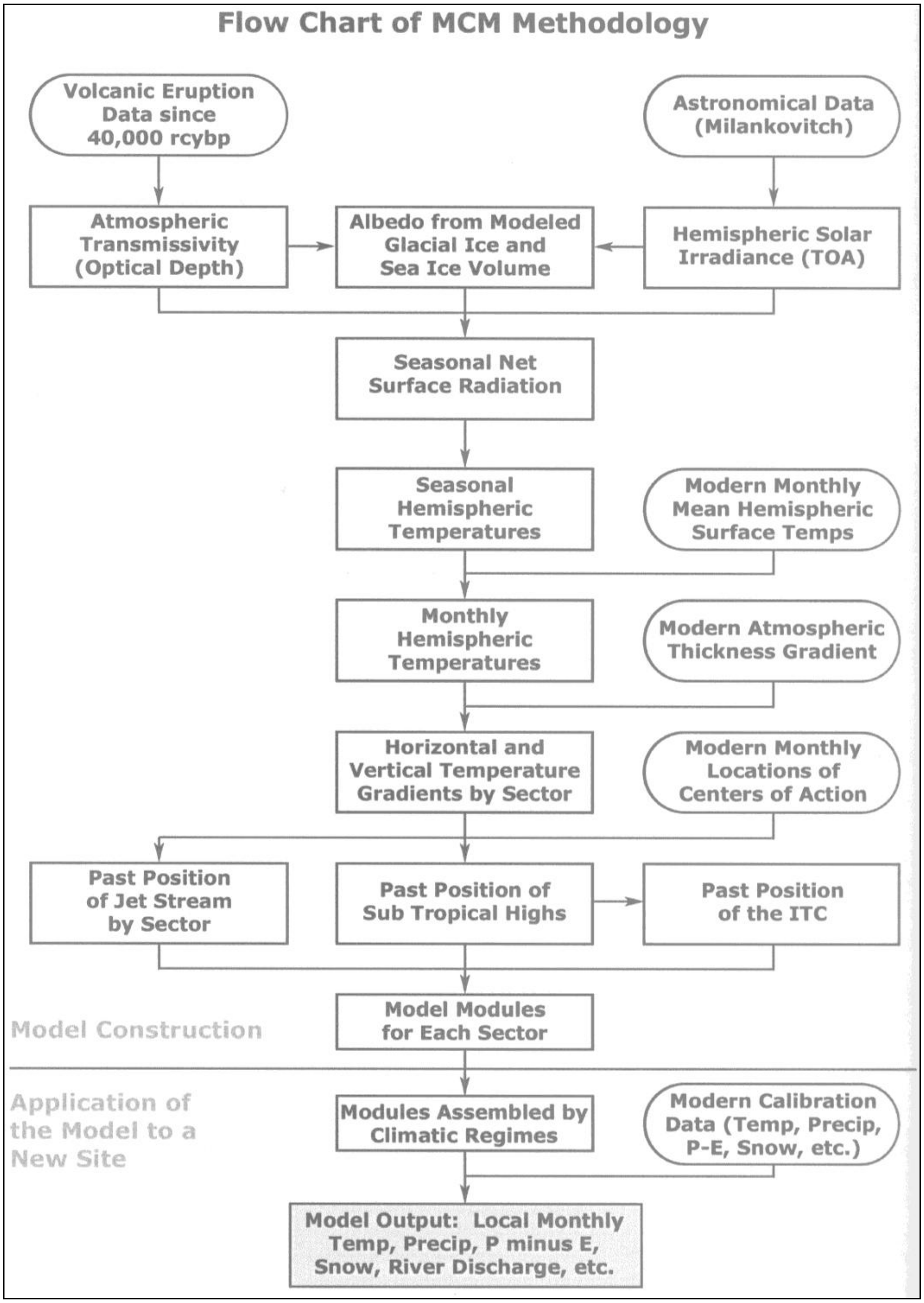


Figure 5.0 – Overview flow chart of the Bryson Macrophysical Climate Model. The methodology database contains more than 2,400 dated eruptions, dating back to 40,000 years (Bryson, et al. 2006).

- Site-specific: models the climate of a specific archaeological, historic, or palynological site of interest
- Implicitly includes local influences such as topography (particularly relevant in mountainous terrain).
- Accuracy comparable to that of GCMs (Ruter, et al. 2004)

METHODOLOGY: A DAILY CLIMATE RECORD FOR WATERSHED INVESTIGATION

It is important to restate that the purpose of this analysis is to construct plausible hydrologic inputs to the Palenque watershed which 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. The 100-year MarkSim simulations were used to scale the climate trends provided by Bryson to produce the daily variability with the long term climate trends. The approach is to use the method of proportionality (IPCC, 1996). Of course the approach can only provide an inference or index of past conditions of watershed inputs.

Constructing the Daily Series

In order to model the Palenque Watershed (Chapter 6) daily precipitation and temperature were needed. The Bryson model only supplied 100-year monthly averages; while the MarkSim model simulated daily data, it only did so for a single 100 year period. In order to simulate daily data for several 100-year periods (500 BC – 401 BC, AD 601 – AD 700, and AD 1901 – AD 2000) (Appendix C) a ratio of difference between the 100-year Bryson average and the MarkSim 100-year average was calculated. This was achieved by dividing the Bryson 100-year average for precipitation and temperature ($\overline{P}_{100yrs}^{MarkSim}$, $\overline{T}_{100yrs}^{Bryson}$) by the MarkSim 100-year average for precipitation and temperature ($\overline{P}_{100yrs}^{MarkSim}$, $\overline{T}_{100yrs}^{MarkSim}$). This ratio is then multiplied by each daily MarkSim value (see examples below).

Precipitation

Daily precipitation (P_{daily}) was calculated by 1) dividing the 100-year average precipitation that was simulated with the Bryson model ($\overline{P}_{100yrs}^{Bryson}$) by the 100-year average precipitation from the MarkSim model ($\overline{P}_{100yrs}^{MarkSim}$); 2) multiply the previous value by each MarkSim daily value ($P_{daily}^{MarkSim}$).

$$P_{daily} = P_{daily}^{MarkSim}\left(\frac{\overline{P}_{100yrs}^{Bryson}}{\overline{P}_{100yrs}^{MarkSim}}\right)$$

Example: September 23, 100 BC

$\overline{P}_{100BC}^{Bryson}$ = 3001.10 mm
$\overline{P}_{100yrs}^{MarkSim}$ = 2970.78 mm
$P_{Sept.23,yr.1}^{MarkSim}$ = 15.7 mm
$P_{Sept.23}$ = 15.86 mm

$$15.86 = 15.7\left(\frac{3001.10}{2970.78}\right)$$

Temperature

Daily temperature (T_{daily}) was calculated using the same method as the daily precipitation; 1) dividing the 100-year average temperature that was simulated with the Bryson model ($\overline{T}_{100yrs}^{Bryson}$) by the 100-year average temperature from the MarkSim model ($\overline{T}_{100yrs}^{MarkSim}$); 2) multiply the previous value by each MarkSim monthly value ($T_{daily}^{MarkSim}$).

$$T_{daily} = T_{daily}^{MarkSim}\left(\frac{\overline{T}_{100yrs}^{Bryson}}{\overline{T}_{100yrs}^{MarkSim}}\right)$$

Example: September 23, 100 BC

$\overline{T}_{100BC}^{Bryson}$ = 25.55 °C
$\overline{T}_{100yrs}^{MarkSim}$ = 26.98 °C
$T_{Sept.23,yr.1}^{MarkSim}$ = 27.85 °C
$T_{Sept.23}$ = 26.49 °C

$$26.49 = 27.85\left(\frac{25.55}{26.98}\right)$$

Monthly Data

<u>Precipitation</u>

Monthly totals were first taken from the daily simulations provided by MarkSim. Next, the monthly precipitation ($P_{monthly}$) was calculated by 1) dividing the 100-year average precipitation that was simulated with the Bryson model ($\overline{P}_{100yrs}^{Bryson}$) by the 100-year average precipitation from the MarkSim model ($\overline{P}_{100yrs}^{MarkSim}$); 2) multiply the previous value by each MarkSim monthly value ($P_{monthly}^{MarkSim}$).

$$P_{monthly} = P_{monthly}^{MarkSim}\left(\frac{\overline{P}_{100yrs}^{Bryson}}{\overline{P}_{100yrs}^{MarkSim}}\right)$$

Example: September 100 BC

$\overline{P}_{100BC}^{Bryson} = 2982$ mm
$\overline{P}_{100yrs}^{MarkSim} = 2970.78$ mm
$P_{Sept.yr.1}^{MarkSim} = 428$ mm
$P_{Sept.} = 432.28$ mm

$$432.28 = 428\left(\frac{3001.10}{2970.78}\right)$$

<u>Temperature</u>

Monthly average temperature was first taken from the daily simulations provided by MarkSim. Next, the monthly average temperature ($\overline{T}_{monthly}$) was calculated using the same method as the precipitation; 1) dividing the 100-year average temperature that was simulated with the Bryson model ($\overline{T}_{100yrs}^{Bryson}$) by the 100-year average temperature from the MarkSim model ($\overline{T}_{100yrs}^{MarkSim}$); 2) multiply the previous value by each MarkSim monthly value ($\overline{T}_{monthly}^{MarkSim}$).

$$T_{monthly} = T_{monthly}^{MarkSim}\left(\frac{\overline{T}_{100yrs}^{Bryson}}{\overline{T}_{100yrs}^{MarkSim}}\right)$$

Example: September 100 BC

$\overline{T}_{100BC}^{Bryson} = 25.55$ °C
$\overline{T}_{100yrs}^{MarkSim} = 26.98$ °C
$\overline{T}_{Sept.yr.1}^{MarkSim} = 26.86$ °C
$\overline{T}_{Sept.} = 25.51$ °C

$$25.51 = 26.86\left(\frac{25.55}{26.98}\right)$$

RESULTS

Credibility of the Simulation

The first positive sign that lent creditability to the results of the climate simulation were the values given for annual average precipitation (3031 mm) and temperature (25.7 °C) (Figures 5.1 & 5.2). These averages agree well with the independently observed local meteorological data from the Palenque region (i.e. ~3000 mm and ~26 °C) (INEGI 1989). Secondly, parallels were also seen when the precipitation and temperature from specific dates produced by the simulation were compared to their counterparts gathered from a weather station at the Palenque Airport (Figures 5.3 & 5.4). The examples shown in Figures 4.3 and 4.4 are from annual averages over a 10-year period from 1970-1980. The differences in precipitation are far greater than that of temperature.

The difference of 504 mm or 15% in precipitation is plausible given its R^2 of 0.7912 (Figure 5.5). In addition, this variation can further be explained due to the location of the Palenque Airport and the site of Palenque. The Palenque Airport is located at an elevation of 40 m above sea level in the deforested plains north of the site. The Palenque watershed is 100-350 m above sea level and 9 km southwest on a jungle covered limestone shelf. This abrupt rise in elevation causes a modest orographic effect (e.g. increased precipitation with elevation). An orographic effect occurs when moist air

2500 Years of Simulated Precipitation and Temperature - MarkSim and Bryson		
DATE	Average Precipitation	Average Temperature
500 BC	2970.78	25.63
400 BC	2970.78	25.90
300 BC	2970.78	25.90
200 BC	2970.78	25.90
100 BC	3000.49	25.63
100 AD	3000.49	25.90
200 AD	3030.20	25.36
300 AD	3059.90	25.09
400 AD	3030.20	25.63
500 AD	3030.20	25.90
600 AD	3030.20	25.90
700 AD	3030.20	25.90
800 AD	3030.20	25.90
900 AD	3030.20	25.63
1000 AD	3059.90	25.36
1100 AD	3030.20	25.63
1200 AD	3059.90	25.90
1300 AD	3059.90	25.90
1400 AD	3030.20	25.90
1500 AD	3059.90	25.63
1600 AD	3059.90	25.09
1700 AD	3119.32	24.82
1800 AD	3059.90	26.17
1900 AD	3119.32	24.82
2000 AD	2970.78	26.99
Averages	**3031.38**	**25.70**

Figure 5.1 – 2,500 years of Bryson/MarkSim simulated precipitation and temperature.

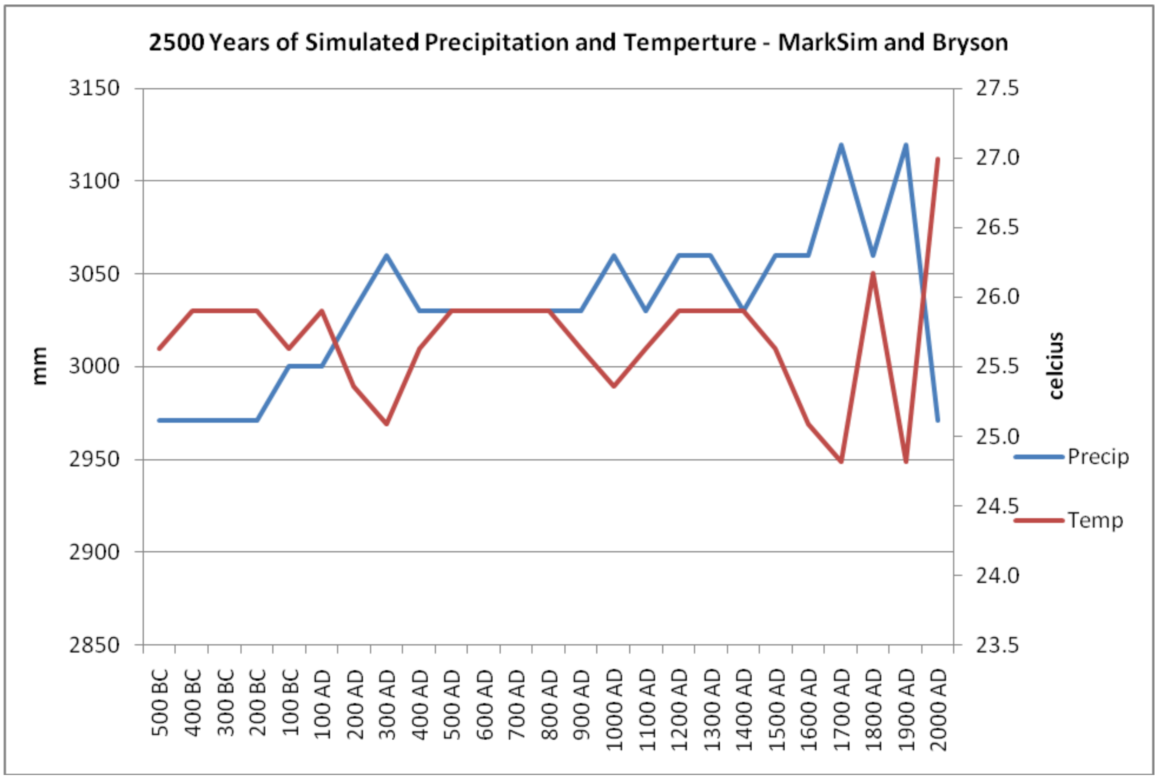


Figure 5.2 – 2,500 years of Bryson/MarkSim simulated precipitation and temperature.

Average Precipitation (mm) 1970-1980		
Month	Bryson/MarkSim	INEGI
Jan	248.75	148.00
Feb	179.17	110.00
Mar	42.65	117.70
Apr	20.21	98.70
May	99.68	149.50
Jun	357.76	312.40
Jul	345.85	248.50
Aug	396.16	270.10
Sep	512.54	495.20
Oct	668.78	400.70
Nov	193.16	238.60
Dec	202.09	173.50
Totals	**3266.80**	**2762.90**

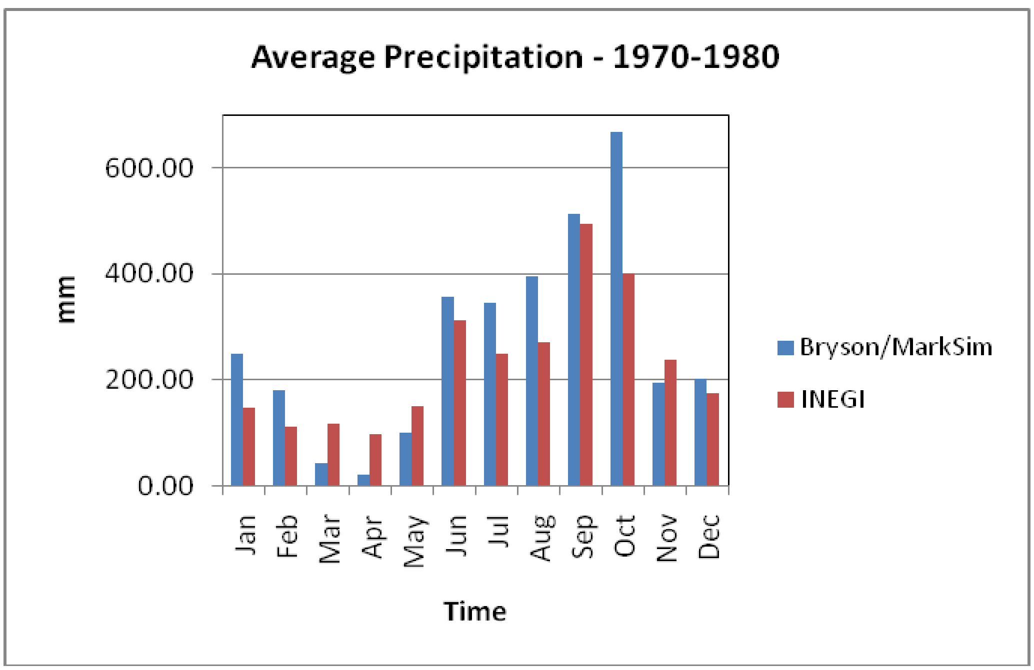


Figure 5.3 – Average simulated precipitation (Bryson/MarkSim) vs. average observed precipitation (INEGI).

Average Temperature (C°) 1970-1980		
Month	**Bryson/MarkSim**	**INEGI**
Jan	21.8	22.9
Feb	23.7	23.4
Mar	24.1	25.8
Apr	26.0	27.7
May	27.2	28.8
Jun	27.5	28.3
Jul	26.9	27.5
Aug	25.8	27.5
Sep	25.4	27.0
Oct	24.3	26.0
Nov	23.1	24.4
Dec	22.5	22.9
Totals	**24.9**	**26.0**

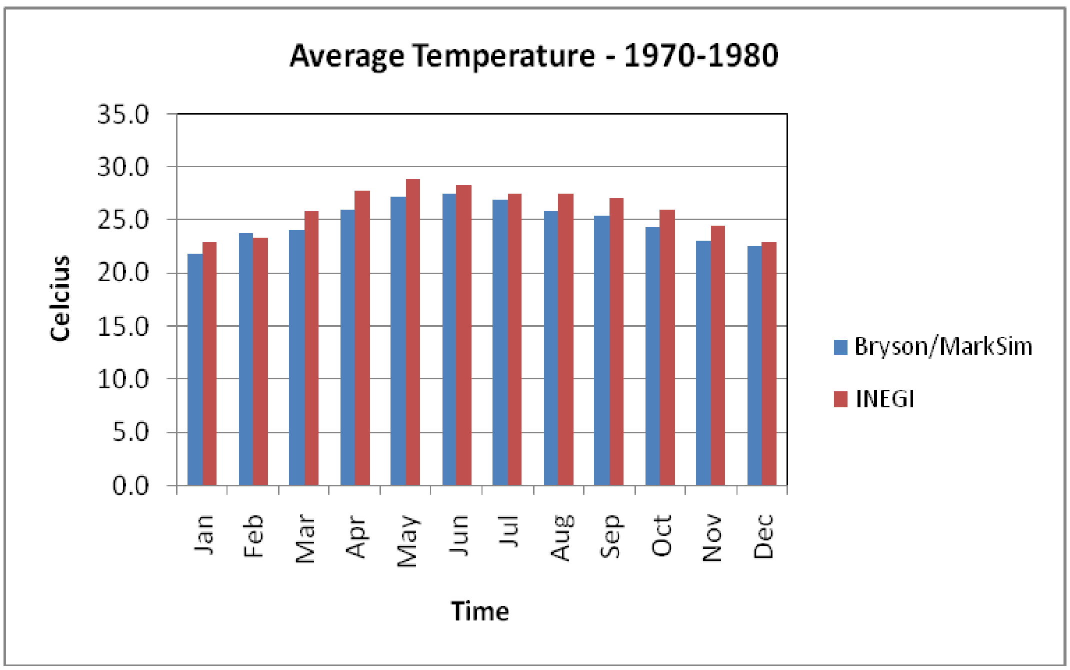


Figure 5.4 – Average simulated temperature (Bryson/MarkSim) vs. average observed precipitation (INEGI).

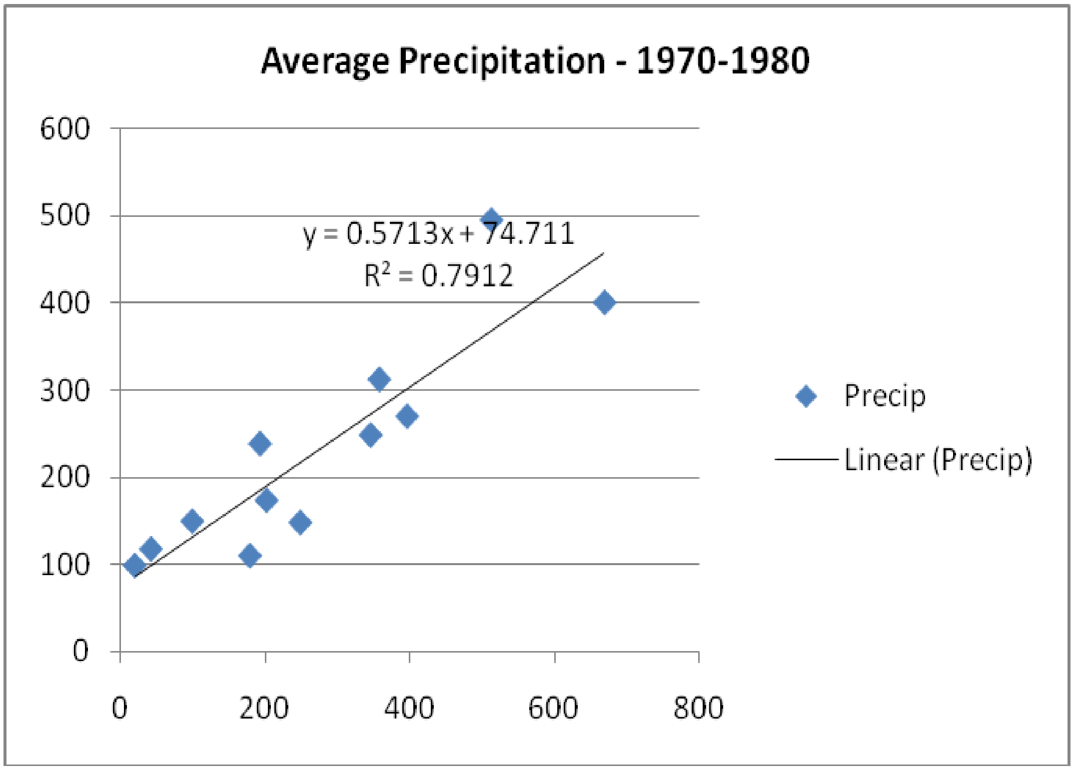


Figure 5.5 – The difference of 504 mm or 15% in precipitation has an R^2 of 0.7912.

flowing from the ocean encounters a mountain barrier and is forced up and over the mountains. The air continues to cool as it rises, and the moisture condenses and precipitates as rain on the windward side of the mountain. As storm systems move south across the plains from the Gulf of Mexico they tend to release more precipitation along the foothills of the Sierra de Chiapas than in the plains themselves. In addition, my own experience along with communication with locals from Palenque, verifies the many instances of downpours at the site while the people in the town of Palenque (8 km east and in the plains) see not a drop. This slight orographic effect can easily explain why the climate simulations performed on the site of Palenque reveal 15% more precipitation than that recorded at the Palenque Airport between 1970 and 1980.

The difference of 1.1 °C or 4% in temperature is also within reason given its R^2 of 0.9093 (Figure 5.6). This slight variation can be justified by applying the “lapse rate”. The “lapse rate” is defined as the negative of the rate of change in an atmospheric variable, usually temperature, with height in an atmosphere. As an average, the International Civil Aviation Organization (ICAO) defines an international standard atmosphere (ISA) with a temperature lapse rate of 6.49 °C/1,000 m from sea level to 11,000 m. As mentioned above, the difference in elevation between the Palenque Airport and the site is 100-350 m. According to the ICAO’s definition of the lapse rate the site of Palenque should on average be 0.65 °C cooler than that recorded at the Palenque Airport between 1970 and 1980. Adjusting for the lapse rate puts the simulated daily temperature for the watershed above Palenque in the same range as the observed airport data. The difference in temperature between the simulation and the Airport weather station shrinks from 1.1 °C or 4% to a mere 0.45 °C or 0.98%.

The 2,500-Year Simulation

Two trends of interest arose from the 2,500 year paleoclimate simulation. The first is the consistency of the climate from AD 400 – AD 900. Long periods of predictable climate can often equate with flourishing populations. For Palenque, as for much of the Maya Lowlands, the period of AD 500 – AD 800 was a period of unparalleled growth and prosperity.

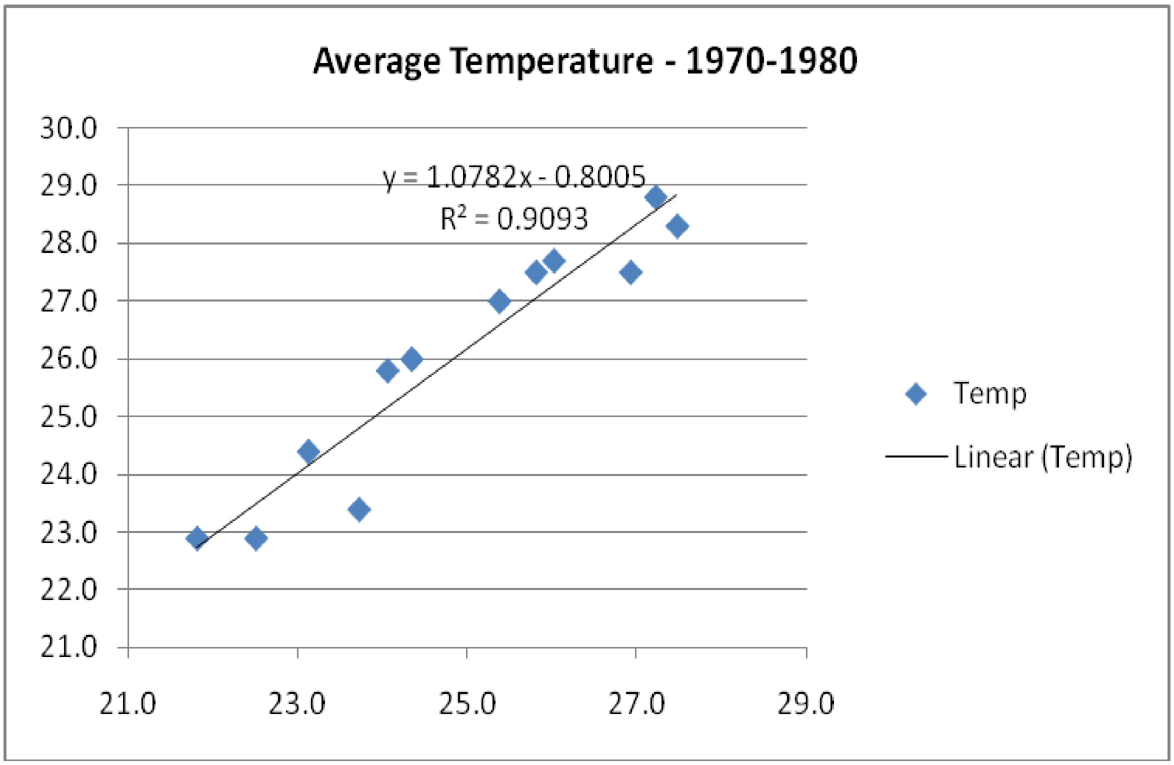


Figure 5.6 – The difference of 1.1 °C or 4% in temperature has an R^2 of 0.9093.

According to the simulation, Palenque began to experience a slight cooling (approximately 1%) during the 9th century. By the 10th century the site had cooled an additional 1% along with a 1% increase in precipitation. This 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). A recent study (Yocom et al 2009) of the El Niño Southern Oscillation (ENSO), the climate-forcing mechanism, offers an example of how climate changes are sometimes very localized. El Niño is a warm event that generally brings moist conditions to the southwestern United States and northwestern Mexico, while La Niña offers cooler temperatures and less precipitation. Interestingly, the opposite is the case for southern Mexico, where El Niño brings dryer and cooler conditions and wetter and warmer climate during La Niña (Yocom et al 2009).

In any case, my research evaluates the impact of storm events, seasonal and long term change on the local hydrologic conditions at Palenque and these reconstructions are suitable for this analysis. In the following chapter these paleoclimatic simulations are utilized to reconstruct the Palenque watershed for several key time periods.

Chapter 6

The Palenque Watershed and Hydrologic Setting

The effects of climate change are predicted (and any many cases have already begun) to impact water resources all over the world. Climatic perturbations also play an important role in changing ecosystem's structure and function (Westerling et al. 2006). Studies on ecosystem response to relatively short disruptions have indicated that species assemblages often recover rapidly from meteorological drought (Matthewes 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 (NRC 2007). Instrumental records of precipitation, temperature, and surface-water flow at many sites throughout Mesoamerica are often non-existent, 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 that were discussed in Chapter 5 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 are transformed into streamflow using deterministic hydrologic models (Linsley 1982). These approaches assume that existing instrumental data adequately represent the characteristics of streamflow or precipitation well beyond the actual period of observations. This chapter details a novel approach that combines simulated climatic records and watershed modeling to produce estimates of long-term streamflow for the Palenque Watershed.

PHYSICAL SETTING

The Palenque upland watershed (Figures 6.0 & 6.1) encompasses 7.21 km^2 and is located approximately 8 km southwest of the town of Palenque in Chiapas, Mexico.

Geology

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 north-west which generally plunge north-westwards beneath the Pliocene and younger sediments of the coastal Tabasco plain and the Gulf of Mexico. The region's geology has 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).

Late Cretaceous (99.6 – 65.5 Ma) limestone covers most of the watershed. The model assumes that the hydraulic properties are, like the soils, very permeable. Macropores are soil or rock fractures/cracks/root holes/bioturbation of all kinds which tend to increase the hydraulic conductivity of the soil and rock. The limestone also weathers along joints and fracture planes (Figure 6.2).

Vegetation

Palenque is classified as a "tropical moist forest" according to the Holdridge Life Zone (Holdridge et al, 1971). Holdridge defines "tropical moist forest" as a tall, multistratal semedeciduous forest with many different species of wide crowned trees 40 – 50 m tall. The subcanopy consists of trees up to 30 m tall, mostly 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, broadleafed herbs, and tree seedlings. Abundant herbaceous vines hang throughout the forest.

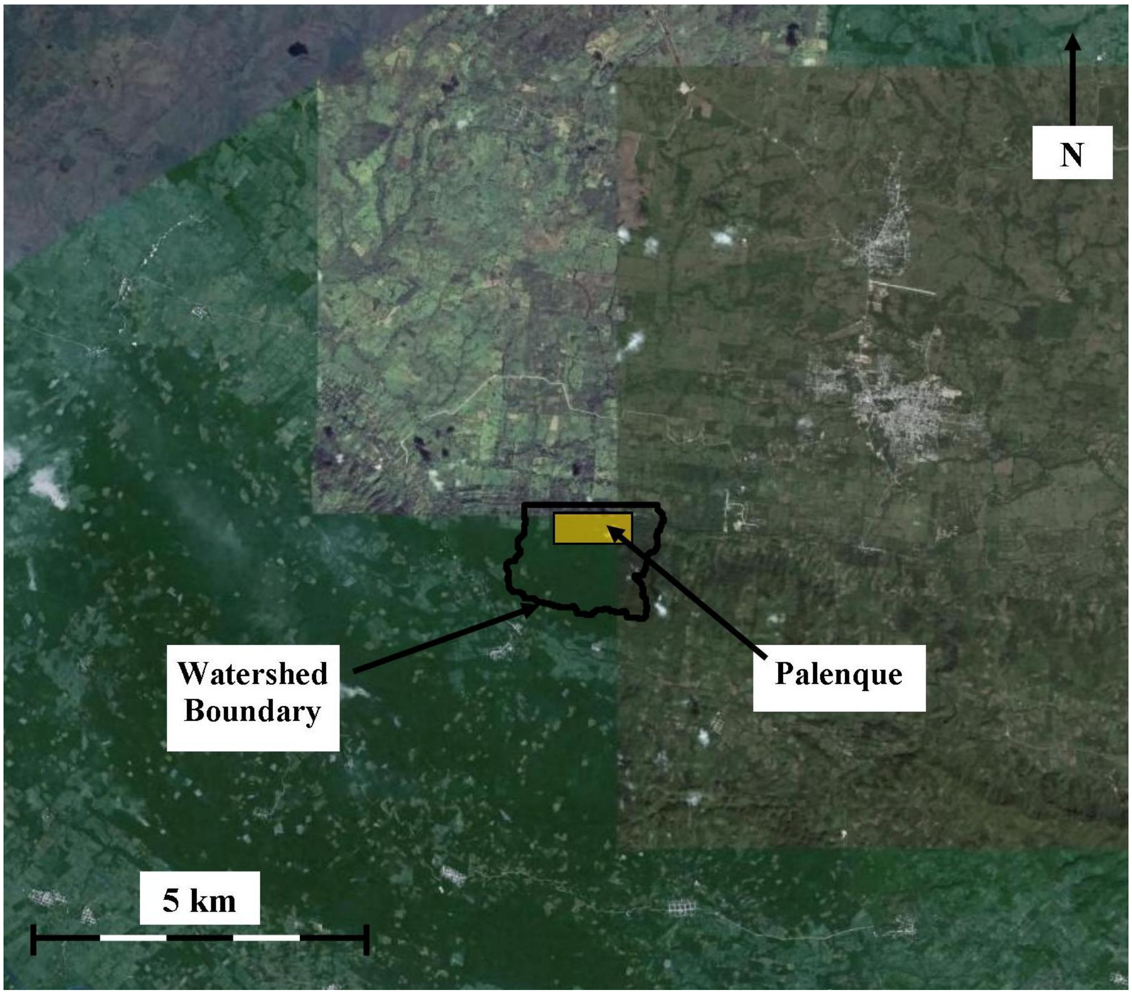


Figure 6.0 – Satellite image of the Palenque Watershed.

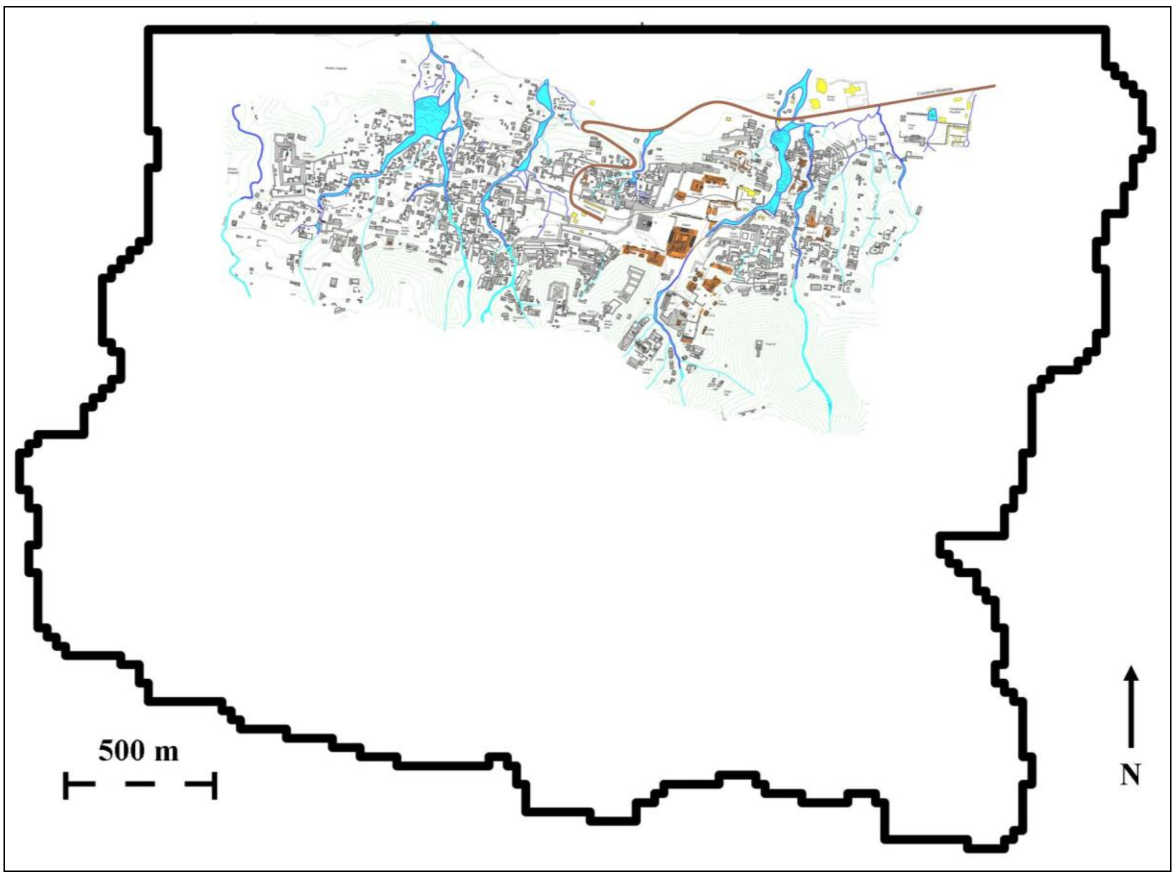


Figure 6.1 – View of the Palenque Watershed.

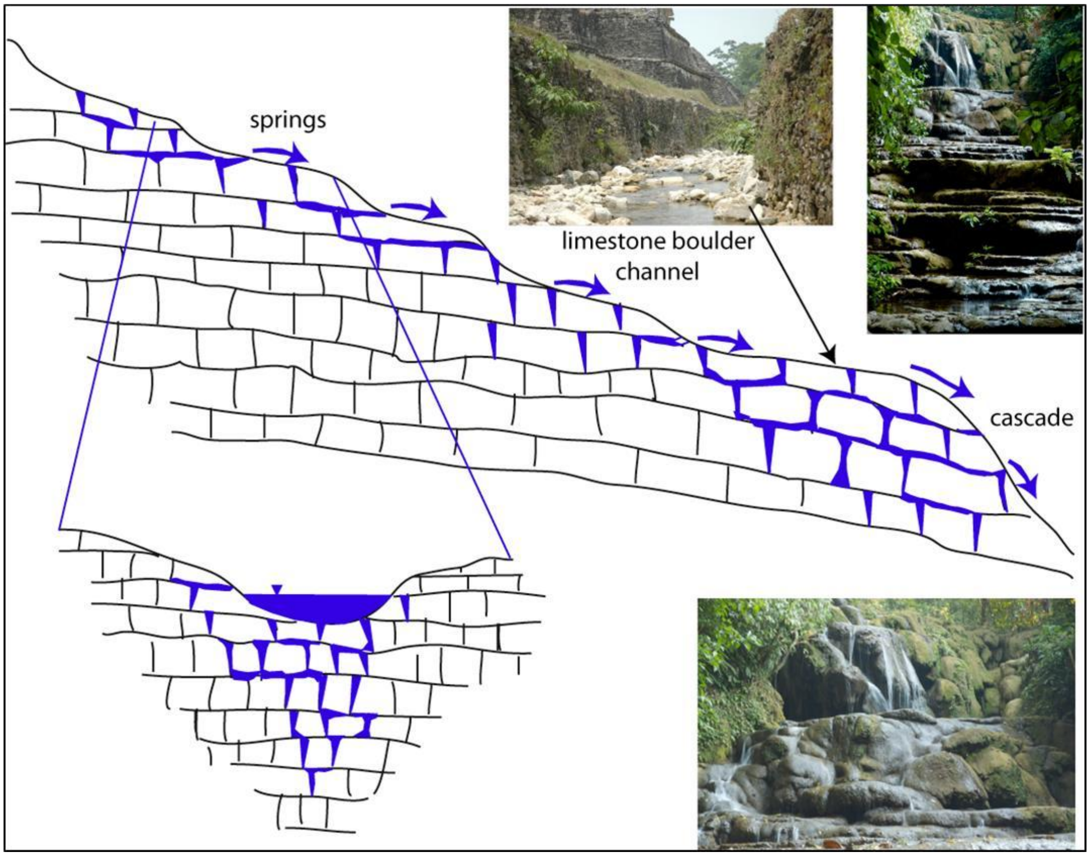


Figure 6.2 - Hydrologic conceptual model for the Cretaceous limestone watershed at Palenque showing the increased dissolution along bedding planes and fractures below the stream channel bed, a boulder channel (top photo) crossing the ruins, and two photos within the groundwater discharge zone showing the pool and ledge cascade and accreting tufa deposits.

Soils

The Palenque watershed is composed of two main soil types, nitosols to the north and regosols in the south (Figure 6.3).

Eutric Nitosols (Ne)

Eutric nitosols are found in the northern half of the watershed. They have a base saturation of 50% or more and are generally found on almost flat to sloping terrain. nitosols are deep, clayey red soils with an argillic B horizon. These soils have a uniform profile, are porous, have a stable structure and a deep rooting volume. Their moisture storage capacity is high. They are among the best agricultural soils.

Eutric Regosols (Re)

Eutric regosols are located in the south of the watershed, down below the escarpment. They are soils without profile development, consisting of loose, non-alluvial soil material. They are developed from unconsolidated materials, usually sands that possess little or no profile development. Regosols may possess a weakly developed A horizon with less than 1% organic matter. Because of the sandy texture regosols have a low available water capacity and low nutrient content. They occur in areas with little precipitation or on steep slopes subject to severe erosion. Those with lime accumulation are calcaric regosols. Eutric regosols have a base saturation of 50% or more. They have limited agricultural value, especially where soil depth is limited. Water retention in regosols is low. They tend to be very permeable, do not store water, and are drought prone.

THE PENN STATE INTEGRATED HYDROLOGIC MODEL (PIHM)

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. Numerical simulation of coupled nonlinear hydrologic processes provides an efficient and flexible approach to watershed simulation. PIHM (Penn State

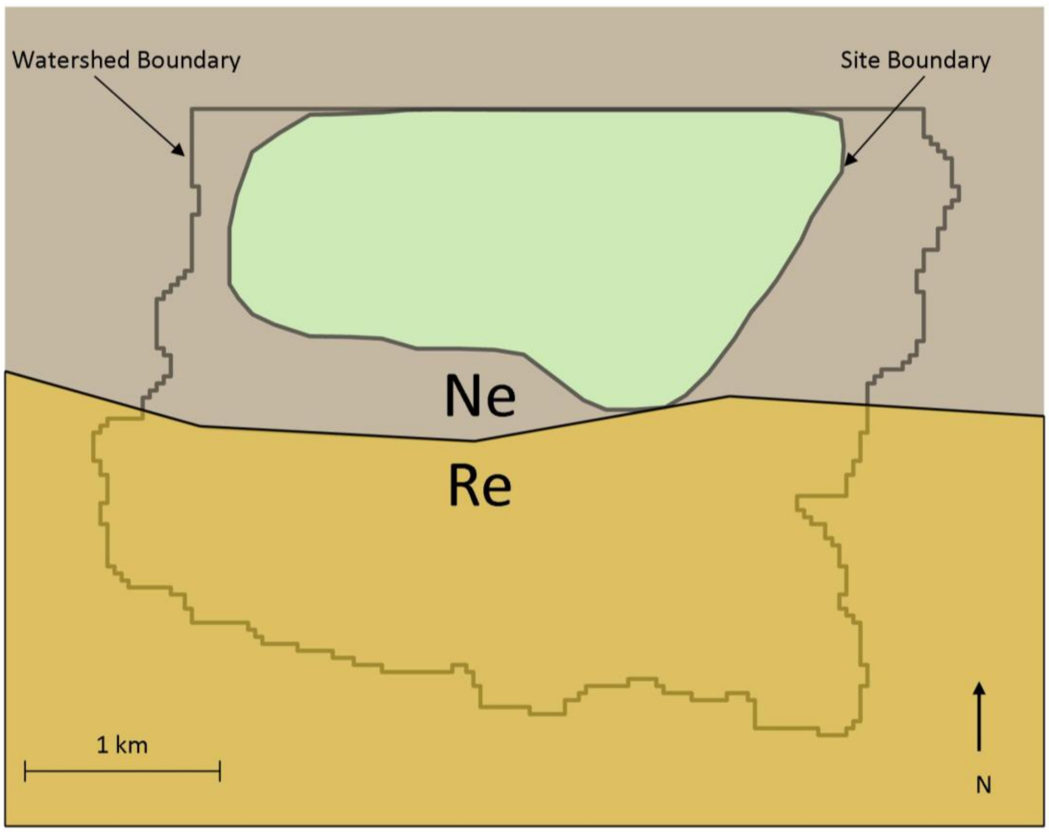


Figure 6.3 – Soils of the Palenque Watershed (INEGI).

Integrated Model) (2007 Qu and Duffy) represents a new strategy for watershed modeling where 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. The approach reduces governing the complex model equations to a simplified form based on the finite volume method (Ferziger and Peric, 2002). The model solves the systems of equations on an unstructured triangular grid, referred to as a triangular irregular network (TIN). The systems of equations are solved with an efficient ODE solver. 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 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 (2007 Qu and Duffy).

The "control-volume" in the finite volume formulation is a prismatic or linear physical element which is also called model kernel with all the physical process equations and constitutive relationships identified. Figure 6.4 shows a typical kernel defined on a triangular land surface element and a channel element (the grid is modified for channels). PIHM and PIHM_GIS represent a community modeling tool and GIS tool developed under NSF Hydrologic Sciences funding for scientific application to Hydrologic Observatories. This effort serves as a test of the overall modeling strategy to demonstrate the utility of integrated models for ungauged basins, but where land cover, soil maps, topography, and climate data is available or can be estimated (2007 Qu and Duffy).

The important distinction of PIHM from other watershed models is that the physical model and data-layers (Figure 6.4) are explicitly linked (tightly coupled) through a data-model and GIS interface which is discussed next.

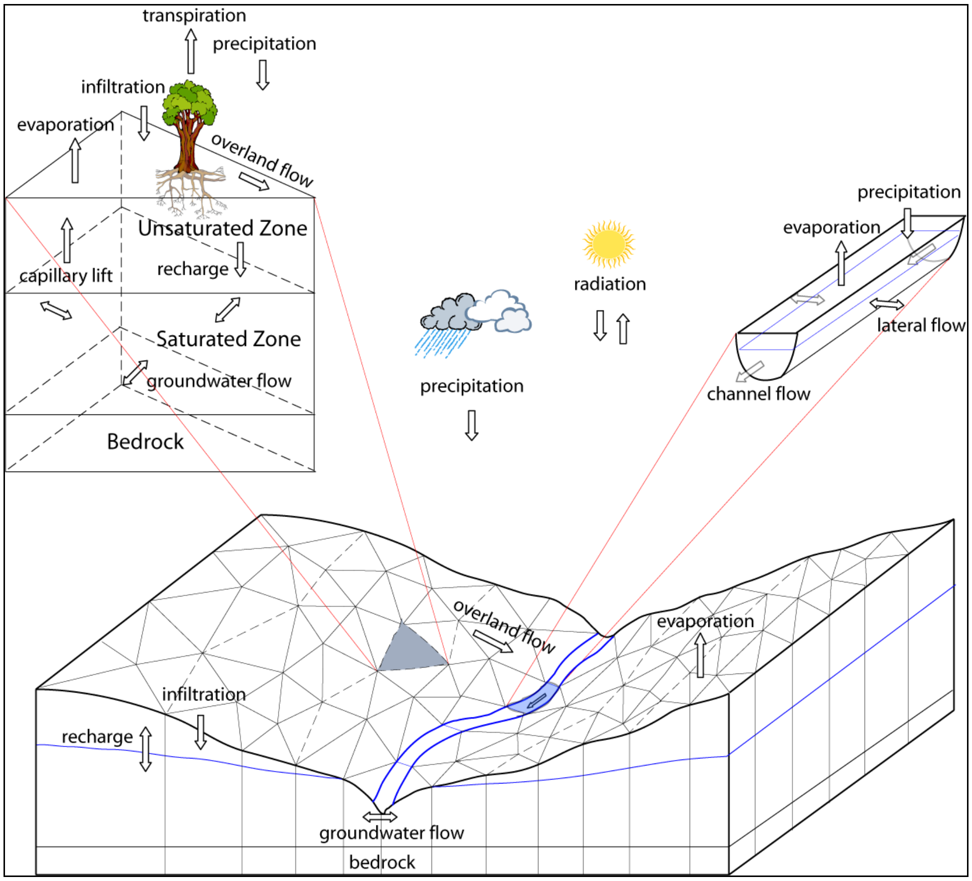


Figure 6.4 - Example of a user-specified discretization of a river-reach with a prismatic finite volume approximation for surface and groundwater flow. The Penn State Integrated Model simulates land surface, subsurface and channels processes. Details are available at http://www.pihm.psu.edu/.

Data-Model and GIS Framework

PIHMgis is an integrated and extensible GIS system with data management, data analysis, mesh generation, with distributed modeling capabilities. The underlying philosophy of this integrated system is shared rules for the data and the physical model. This makes it possible to fairly quickly generate a model which 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, as well as providing algorithms for hydraulic parameterization of soil and land cover. The open architecture is particularly suited to the rapid prototyping of new model functions in support of diverse hydrologic modeling applications.

PIHMgis was developed using basic QGIS source code (www.qgis.org). The GUI component of PIHMgis has been written in Qt, which is a cross-platform graphical widget-based toolkit in C++ while the algorithms and the hydrologic model (PIHM) have been coded in C and C++. Basic support PIHMgis comes from QGIS. PIHMgis runs on all major platforms, and has extensive international support. Non-GUI features include SQL database access, XML parsing; thread management, and a unified cross-platform API for file handling. PIHM is available as Open-Source code on Source Forge (http://sourceforge.net/projects/pihmmodel/) and at the Penn State web site (www.pihm.psu.edu) and (http://sourceforge.net/projects/pihmgis).

LANDCOVER AT PALENQUE

Running PIHMgis at Palenque required the input of a small portion of the daily climate simulations discussed in Chapter 5. The model also required the identification and creation of different landcovers. After much experimentation three scenarios were developed that cover a range of climate conditions and possible land cover settings (Table 6.0).

Time Period	Land Cover		
	Primary Forest	Maya Urban	Modern
500-401 BC	X		
AD 601-700		X	
AD 1901-2000			X

Table 6.0 – PIHMgis scenarios for the Palenque Watershed

Forested

For the model that is discussed below, I used the US Environmental Protection Agency's 2001 National Land Cover Data (NLCD 2001). The most appropriate category, according to the NLCD 2001, was "forest/evergreen". They define "forest/evergreen" as "trees > 3 meters in height, canopy closure >35% (<25% intermixture with deciduous species), of species that do not seasonally lose leaves" (mdafederal.com).

Deforestation

Evidence suggests that deforestation was common among the Maya, especially those living near urban centers (Webster 2002). Although increases in agricultural production caused much deforestation, demand for stucco for monumental stone structures played an even larger role (Abrams and Rue 1988, Shreiner 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 non-reversible 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 addition to paving their expansive plaza floors. Because it was a sign of wealth and prestige, the stucco had to be constantly maintained. Thus the high temperature required for the calcination process coupled with the high demand for aesthetics stimulated deforestation.

Reconstruction of a Maya kiln used for the calcination process determined that 1 ha of forest with trees greater that 5 cm diameter will provide 444 kg of quicklime

(Shreiner 2002). The quicklime contribution to a cubic meter of plaster is 325 kg. The pyramid of El Tigre, from the Preclassic site of El Mirador in northern Guatemala, required 2200 m^3 of exterior wall plaster and pavement. At 325 kg per m^3 of exterior plaster, 715,000 kg of quicklime would have been needed for the plaster surface on El Tigre. Astonishingly, this equates to 1630 ha (16.3 km^2) of forest trees (Shreiner 2002). 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.

Deforestation was probably a side effect of Palenque's population. Massive deforestation in the Palenque area could have negatively affected the ancient Maya by exacerbating flooding, droughts, and erosion. Vegetation helps to prevent flooding by absorbing water from the soil. The plants eventually release this water into the atmosphere through a process called transpiration, which accounts for 10% of all evaporation.

Ironically, these very same floods caused by deforestation can also lead to severe localized, and sometimes widespread meteorological droughts by affecting the hydrological processes of a watershed. When the rain water flows quickly through a watershed, very little enters the water table. The lowering of water table levels can then cause springs to dry and stream and river flow to decrease.

Palenque would have been highly susceptible to erosion caused by deforestation due to its topography. Vegetation assists in preventing erosion with roots that cling to the soil and leaves that protect the soil by slowing the speed of rain. The 16 non-contiguous kilometers of architectural terracing found in Palenque might have been in response to erosion caused by deforestation (Figure 4.6).

Urbanism

The urban landcover 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% to simulate compaction by urban traffic.

THE HYDROCLIMATIC AND LANDCOVER SCENARIOS

The first scenario uses a 100-year daily climate simulation produced for 500 BC – 401 BC with primary forest landcover (100%) (Figure 6.5). This time period was chosen because it is widely accepted that the Palenque shelf was completely devoid of human occupation due to an absence of Preclassic pottery and architecture (discussed in Chapter 1). There is no evidence of occupation in the area until circa 100 BC. It is safe to say the area was largely undisturbed so the climate and vegetation simulate the pre-settlement condition.

The second 100-year scenario was for AD 601 – AD 700, the plausible height of Palenque's population and urbanization. The landcover developed for this scenario was a mix of forested (40%), deforested (40%), and urban (20%) land cover types (Figures 6.6). This time period was necessary to simulate the effect of human occupation and urbanization had on the watershed.

The third 100-year scenario was for the modern period, AD 1901 – AD 2000, which we use a comparison to the measured record of tropical climate observations. The landcover for this recent period was again a mix of forested (75%), deforested (20%), and urban (5%) (Figures 6.7), to approximate what exists today at Palenque. This span of time is also useful because of the opportunity to compare the scenario with descriptions from the local population of flood and drought events that have taken place in the last 50 years.

RESULTS

The scenarios described above produced varying levels of peak, low, and high flows. These differences are caused first and foremost by changes in landcover and attributed only secondarily to climatic variations. The stream with the largest average daily output (23,204 m^3/per day) is unnamed, and is located on the eastern edge of the watershed (Figures 6.8 & 6.9). The Otolum stream, discussed extensively in Chapter

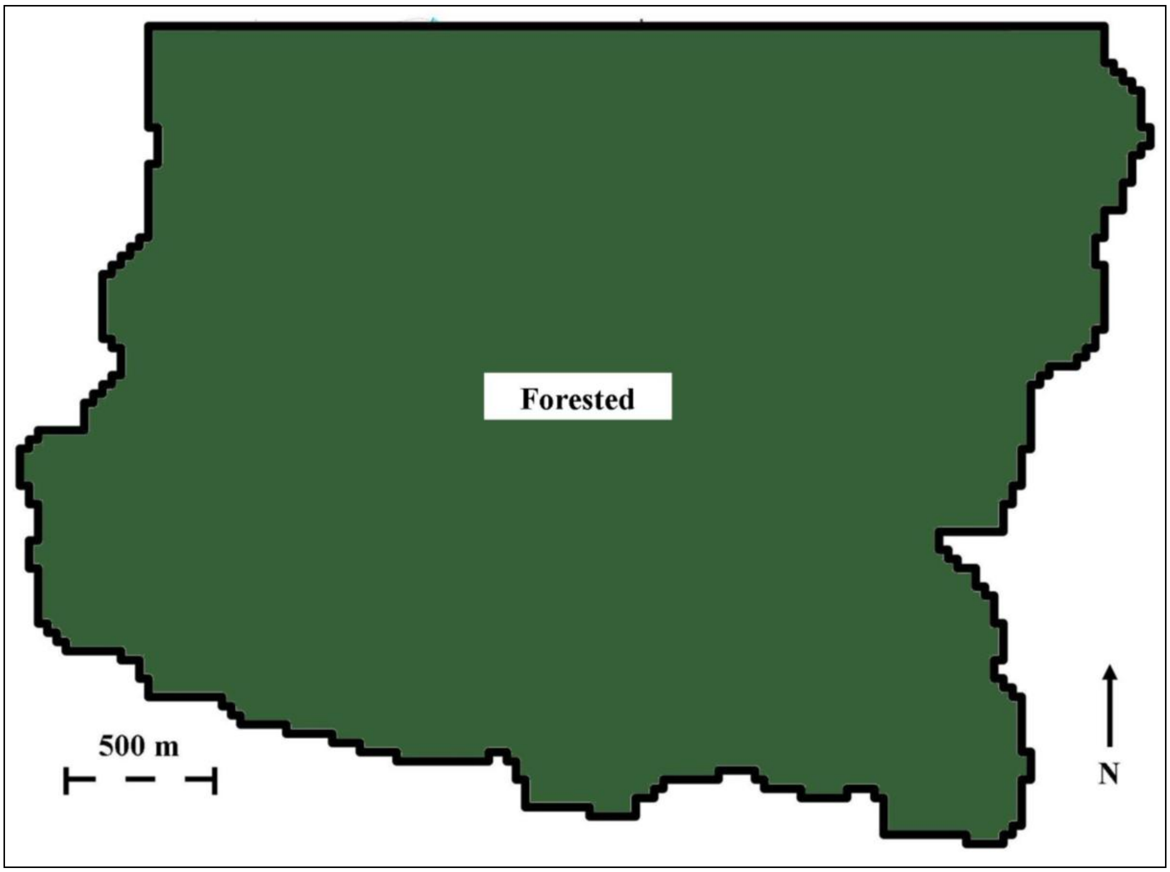


Figure 6.5 – Landcover for the Palenque Watershed during 500 BC – 401 BC.

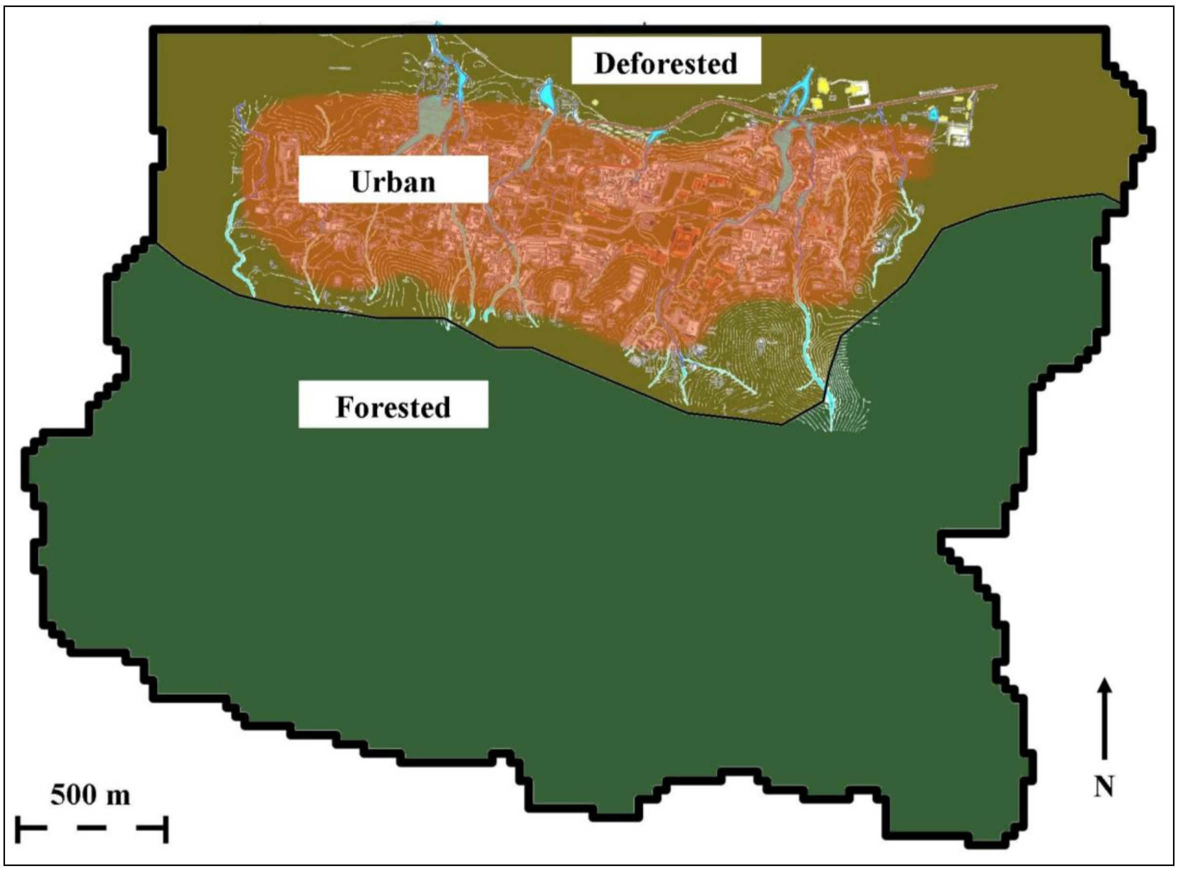


Figure 6.6 – Estimated landcover for the Palenque watershed from AD 601 – AD 700.

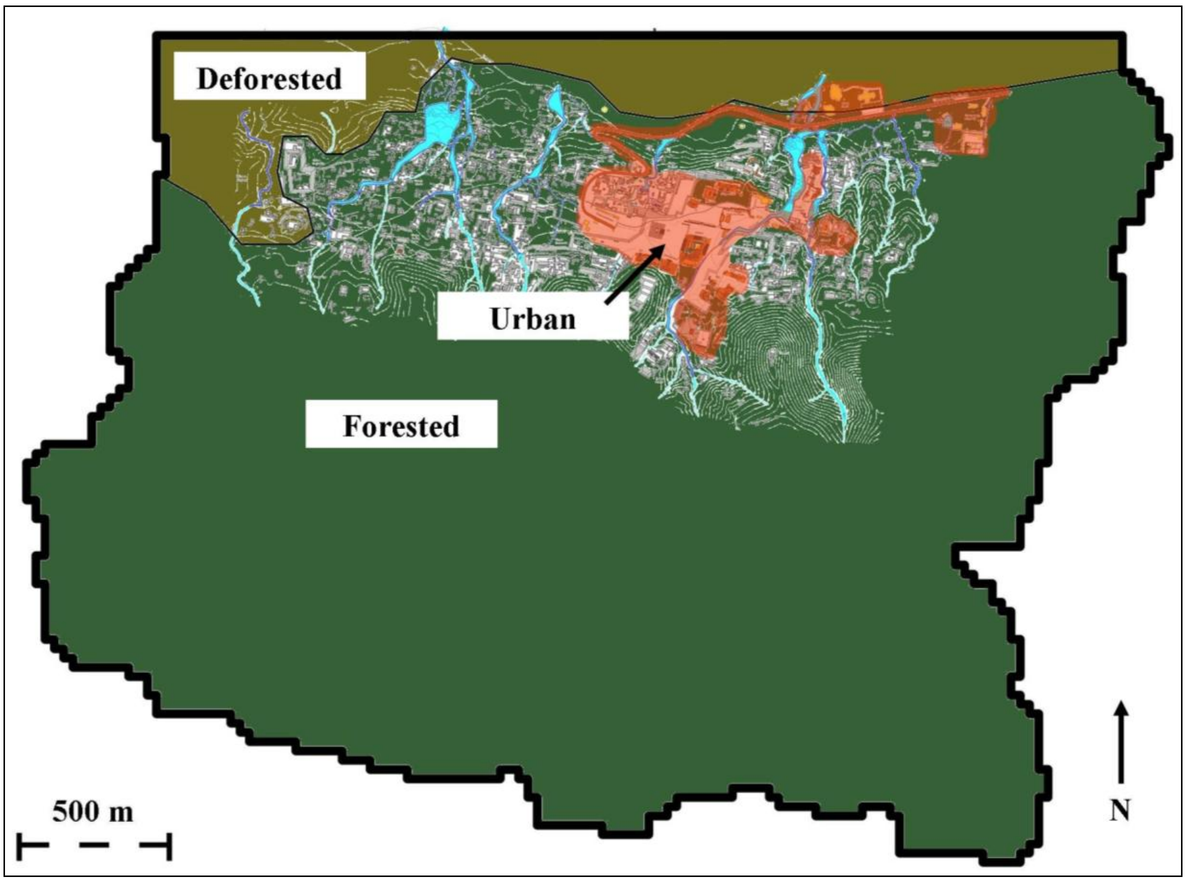


Figure 6.7 – Approximate landcover of the Palenque watershed from AD 1901 – AD 2000.

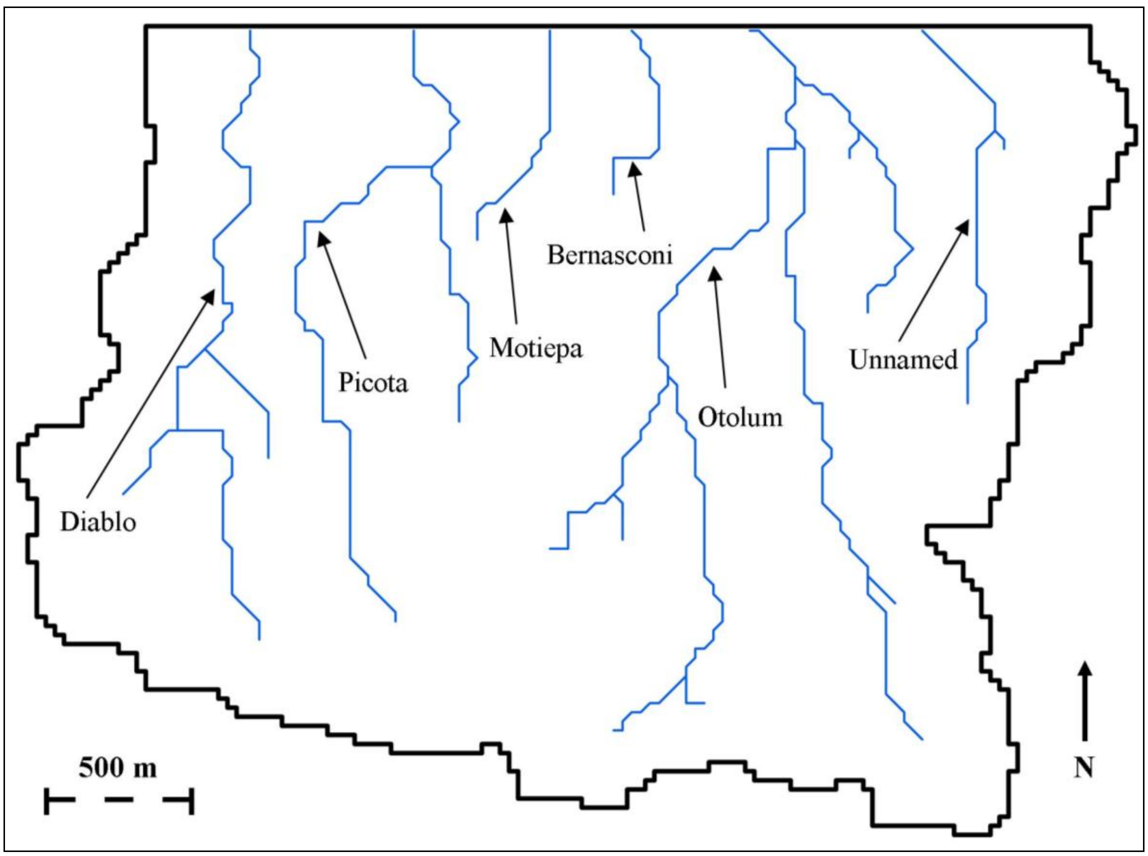


Figure 6.8 – Stream locations within the Palenque watershed.

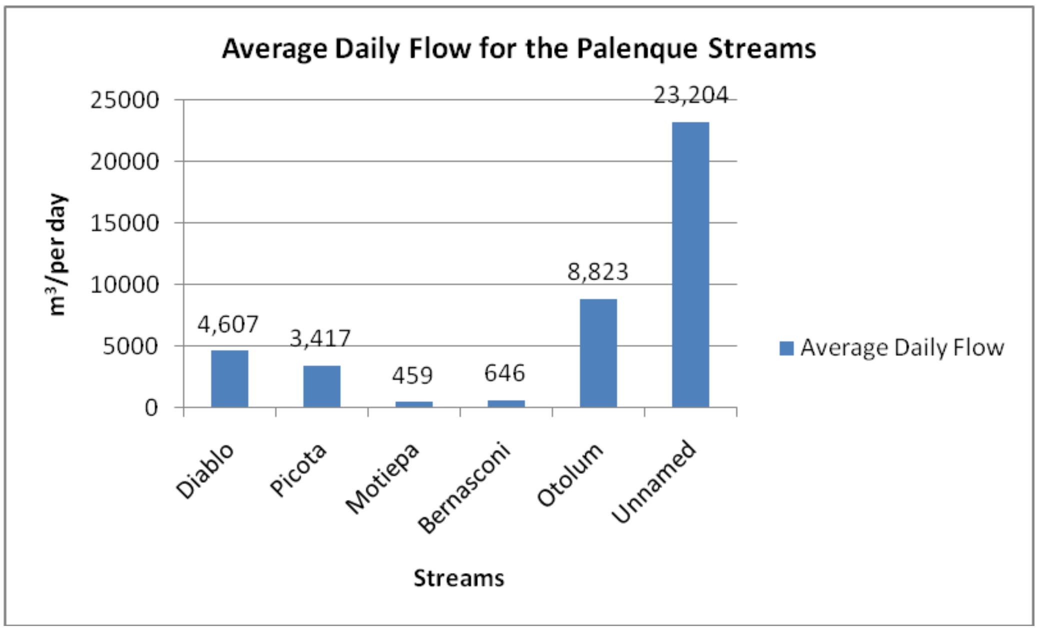


Figure 6.9 – Average daily flow for the Palenque streams.

7, produces the second largest discharge (8,823 m^3/per day) and flows through the site's main center. Results of the three scenarios are described below:

500 BC – 401 BC

The results from 500 BC – 401 BC show an average daily discharge of 36,491 m^3/per day for the entire watershed (Figures 6.10 & 6.11). The complete forest-cover, along with an absence of impermeable surfaces (e.g. plaster/stucco plazas), could be attributable to the low runoff. According to the climate simulation the precipitation for 500 BC – 401 BC was very close on the average to that of AD 1901 – AD 2000, but 2% dryer than the AD 601 – AD 700 (Figure 6.12). As for temperature, the simulations show that the 4th century BC was 5% cooler than the 20th century and 1% cooler than the 6th (Figure 6.12).

AD 601 – AD 700

The results from AD 601 – AD 700 show the highest average daily discharge of the three time periods simulated with 51,154 m^3/per day (Figures 6.10 & 6.11). This results in a greater than 40% increase in total runoff when compared to the other two time periods. The deforestation levels along with the presence of urban landcover (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 AD 601 – AD 700 was 2% higher than that of the other two scenarios (Figure 6.12). The temperature experienced n a 1% increase from that of the 4th century BC and was 4% cooler than the 20th century (Figure 6.12).

AD 1901 – AD 2000

The simulations from the last century show the lowest average daily discharge of the three scenarios with 35,823 m^3/per day (Figures 6.10 & 6.11). The precipitation during this time period and that of the 4th century BC are nearly the same, but the temperature increased by a full 1.4 °C (Figure 6.12). This significant rise in temperature

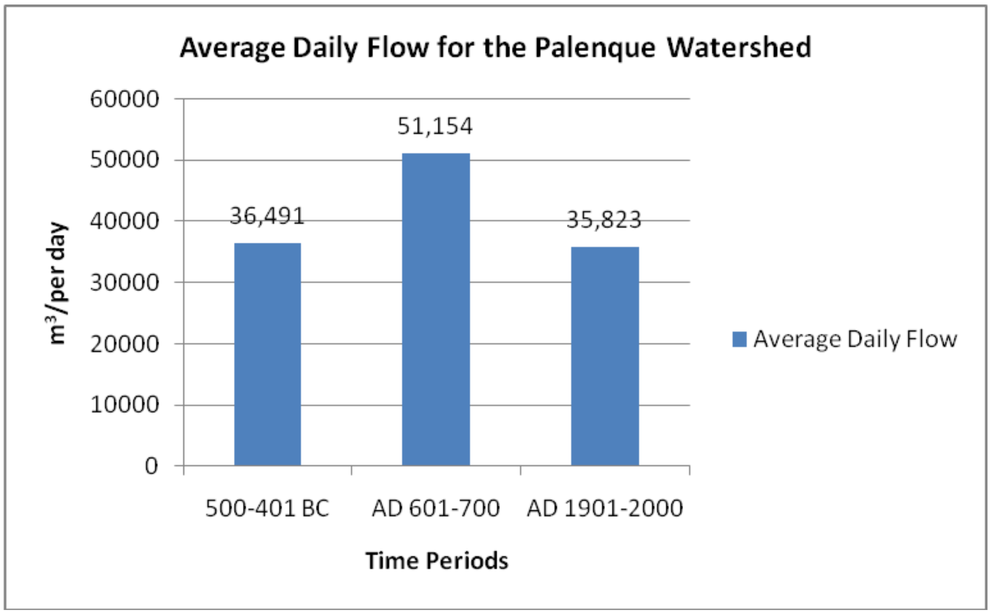


Figure 6.10 – Average total daily discharge for the Palenque Watershed.

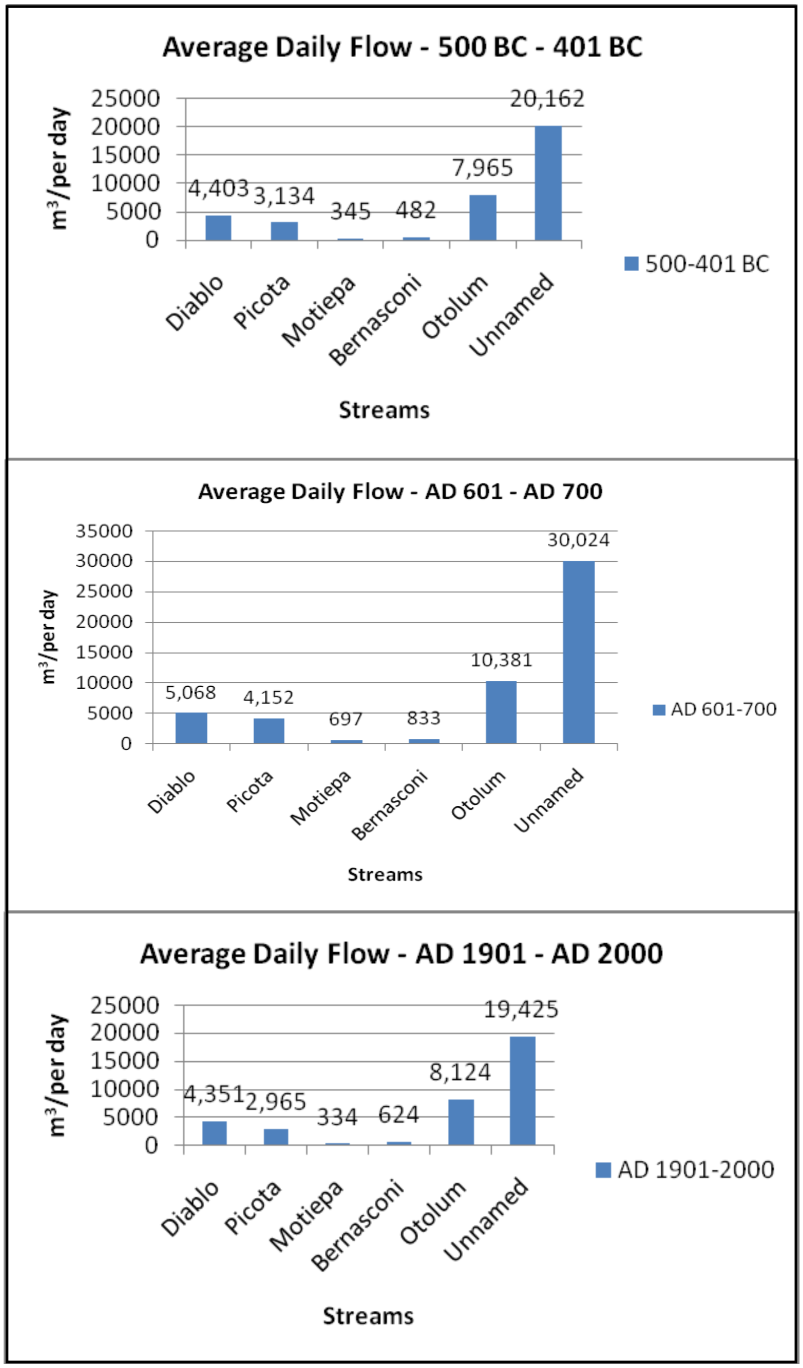
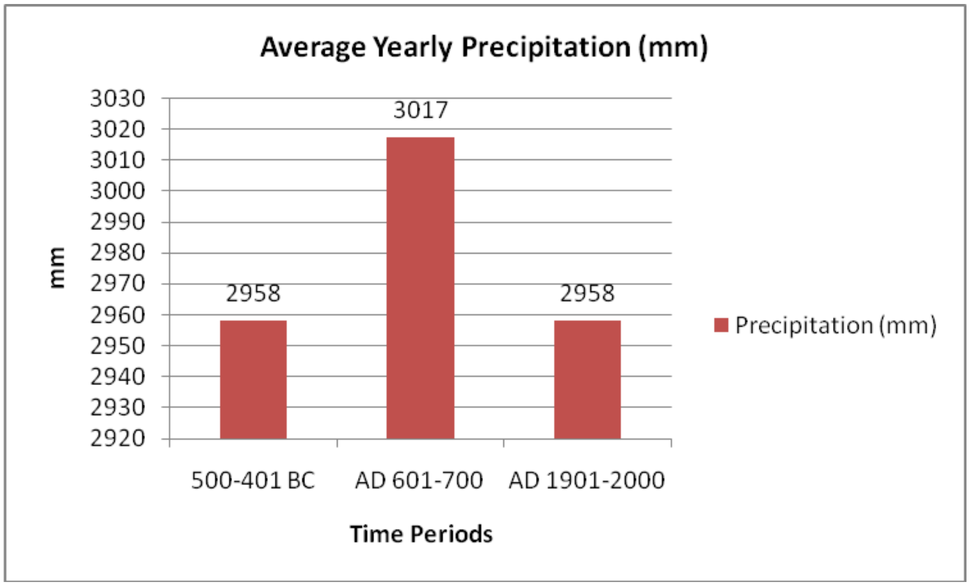


Figure 6.11 – Average daily flow for each of the Palenque streams for all three time periods.



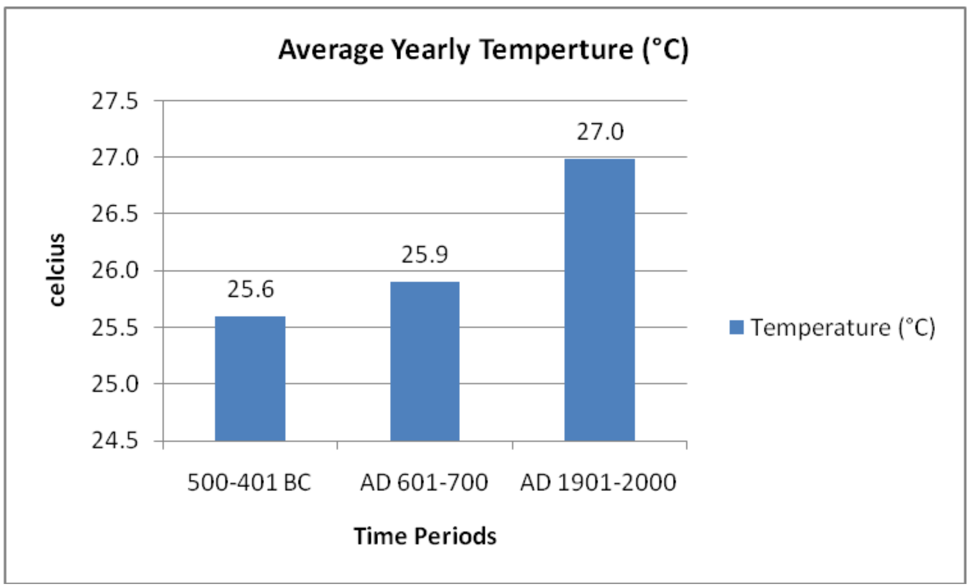


Figure 6.12 – Average yearly precipitation and temperature for three time periods.

coupled with less forest and an increase in urban cover are the causes for the 2% drop in daily flow.

SIMULATED FLOOD AND DROUGHT EVENTS

The scenarios described above of wetter or dryer 100-year climate periods with changing land cover make it possible to reconstruct the 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 urban land cover increases leading to much larger runoff; and warmer-dryer conditions leading to deeper hydrological drought (lower runoff).

One of the most frequently applied low and high flow indices is derived from a series of the annual minimum and maximum of the *n*-day average flow (Hisdal et. al 2004). For example if *n*=7, the entry from September 29, 1975 is in fact the average flow over 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 *7*-day duration through the daily data. Based on the filtered hydrographs mean annual minimum or maximum (*MAM* or *MAMX*) for *7*-day indices, can be derived. In this case, both *7*-day and *30*-day were used for *n* averages to find the lowest (drought) and highest (flood) flows for 500 BC – 401 BC, AD 601 – AD 700, and AD 1901 – AD 2000.

The flood events in Palenque (Figures 6.13 – 6.17) are linked to both rainfall and landcover. As mentioned above, the landcover for the 4th century BC is 100% forest. Forest cover slows the runoff from rainfall. The landcover used for the time period AD 601 – AD 700 was a mix of forest, deforested, and urban. Figures 6.15 and 6.16 show the drastic effects that a change in landcover can have on a watershed.

The hydrological droughts in the Palenque watershed (Figures 6.18 – 6.22) are not as severe due to urbanization. Figure 6.26 shows a 2% increase in rainfall for AD 601 – AD 700 equated to a 30% increase in the 30-day average low flow when compared to 500 BC – 401 BC and AD 1901 – AD 2000 (Figure 6.21). During the worst 7-day drought of AD 601 - AD 700 the Otolum was still flowing at 204 m^3/per day (204,000 liters) (Figure

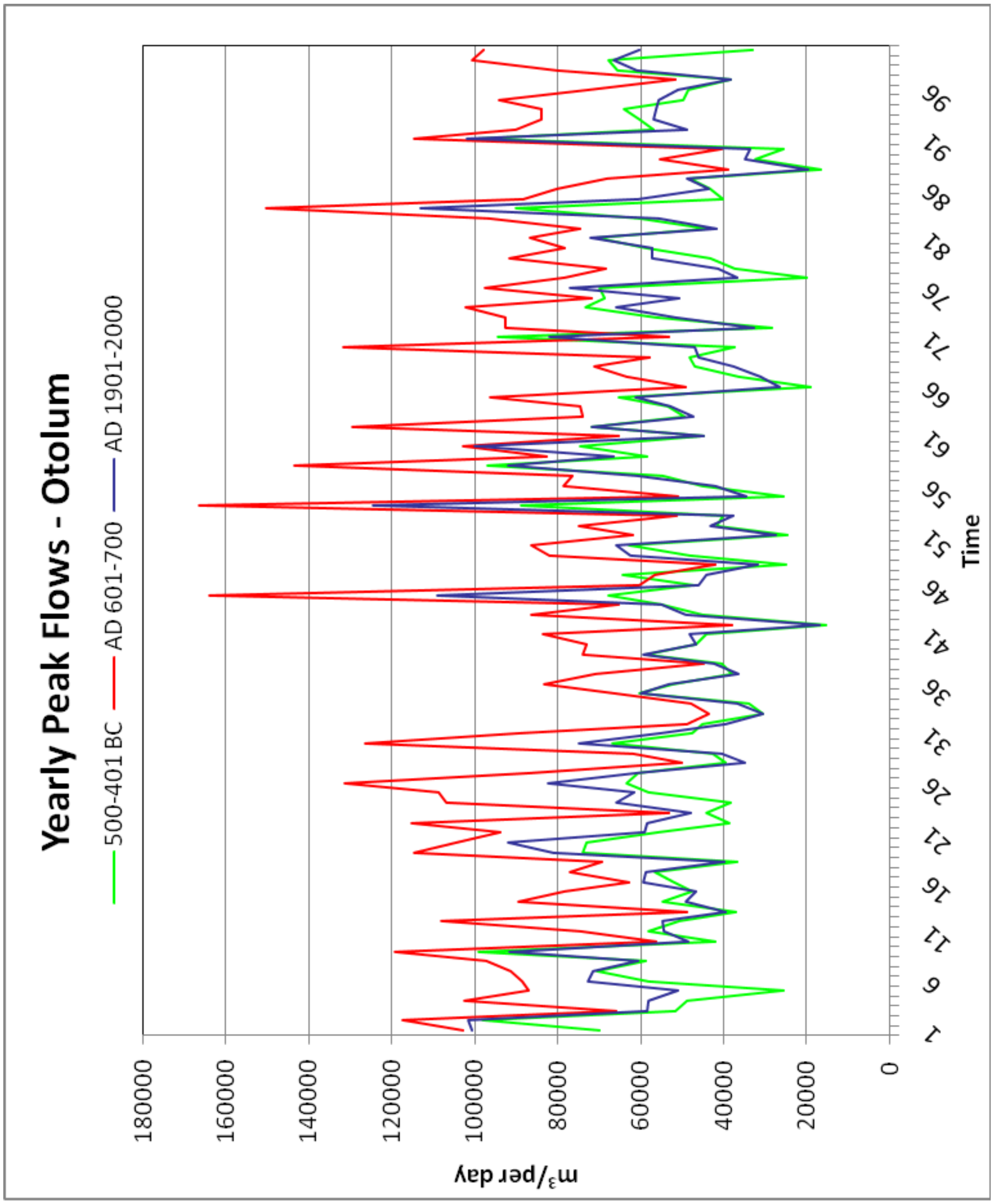


Figure 6.13 – Yearly peak flows (flood events) of the Otolum Stream for all three time periods.

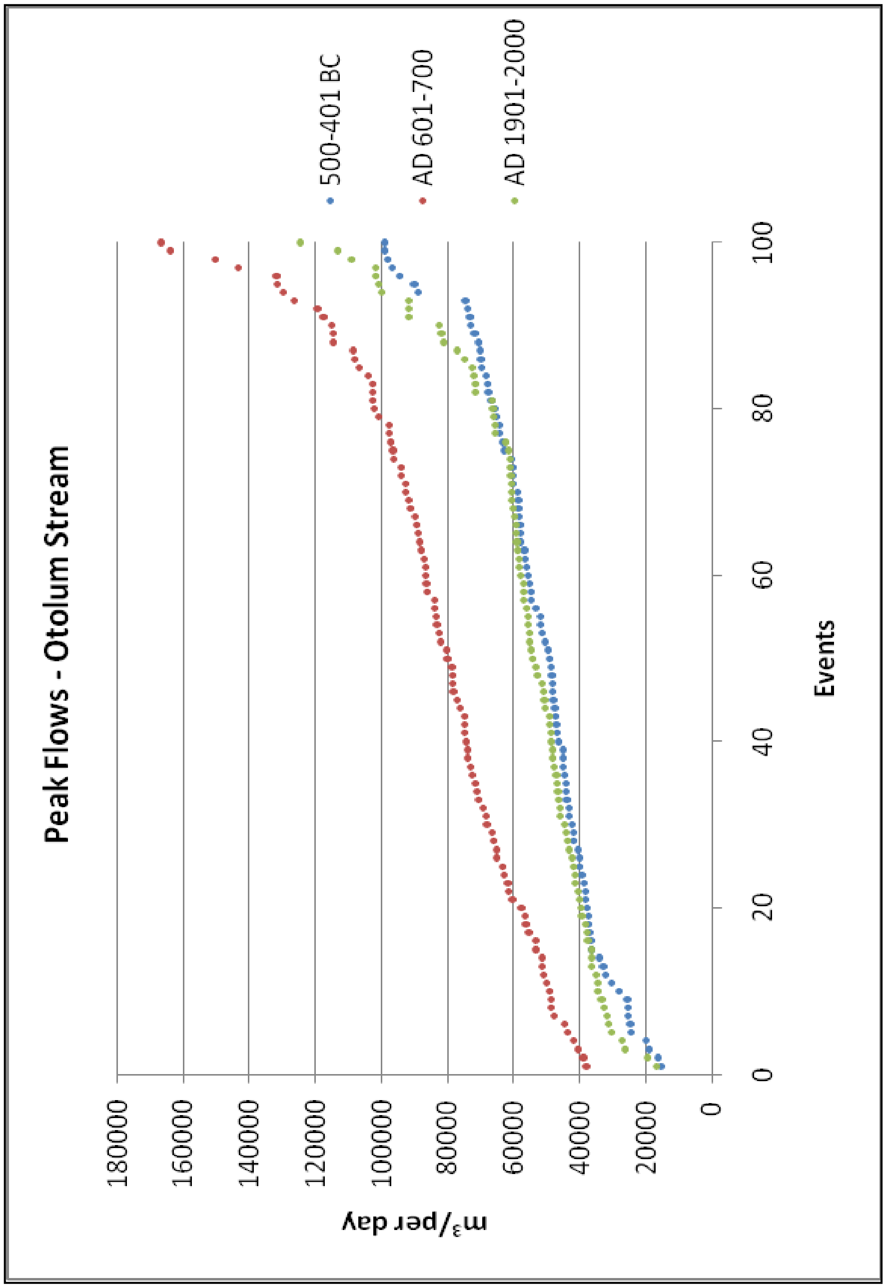


Figure 6.14 – Yearly peak flows (flood events) of the Otolum Stream for all three time periods, arranged from smallest to largest.

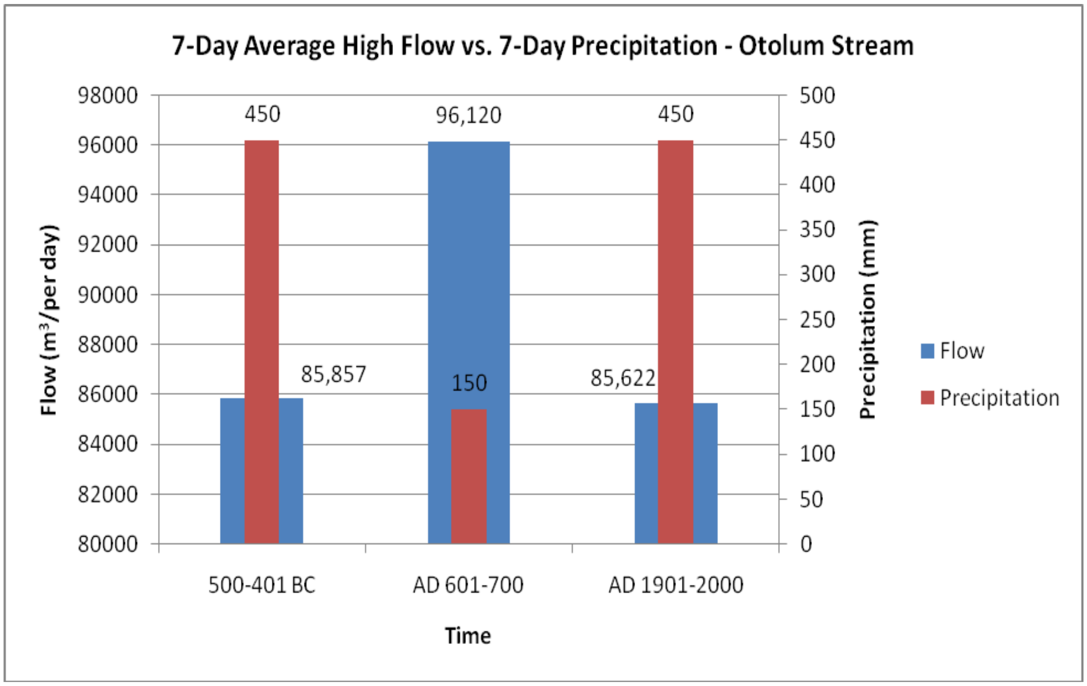


Figure 6.15 – The 7-day average peak flows (flood events) of the Otolum vs. the 7-day precipitation total for all three time periods.

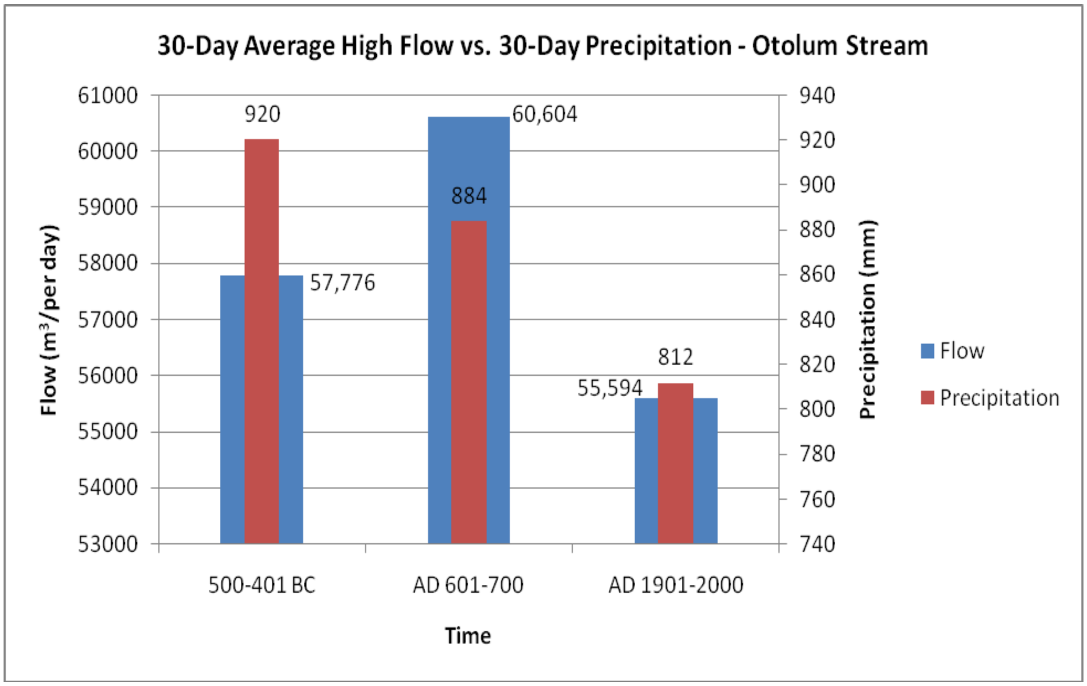


Figure 6.16 – The 30-day average peak flows (flood events) of the Otolum vs. the 30-day precipitation total for all three time periods.

500 - 401 BC	
n-day	***Q* (m^3/day)**
1	52452.944
7	38930.387
30	27614.612

601 - 700 AD	
n-day	***Q* (m^3/day)**
1	82194.769
7	44367.568
30	30492.656

AD 1901 - 2000	
n-day	***Q* (m^3/day)**
1	82194.769
7	44367.568
30	30492.656

Figure 6.17 – The 1, 7, and 30-day average peak flows (flood events) of the Otolum.

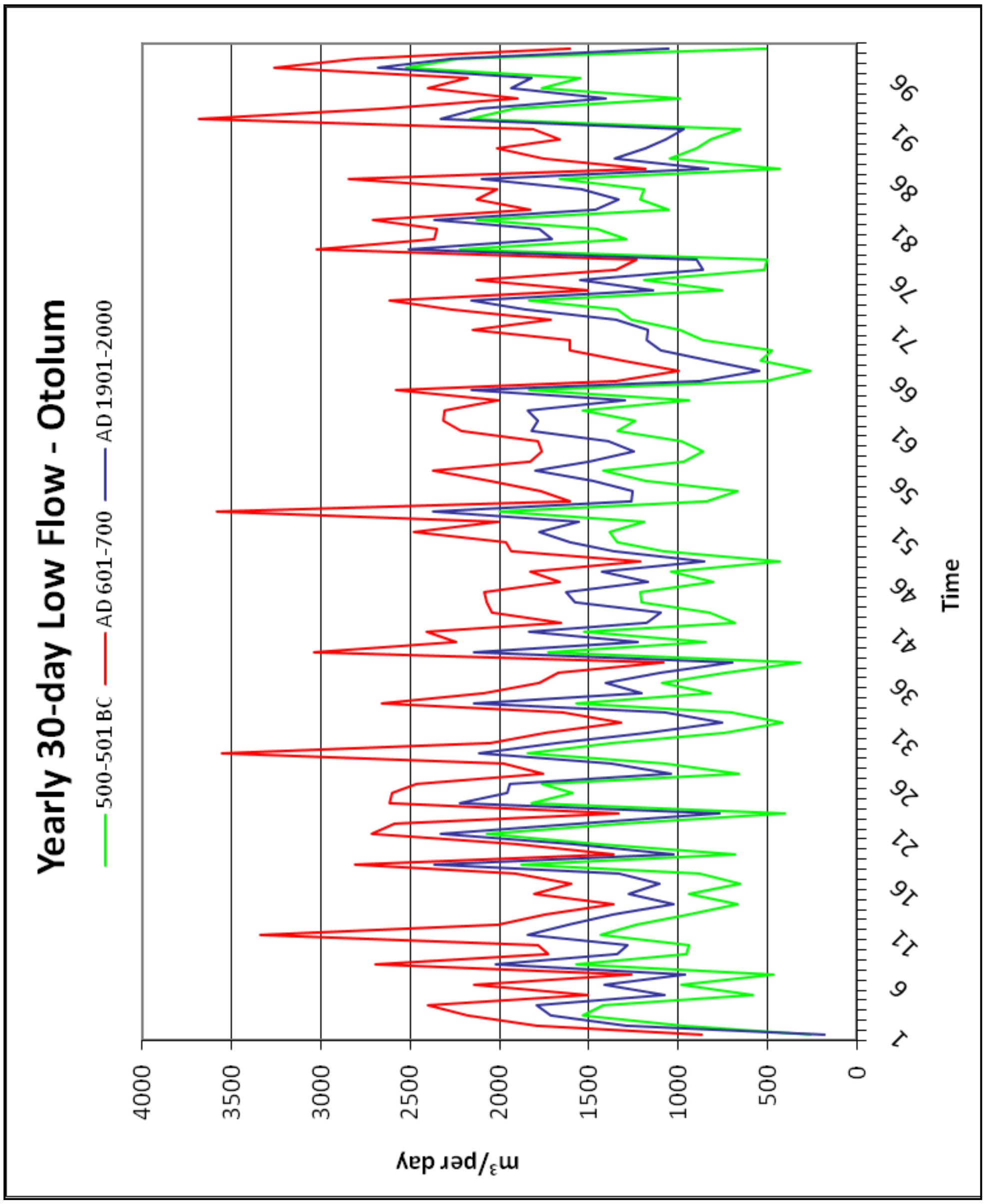


Figure 6.18 – Yearly low flows (drought events) of the Otolum Stream for all three time periods.

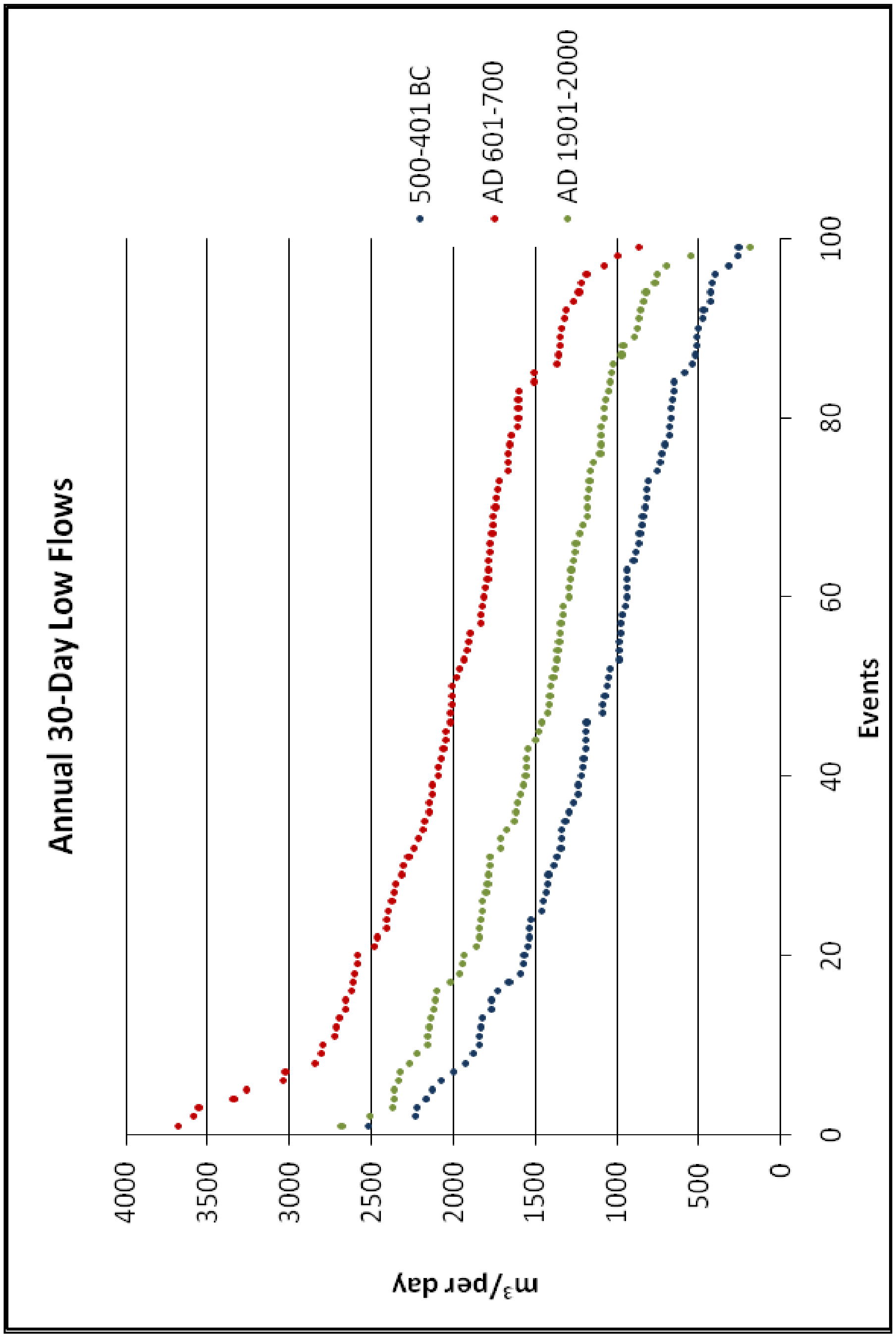


Figure 6.19 – Yearly low flows (drought events) of the Otolum Stream for all three time periods.

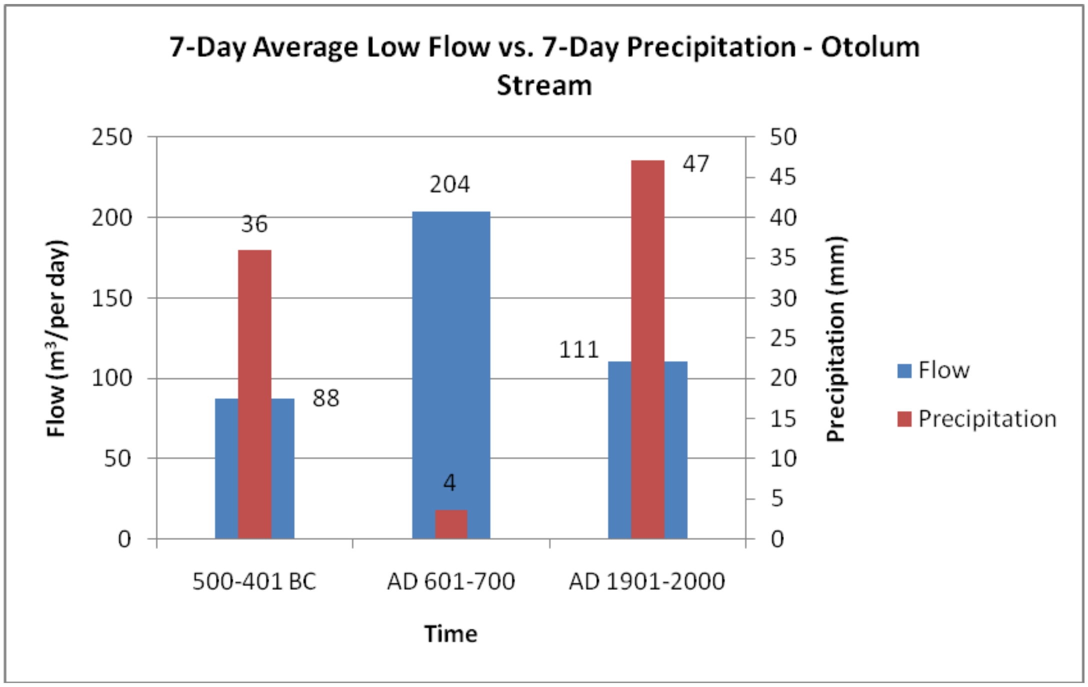


Figure 6.20 – The 7-day average low flows (drought events) of the Otolum vs. the 7-day precipitation total for all three time periods.

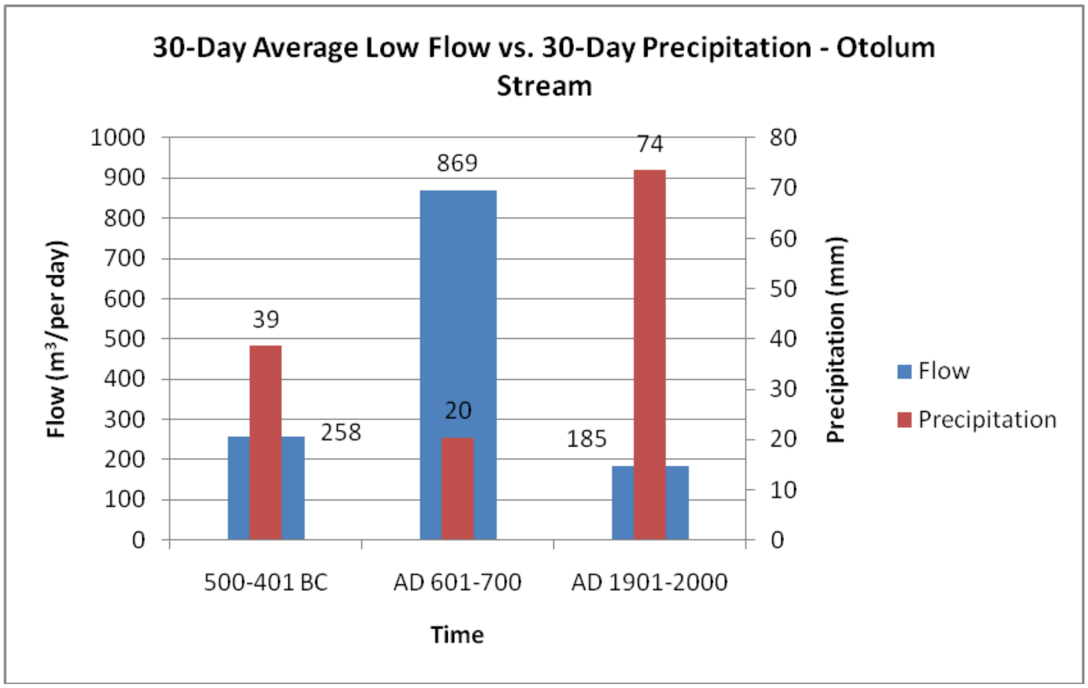


Figure 6.21 – The 30-day average low flows (drought events) of the Otolum vs. the 30-day precipitation total for all three time periods.

500 - 401 BC	
n-day	*Q* (m^3/per day)
1	572.20
7	677.56
30	1138.40

601 - 700 AD	
n-day	*Q* (m^3/per day)
1	1328.32
7	148.37
30	2048.23

AD 1901 - 2000	
n-day	*Q* (m^3/per day)
1	936.43
7	1042.21
30	1486.74

Figure 6.22 – The 1, 7, and 30-day average low flows (drought events) of the Otolum.

6.20). The storing of a mere 50% of this daily flow (102,000 liters) would have provided an ample water supply for a population of more than 17,000 based on 6 l per person/per day (Back and Lesser 1977) (more on storing water in Chapters 7 and 8). As mentioned in Chapter 3, the population of Palenque is estimated at a little over 6,000 at its peak. In addition, this 7-day low flow estimation is based on just one of Palenque's six major waterways, the Otolum. According to these simulations, Palenque never experienced a hydrological drought severe enough to cause major disruptions in daily life, much less abandonment.

EFFECTS OF DROUGHT ON MAIZE

As mentioned in Chapter 1, maize was the staple crop for the Maya. Maize is an efficient user of water in terms of total dry matter production and among cereals it is potentially the highest yielding grain crop. For maximum production, maize requires an average of 650 mm of water from planting to harvest (FAOUN 2002). As with most crops, irrigation and rainfall have a pronounced effect on grain yield.

Maize is relatively tolerant to water deficits during the vegetative and ripening periods (Figures 6.23). Greatest decrease in grain yields is caused by water deficits during the flowering period including tasselling and silking and pollination, due mainly to a reduction in grain numbers per cob. This effect is less pronounced when in the preceding vegetative period the plant has suffered water deficits. Severe water deficits during the flowering period, particularly at the time of silking and pollination, may result in little or no grain yield due to silk drying. Water deficits during the yield formation period may lead to reduced yield due to a reduction in grain size. Water deficit during the ripening period has little effect on grain yield (FAOUN 2002).

Careful analysis of the most severe simulated meteorological/agricultural droughts in Palenque did not reveal a time period that would have catastrophically affected agricultural productivity. Although there were times where the total rainfall during the summer growing season (Figure 6.24) dipped to as low as 650 mm, the

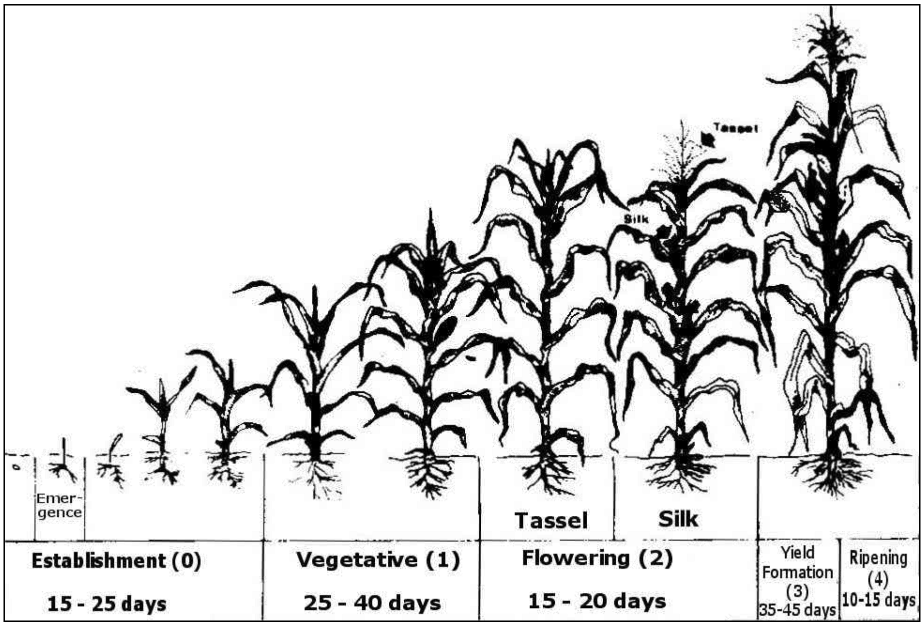


Figure 6.23 – This schematic graph shows the growth periods of maize (FAOUN 2002).

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

Figure 6.24 – Estimated calendar for the Palenque summer growing season for maize.

streams continued to deliver water to the channelized fields in the plains to the north of the site that were discussed in Chapter 1.

SUMMARY

There are important differences in the three scenarios discussed above that have implications for understanding the “hydrologic” and water supply conditions at Palenque during extended (century-long) wetter and dryer period of climate. The causes of these distinctions become evident when the percentage of change in climatic conditions is compared to that of the total discharge. For example, AD 601 – AD 700 (mix of forest, deforestation, and urban) had an impressive 28% increase in discharge but with only a mere 2% rise in rainfall and a 1% increase in temperature when compared to 500 BC – 401 BC (100% forested). The definitive leading factor driving the rise in stream flow is the difference in landcover. 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 hydrological droughts simulated in Chapter 5 are contrary to the great “megadrought” theory causing Maya abandonment theory put forth over the last 10 years (Curtis and Hodell 1996, Gill 2000, Haug et al 2003, Gill et al 2007). According to the scenarios presented in this chapter, the Maya of Palenque, under no circumstances, were forced to leave their homes in search of water. Even during the worst simulated drought, Palenque had more than enough water to supply its households as well as its agricultural fields. The following chapter details the hydraulic engineering designed by the Palencanos to manage their abundance of water.

Chapter 7

Hydraulic Engineering of OT-A1

As discussed in Chapter 4, the watercourses at Palenque (Figure 1.1) generally run in a northerly direction. Beginning in the uplands along the first rise of the Chiapas Plateau, the spring-fed streams flow toward the plains of Tabasco. Fifty-six known springs supply nine separate watercourses that move through the site's interior. The arroyos are home to Palenque's many different water management features documented by the author (2002).

The climatic and watershed simulations detailed in Chapters 4 and 5 were applied to the Otolum Stream and sub-watershed with the intention of developing a better understanding of its response to flood and hydrological drought events as it represents the most important or at least the most developed water features at Palenque. In addition, the hydrological modeling helps to create a clearer picture of the functionality and capabilities of the water management features engineered on the Otolum.

THE OTOLUM STREAM (FIGURES 7.0 & 7.1)

The Otolum is Palenque's longest and most impressive stream. Its perennial waters flow through the site's center by way of a sophisticated aqueduct. Subsequent to passing under Palenque's only remaining fully functional bridge (OT-B1), the Otolum tumbles over a remarkable series of cascades with travertine terraces formed from cold water springs of limestone groundwater. These travertine terraces are deposited as lime, but the microorganisms and living bacteria create an organic look (Figure 7.2) that gradually changes as formations grow and water is forced to flow in new directions.

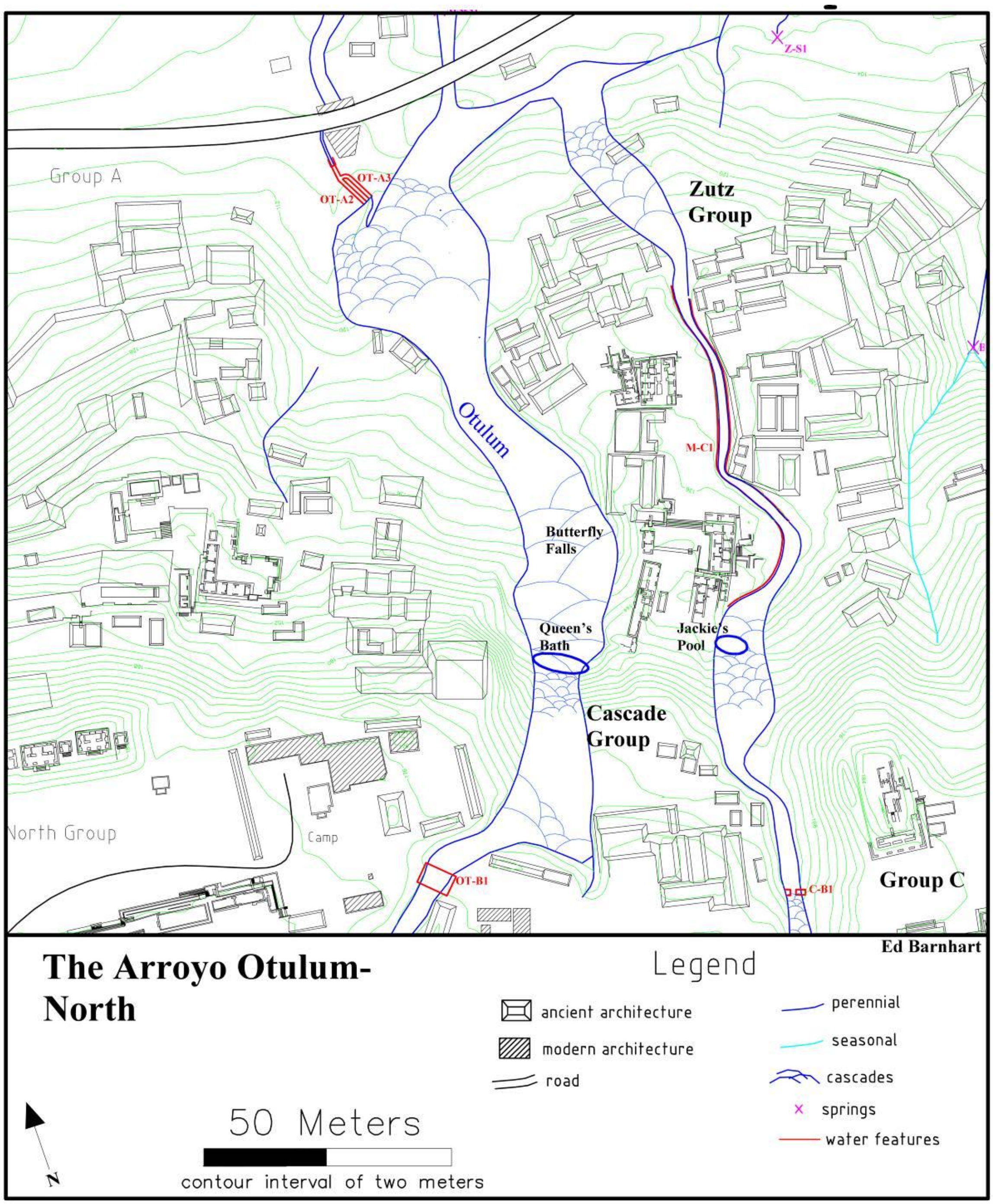


Figure 7.0 – The northern section of the Otolum Stream.

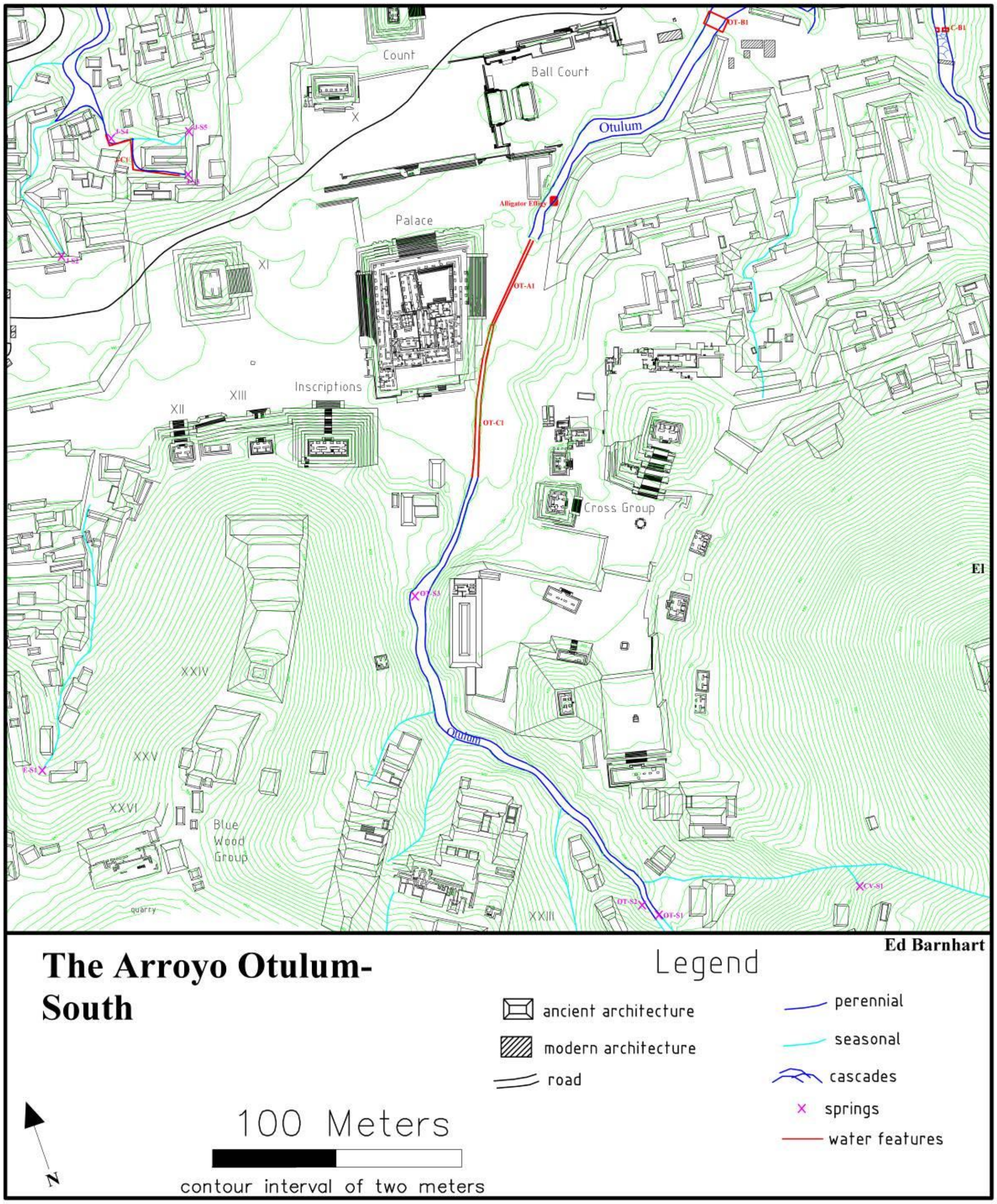


Figure 7.1 – The southern section of the Otolum Stream.

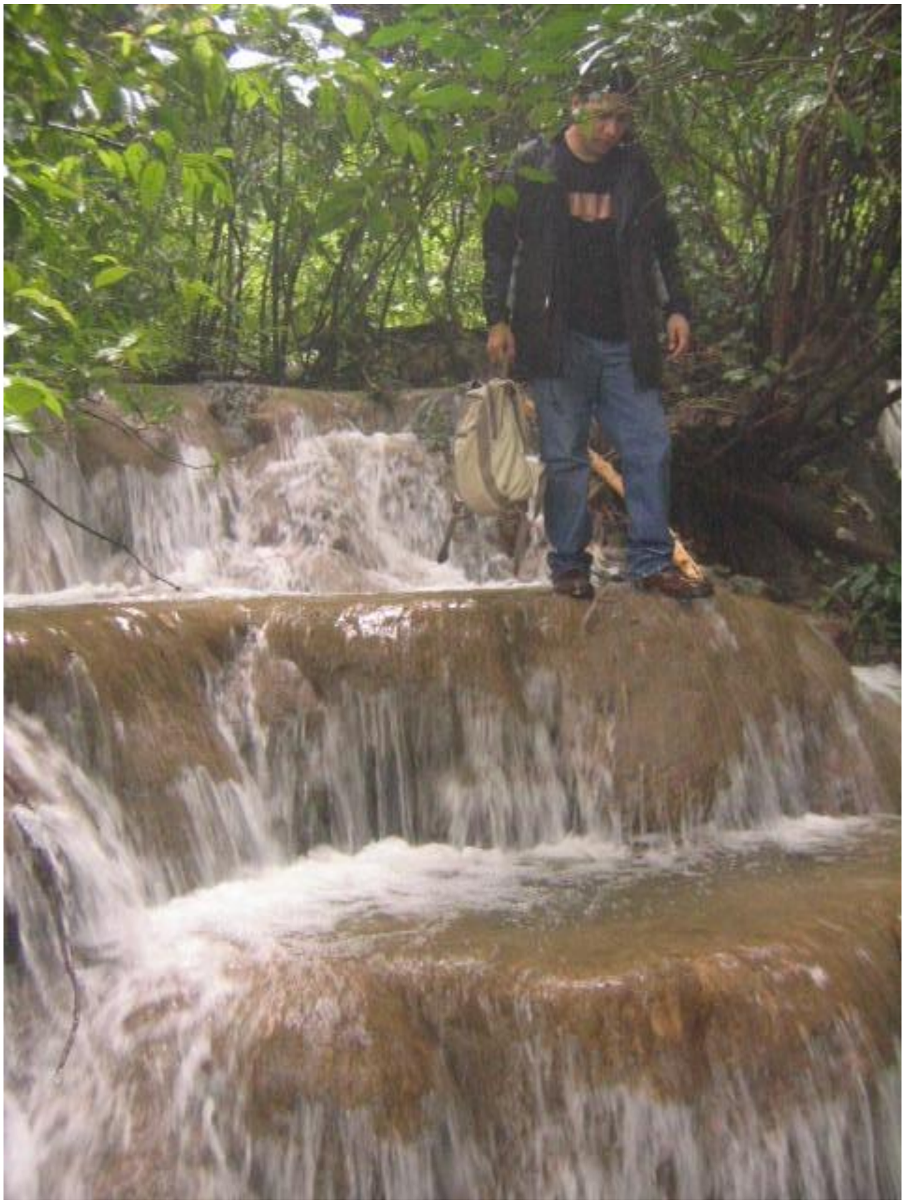


Figure 7.2 – The travertine terraces of the Otolum Stream.

South of the point where the perennial waters of the Otolum begin, a seasonal arroyo climbs to an elevation of 240 m. The perennial flow of the stream begins with springs OT-S1 and OT-S2, the true headwaters of the Otolum. The stream meanders in a northerly direction, forming the natural boundary of the Cross Group's western edge (Figure 7.1). At this point, a seasonal tributary extending from the Schele Terraces (Figure 7.3) joins the Otolum. The stream collects more water at OT-S3 (Figure 7.1) before entering the walled channel, OT-C1 (Figure 7.4).

The OT-C1 stretches 97 m before entering the OT-A1. This walled channel was actually an aqueduct during Classic times. Excavations at the entrance to OT-C1 show the foundation for the walls were much narrower than that of the walled channel today. The width of the base was similar to that of the aqueduct itself, narrow enough to support a corbelled arch. Maps of Palenque created by early explorers illustrate that the Otolum did not then flow through OT-A1 (Figure 4.1). Blom stated that the aqueduct was "blocked by its fallen roof" (Blom 1925:173). The collapse forced the Otolum to flow just to the east of the aqueduct and cut a new streambed (discussed in Chapter 4). Blom's map (Figure 7.5) clearly shows that the diversion of the stream began at the same location where the walled channel begins today and re-entered at the aqueduct's northern end (Figure 7.6). During the 1950s archaeologists began to clean out the debris and rebuild the walls (Figures 7.7 and 7.8). After the collapse was cleared, the water from the Otolum split in two directions. The stream once again flowed through the aqueduct but continued to flow into its new channel. Not until 1985 did archaeologists decide to block off the side flow of the Otolum and force all of the water back into the aqueduct. The new channel was filled with earth, and no trace is left of it today.

The intact section of OT-A1 is in excellent condition and carries the Otolum 58.5 m beneath the floor of the plaza (Figure 7.9) at an elevation of 187.50 m. There is evidence of four separate construction phases of OT-A1. It appears that the Maya of Palenque continued lengthening the aqueduct by extending construction to the south. The earliest building phase of the aqueduct, Section A, extends southward from the exit approximately 40 meters (Figures 7.9 - 7.11). This is OT-A1's best-preserved section,

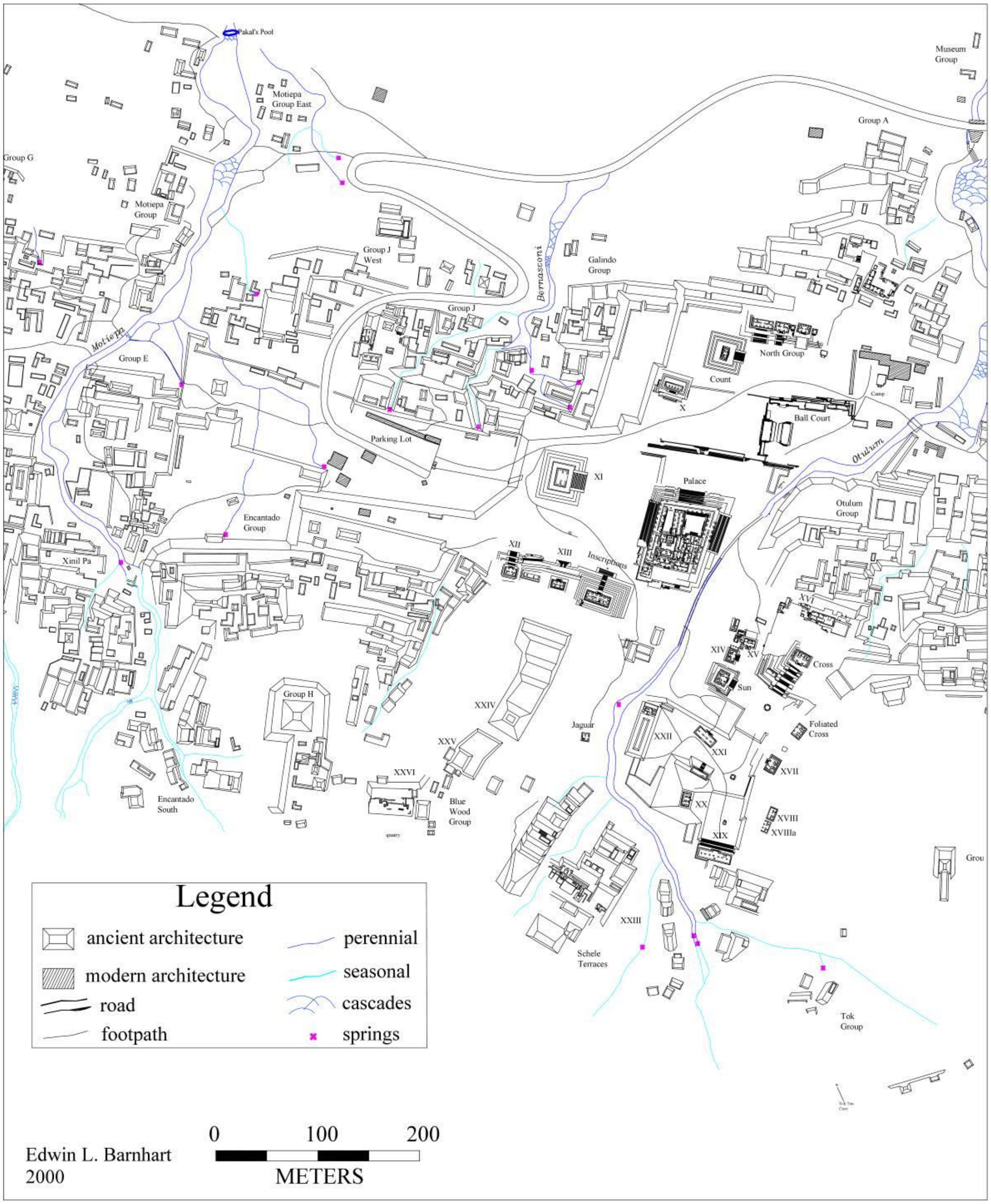


Figure 7.3 – The springs of the Otolum Stream.

Figure 7.4 - The Otulum flowing through OT-C1, also referred to as Section D. Note that Section D and C join together where the man is standing.

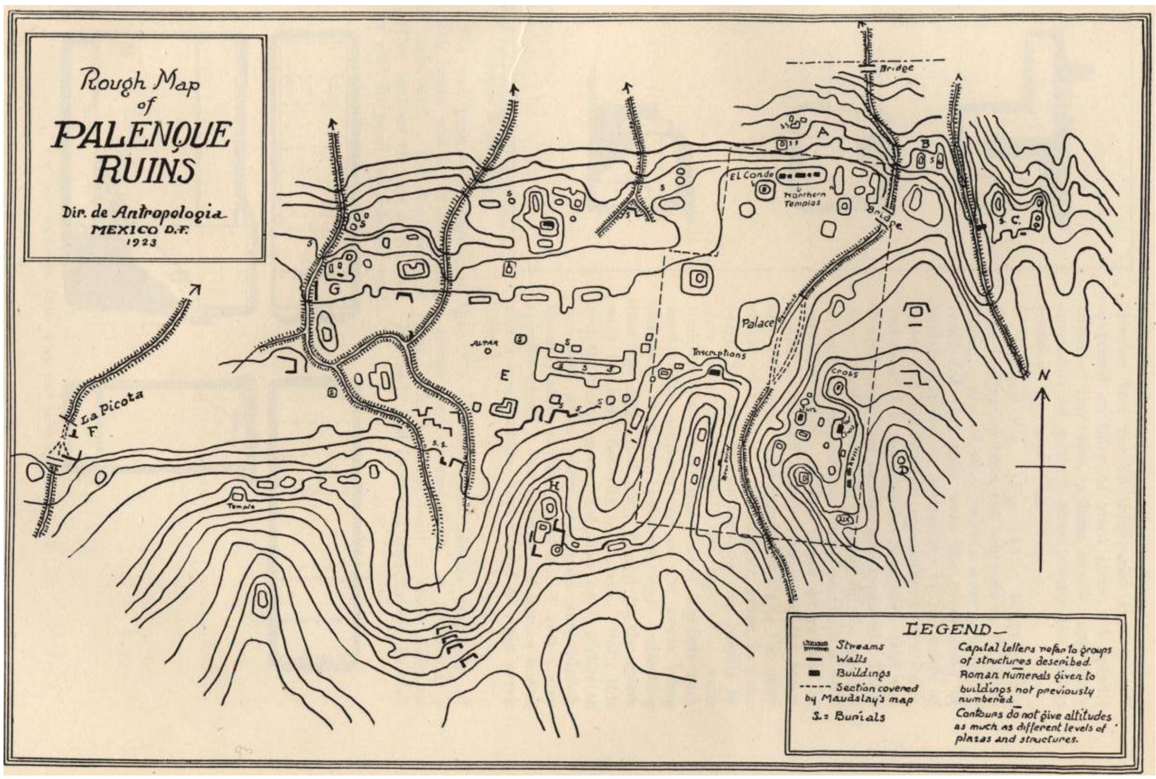


Figure 7.5 – An early map of Palenque by Frans Blom (Blom 1926).

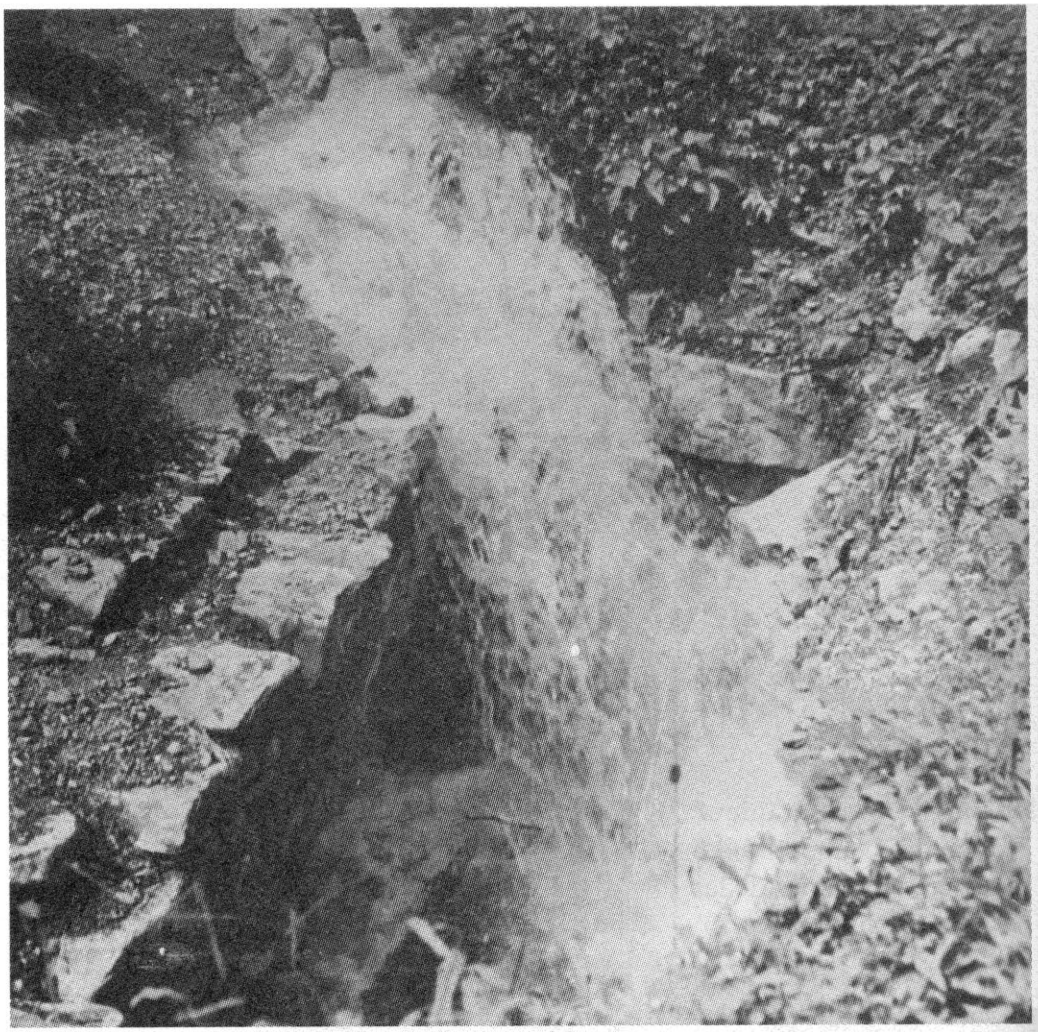


Figure 7.6 – The Otolum flowing back into OT-A1. This is at the northern end of Section A (Moll 2007).

Figure 7.7 – Collapse section of OT-A1 (Moll 2007).

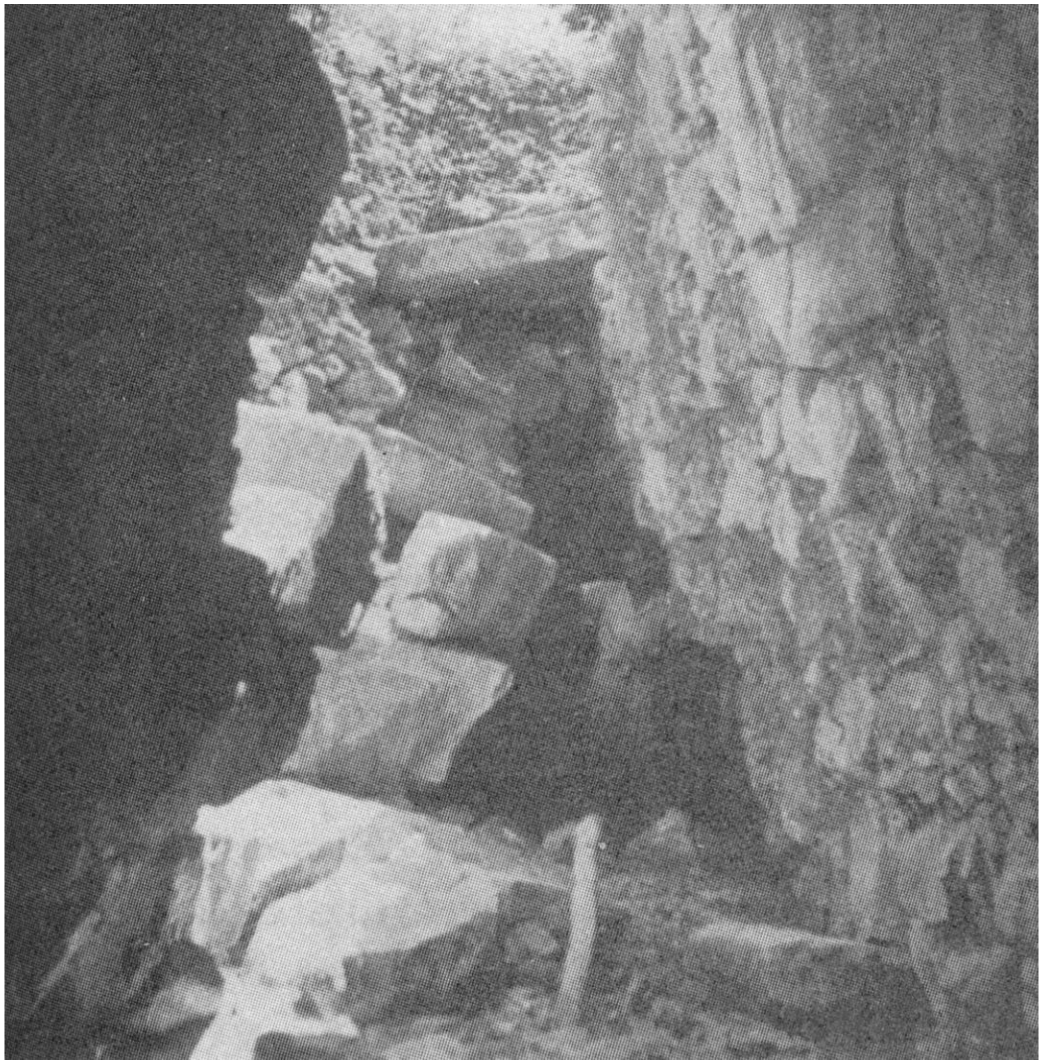


Figure 7.8 – Partial collapse of the southern end of Section C (Moll 2007).

Figure 7.9 – Interior of OT-A1, Section A.

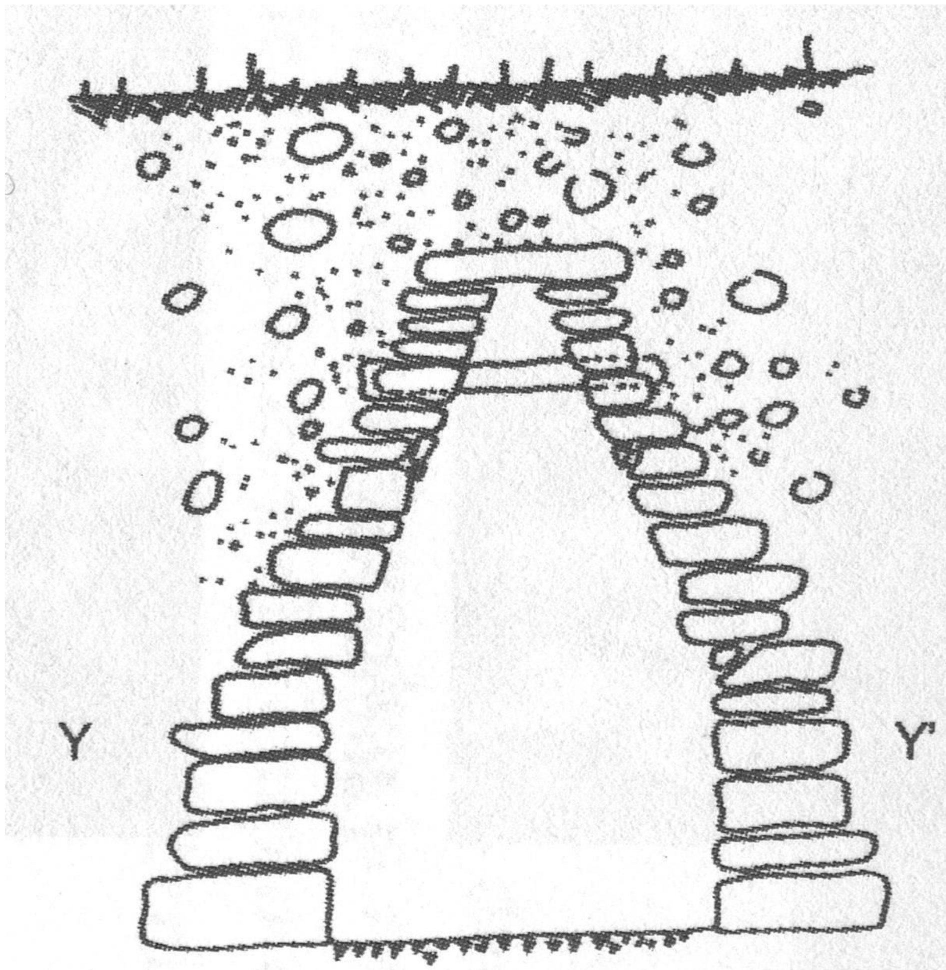


Figure 7.10 – Section A of OT-A1 (Moll 2007).

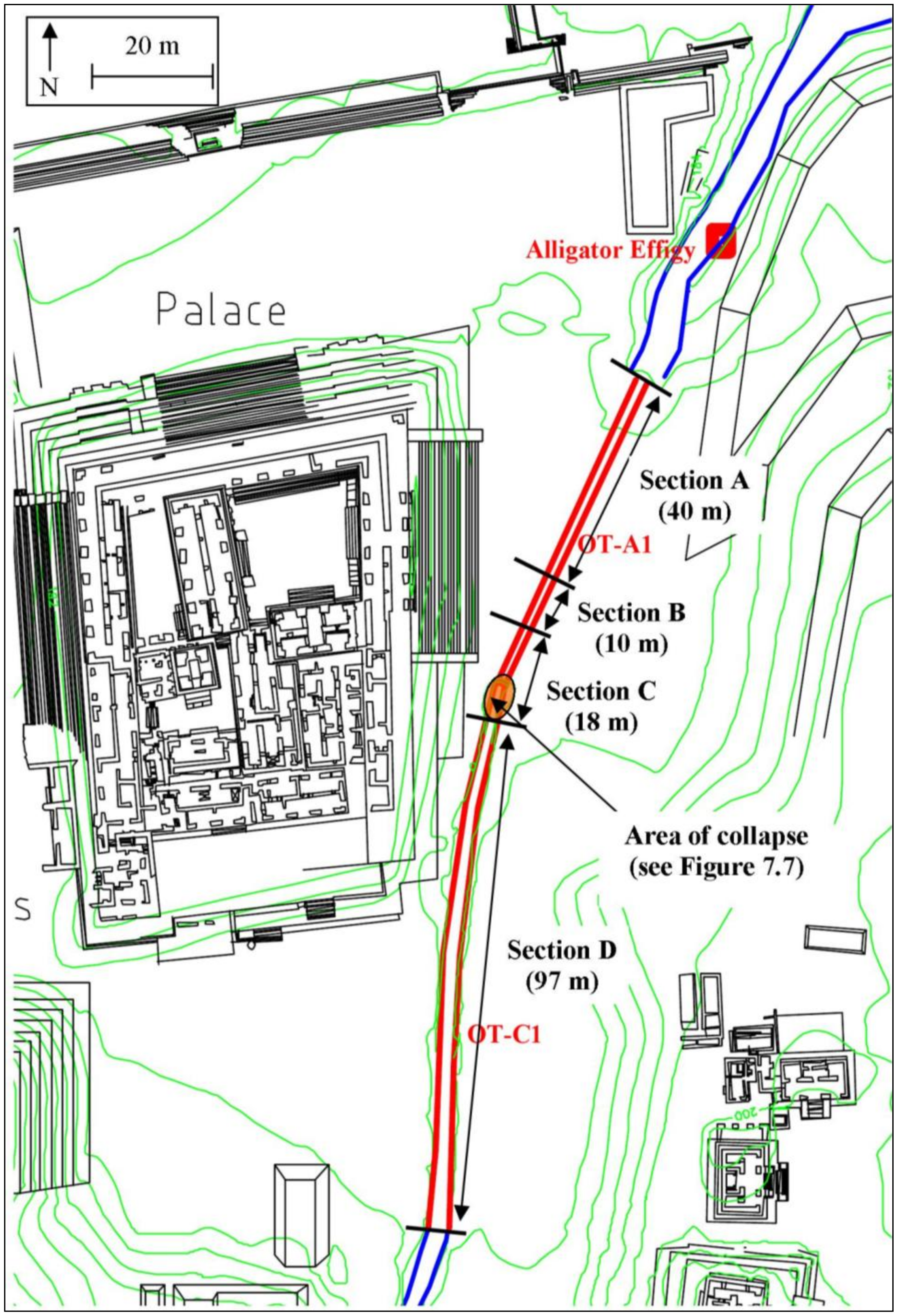


Figure 7.11 – The four construction phases of OT-A1.

consisting of large cut-stone support beams found in the corbelled arch. The second phase (Section B) stretches roughly 10 m and is almost identical in construction except for the absence of the stone support beams. The vault on the east side is under stress and is sagging. OT-A1's third phase (Section C) extends the remaining 8 m before the entrance but appears to have continued another 10 m prior to the collapse. This is uncertain, though, because the archaeologists of the 1950s widened the wall artificially in this area.

After the stream exits OT-A1, a wall on the east side continues for 27 m. The water then passes an extraordinary work of art, positioned 1 m above the flow of water--an enormous alligator effigy (Figure 7.12). It measures 3.44 m in length, 1.10 m in height, and 86 cm thick, or about 3.50 m^3. When the Otolum was fully maintained by the Maya and clear of all debris, the water level would have been substantially higher. This is also true today throughout the rainy season. During times of high water, the alligator would have appeared to be floating atop the waters of the Otolum (Stephen D. Houston, personal communication, 2000).

The stream then snakes slightly eastward, passing the ball court and approaches OT-B1, the Otolum Bridge, which measures 10.25 m x 10.25 m and is in superb condition. Today tourists and workers use the bridge on a daily basis. The water passes through a corbelled arched opening directly in the middle of the bridge. The passage is about 1 m in width. After passing beneath the bridge, the water begins to cascade over the falls and into the Queen's Bath (Figure 7.0). The water then topples through a multiple number of small pools that have been nicknamed the Butterfly Falls (Figures 7.0 and 7.2).

At an elevation of 110 m the stream gathers in a small and shallow natural pool and then enters a set of parallel aqueducts (Figure 7.13). OT-A2 has been obstructed from view by a large tree that grows directly atop the entrance. The Otolum waters still manage to find their way into the aqueduct. OT-A2 travels north at a bearing of 27° for 19.4 m before exiting into the natural streambed (Figure 7.14). The second aqueduct, OT-A3, is heavily calcified and partially

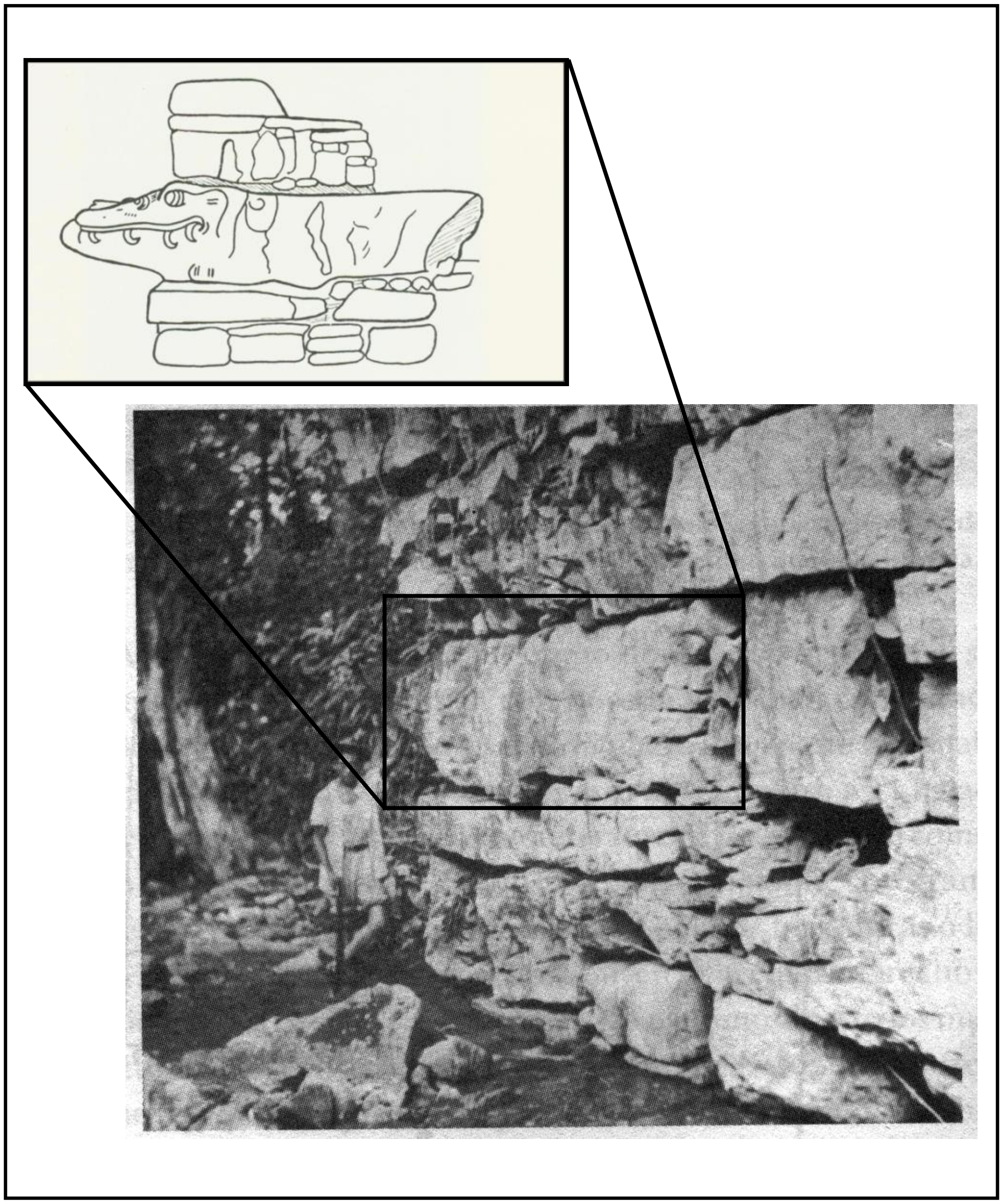


Figure 7.12 - The carved alligator/caiman found at the exit of OT-A1.

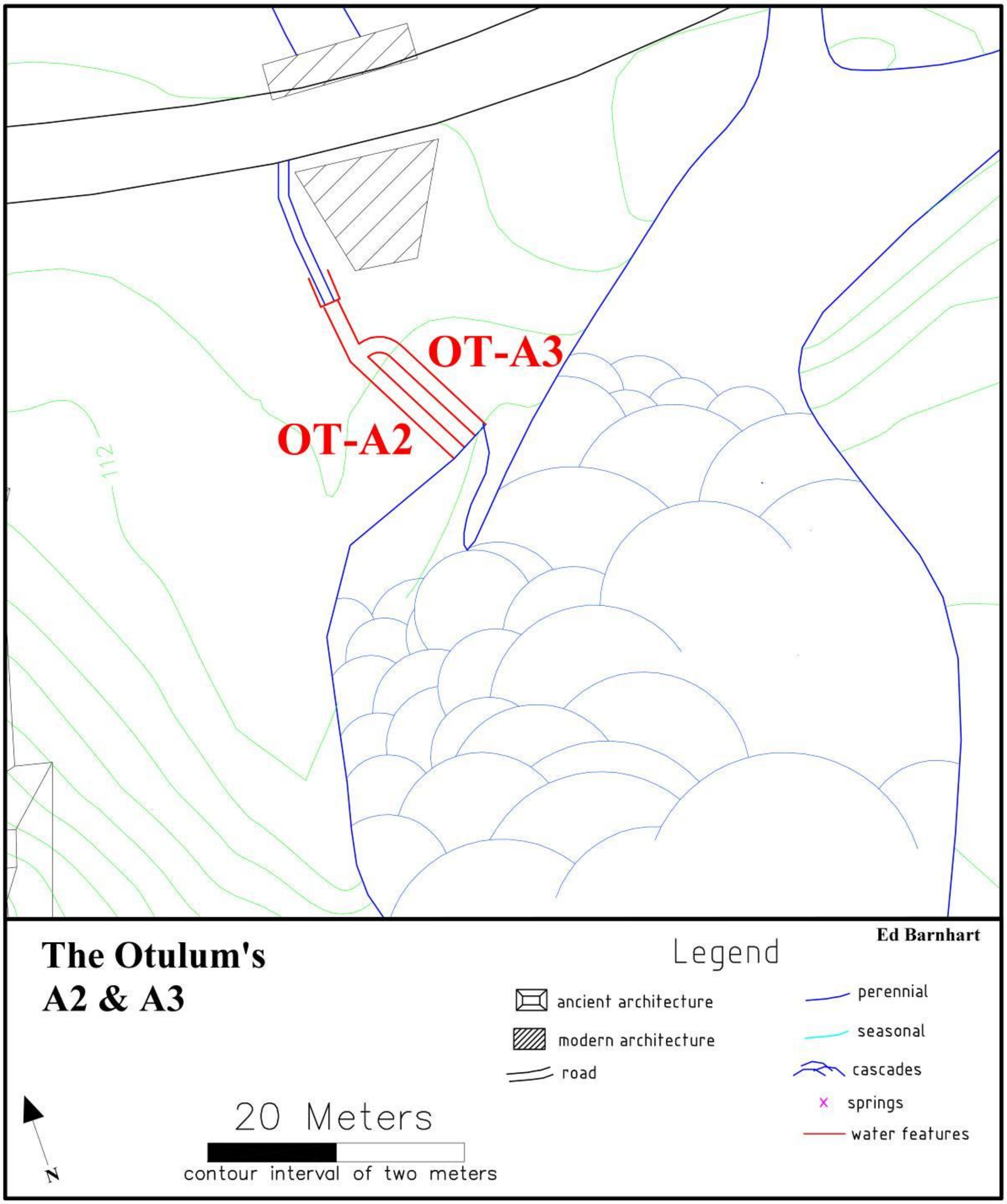


Figure 7.13 – Map of OT-A2 & OT-A3.

Figure 7.14 - The interior of OT-A2, showing the exit of OT-A3 on the left.

collapsed. Despite the damage, the majority of the water flows through this feature. Both aqueducts have similar dimensions, averaging 1.10 m in height and 80 cm in width. The entrance of OT-A3 contains a set of peculiar niches approximately 5 cm^2 (Fig. 7.15). One is located on the west wall, while the other faces it on the east wall. It is possible that they served as a holding device for a sluice gate of some kind. Downstream from the niches, the aqueduct becomes badly damaged. The water continues through OT-A3 at a bearing of 27° for 13.6 m. At this point, the aqueduct changes direction with a rapid curve to the west. OT-A3 feeds into OT-A2 and the waters rejoin, exiting together. The Otolum then passes under the road and through the Museum Group and eventually joins the waters of the Michol River.

OT-A1 – FLOOD RESPONSE

Gauging the effectiveness of OT-A1's ability to cope with flood events is essential to understanding the hydraulic design used by Maya engineers. The investment of labor into the construction of the aqueduct must have been fairly great given its size and complexity. Pitting OT-A1 against the largest simulated floods on the Otolum is the best way to understand the aqueduct's design capabilities and limits.

First, the *flow rate* (Q) of OT-A1 needed to be established. The flow rate is simply the volume of fluid which passes through a given surface per unit time (e.g. m^3/per sec.) (Viessman and Lewis 1996). The following formula is used to determine the flow rate of a trapezoidal conduit like that of OT-A1 (Figure 7.16):

$$Q = \left(\frac{1}{n}\right)(A)\left(R_h^{2/3}\right)\left(S_0^{1/2}\right)$$

To calculate the flow rate the following factors must be known:

1) *base width* (*b*)

2) *height of conduit* (*h*)

3) the *channel slope* (*S*)

4) *roughness coefficient* (*n*)

5) *depth of flow*(*d*)

Figure 7.15 - One of the niches at the entrance of OT-A3.

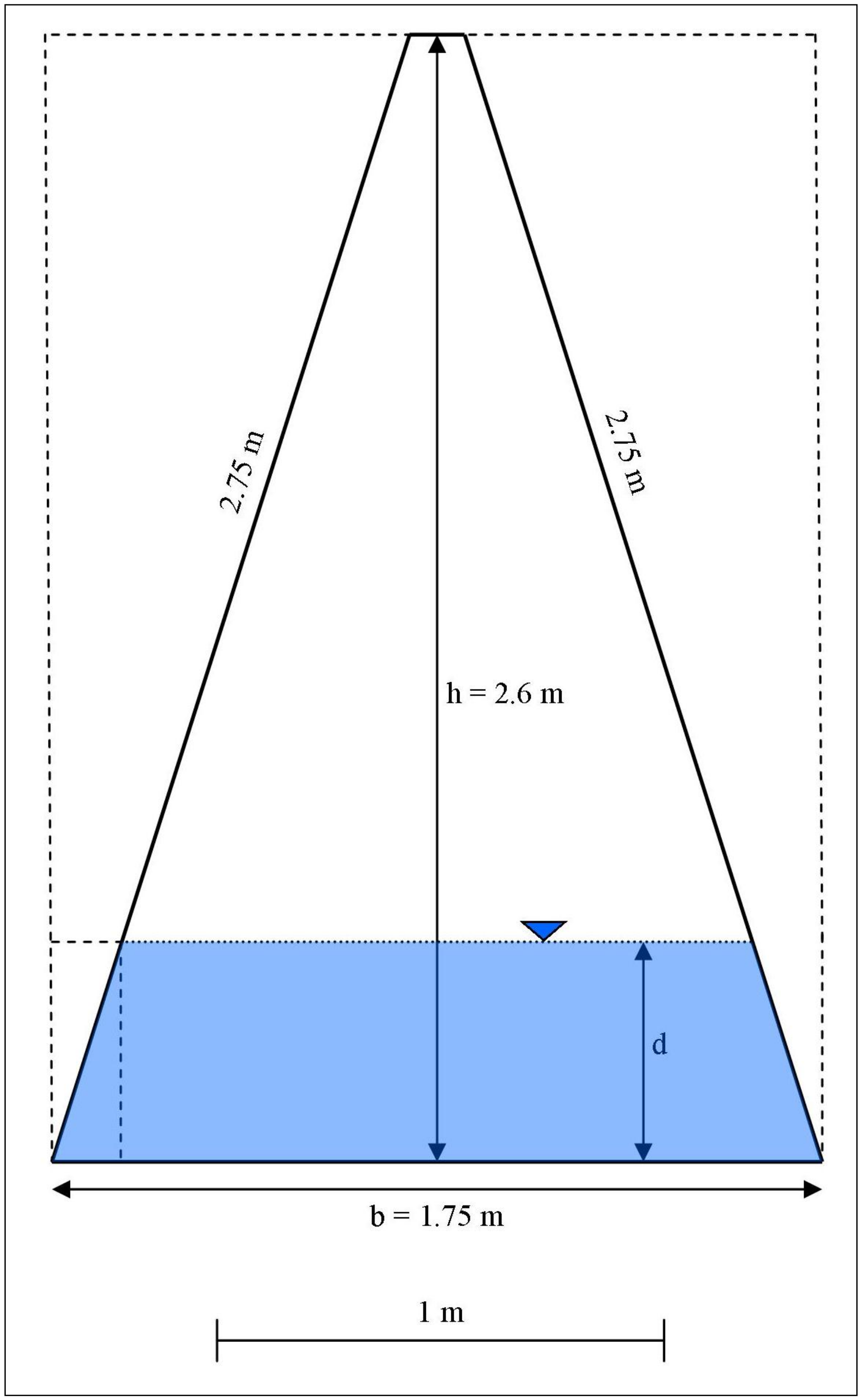


Figure 7.16 – Hydraulic design of OT-A1.

6) *flow area* (*A*): $A = bd - \frac{d^2 b}{2h}$

7) *wetted perimeter* (*P*): $P = b + 2\sqrt{d^2 + \frac{d^2 b^2}{4h^2}}$

8) *hydraulic radius* (R_h): $R_h = \frac{bd - \frac{d^2 b}{2h}}{b + 2\sqrt{d^2 + \frac{d^2 b^2}{4h^2}}}$

In the case of OT-A1, *base width* (*b*), *height of conduit* (*h*), *channel slope* (*S*), and the *roughness coefficient* (*n*) are all constant, while the *flow area* (*A*), *wetted perimeter* (*P*), and *hydraulic radius* (R_h) each change in relation to the *depth of flow* (*d*).

In order to better gauge the usefullness of OT-A1 it is necessary to understand its hydraulic design. Procedures for estimating hydraulic design include the examination of historical or simulated flood flows. Designing on the basis of an estimate of the probable maximum storm or maximum flood that could occur at a locale is called the *critical-event method*. Figure 7.17 is a flow chart containing the details of low flows (green), average flows (blue), over capacity (orange), and plaza flooding (red) for OT-A1. There were only 4 instances within a 100-year period that OT-A1 exceeded capacity (>2.6 m in height). Interestingly, a 25-year flood design is a commonly used hydrology standard when constructing stormwater management features throughout the world today (Dunmore 1997, LCDPW 1999, CKT 2003).

The difference in over-capacity of the conduit and plaza flooding is the additional 0.5 m between the top of the aqueduct and the plaza floor (Figure 7.18). The flow rate was calculated for the construction phase of OT-A1 with the smallest area. The dimensions of Section C (Figures 7.17 and 7.18), the third construction phase of OT-A1, were used to calculate the flow rate. The smallest section of a closed conduit is always used because it will cause the most restrictive flow.

Although the Maya might not have fully understood the consequences, the construction phase they added on to Section C was much wider. During a flood event

Depth (m)	Channel Slope	Flow Area (m^2)	Wetted Perimeter (m)	Hydraulic Radius (m)	Flow (m^3/sec)	Historic Flows (m3/sec)	Simulated Date
0.005	0.20%	0.004	1.761	0.002	0.000		
0.010	0.20%	0.009	1.771	0.005	0.000		
0.025	0.20%	0.022	1.803	0.012	0.002	0.002	AD 6/1 - 6/7/601
0.050	0.20%	0.044	1.856	0.024	0.005	< 0.005	AD 5/1 - 5/31/601
0.075	0.20%	0.066	1.908	0.034	0.010		
0.10	0.20%	0.088	1.961	0.045	0.016		
0.20	0.20%	0.175	2.172	0.081	0.049		
0.30	0.20%	0.263	2.383	0.110	0.090		
0.40	0.20%	0.350	2.594	0.135	0.137		
0.50	0.20%	0.438	2.805	0.156	0.189		
0.60	0.20%	0.525	3.016	0.174	0.244		
0.70	0.20%	0.613	3.227	0.190	0.302		
0.80	0.20%	0.700	3.438	0.204	0.362		
0.90	0.20%	0.788	3.649	0.216	0.423		
1.00	0.20%	0.875	3.860	0.227	0.485		
1.10	0.20%	0.963	4.071	0.236	0.549		
1.20	0.20%	1.050	4.282	0.245	0.614		
1.30	0.20%	1.138	4.493	0.253	0.679		
1.40	0.20%	1.225	4.704	0.260	0.745		
1.50	0.20%	1.313	4.915	0.267	0.812		
1.60	0.20%	1.400	5.126	0.273	0.879		
1.70	0.20%	1.488	5.337	0.279	0.947		
1.80	0.20%	1.575	5.548	0.284	1.015		
1.90	0.20%	1.663	5.759	0.289	1.083		
2.00	0.20%	1.750	5.970	0.293	1.152		
2.10	0.20%	1.838	6.181	0.297	1.221		
2.20	0.20%	1.925	6.392	0.301	1.290		
2.30	0.20%	2.013	6.604	0.305	1.360		
2.40	0.20%	2.100	6.815	0.308	1.429		
2.50	0.20%	2.188	7.026	0.311	1.499		
2.60	0.20%	2.275	7.237	0.314	1.569		
2.70	0.20%	2.363	7.448	0.317	1.639	1.661	AD 11/9/658
2.80	0.20%	2.450	7.659	0.320	1.710	1.740	AD 11/5/684
2.90	0.20%	2.538	7.870	0.322	1.780		
3.00	0.20%	2.625	8.081	0.325	1.851	1.898	AD 1/6/645
3.10	0.20%	2.713	8.292	0.327	1.921	1.928	AD 1/7/654
3.20	0.20%	2.800	8.503	0.329	1.992		
3.30	0.20%	2.888	8.714	0.331	2.063		
3.40	0.20%	2.975	8.925	0.333	2.134		
3.50	0.20%	3.063	9.136	0.335	2.205		

Figure 7.17 – Rating table for OT-A1. Low flows (green), average flows (blue), at capacity (orange), and plaza flooding (red).

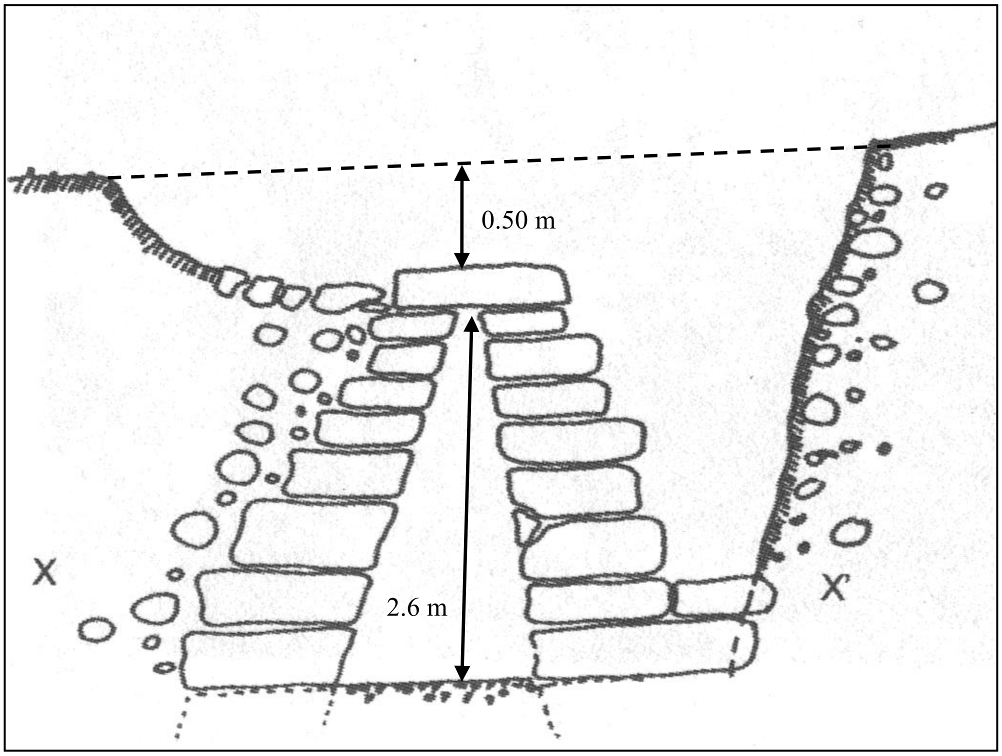


Figure 7.18 – Cross section of OT-A1's Section C. This is the section that was used to determine the flow rate.

this wider entrance of Section D allowed much more water to enter the aqueduct. As the flood waters reached the smaller entrance to Section C it slowed and eventually filled to capacity. With almost 100 meters of rushing flood water backing up an intense amount of pressure would have been placed on the junction of Sections D and C. It was most likely this intense pressure that caused the collapse of the southern few meters of Section C and the entire length of Section D (Figures 7.7, 7.8, and 7.11).

In order to truly compare the effectiveness of OT-A1 it is necessary to determine the flow rate and flood response of the Otolum without the aqueduct. The formulas for calculating the flow rate (Q) of an open channel are as followed (Figure 7.19):

$$Q = \left(\frac{1}{n}\right)(A)\left(R_h^{2/3}\right)\left(S_0^{1/2}\right)$$

To calculate the flow rate the following factors must be known:

1) *base width* (*b*)

2) *height of conduit* (*h*)

3) the *channel slope* (*S*)

4) *roughness coefficient* (*n*)

5) *depth of flow*(*d*)

6) the *flow area* (*A*): $A = bd - \frac{d^2 b}{2h}$

7) the *wetted perimeter* (*P*): $P = b + 2c$

8) the *hydraulic radius* (R_h): $R_h = \frac{A}{P}$

In the case of an open channel, *base width* (*b*), *height of conduit* (*h*), *channel slope* (*S*), and the *roughness coefficient* (*n*) are all constant, while the *flow area* (*A*), *wetted perimeter* (*P*), and *hydraulic radius* (R_h) each change in relation to the *depth of flow* (*d*).

Figure 7.20 is a flow chart containing the details of low flows (green), average flows (blue), over capacity (orange), and plaza flooding (red) for the Otolum flowing through an open channel. According to the simulations using the same flood events that were used on OT-A1, the open channel would have reached full capacity (0.50 m in

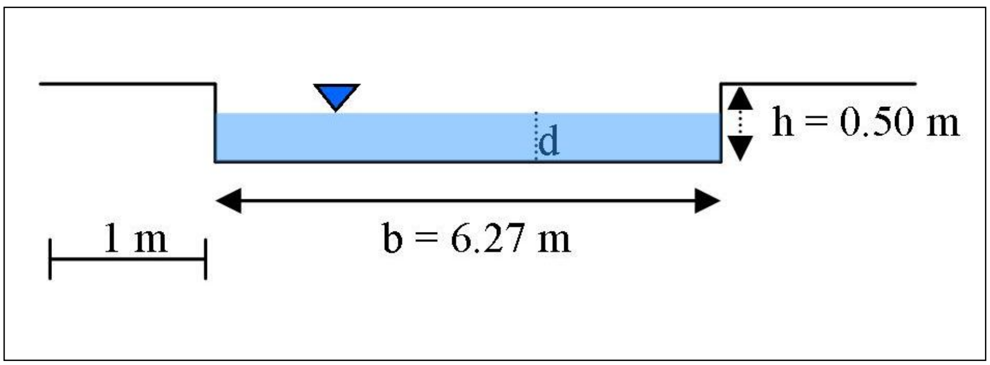


Figure 7.19 – The Otolum in an open channel.

Depth (m)	Channel Slope	Flow Area (m^2)	Wetted Perimeter (m)	Hydraulic Radius (m)	Flow (m^3/sec)	Historic Flows (m^3/sec)	Simulated Date
0.005	0.20%	0.031	6.280	0.005	0.001		
0.010	0.20%	0.063	6.290	0.010	0.003	0.002	AD 6/1 - 6/7/601
0.025	0.20%	0.157	6.320	0.025	0.013		
0.050	0.20%	0.314	6.370	0.049	0.042		
0.075	0.20%	0.470	6.420	0.073	0.082		
0.10	0.20%	0.627	6.470	0.097	0.132		
0.20	0.20%	1.254	6.670	0.188	0.409		
0.30	0.20%	1.881	6.870	0.274	0.789		
0.40	0.20%	2.508	7.070	0.355	1.250		
0.50	0.20%	3.135	7.270	0.431	1.779	1.740	AD 11/5/684
0.51	0.20%	3.198	7.290	0.439	1.836	1.898	AD 1/6/645
0.52	0.20%	3.260	7.310	0.446	1.893	1.928	AD 1/7/654
0.53	0.20%	3.323	7.330	0.453	1.950		
0.54	0.20%	3.386	7.350	0.461	2.008		
0.55	0.20%	3.449	7.370	0.468	2.067		

Figure 7.20 – A flow chart for the Otolum in an open channel. Low flows (green), average flows (blue), at capacity (orange), and plaza flooding (red).

height) once and flooded the plaza (>0.50 m in height) twice within a 100-year period.

OT-A1 – DROUGHT RESPONSE

Even during the worst simulated meteorological droughts (see Chapter 6) the Palencanos had well over 100,000 l of water per day flowing through the Otolum Stream alone. For archaeologists one of the more peculiar aspects of Palenque has been its complete absence of water storage features. Although not a conventional storage feature (e.g. reservoirs, modified *aquadas/bajos*, etc.), OT-A1 could have easily stored water during times of prolonged drought. By temporarily damming the outlet just 1 meter in height and allowing the water to partially fill the aqueduct, the Maya could have stored over 225,000 l of fresh water. In addition, the water would not become stagnant, like that of a reservoir, because of the constant replenishing of spring flow. The overflow from the makeshift dam would slowly make its way over the cascades of the escarpment and could be utilized for irrigating crops in the plains.

SUMMARY

The climatic and watershed simulations applied to OT-A1 allowed for a much clearer picture in regards to its hydraulic design and response to extreme meteorological and hydrological events. A single feature that can both prevent plaza flooding during rain events and store water during times of hydrological drought lends credence to the idea that the Maya of Palenque had an empirical understanding of hydrological engineering. As we shall see next, they used these skills to build one water-related feature that is virtually unprecedented elsewhere in Mesoamerica.

Chapter 8

PB-A1: The Water Pressure System

Water pressure systems were previously thought to have entered the New World with the arrival of the Spanish, but archaeological data, seasonal climate conditions, geomorphic setting, and simple hydraulic theory clearly show that the Maya of Palenque had empirical knowledge of closed channel water pressure predating the arrival of Europeans. The purposeful creation of water pressure to perform useful work or impressive displays are aspects that have received limited archaeological attention. Perhaps the earliest such example was found on the island of Crete in a Minoan palace and dates as early as 1400 BC. Terracotta pipe segments with graded diameter reductions were used to create fountains (Evans 1921-1935). Here I show that the Classic Maya constructed a water pressure system with the potential to control the flow of water at Palenque. By burying a conduit along an ephemeral channel passing through a residential group, upland springs were diverted to build pressure in the conduit to provide a dry-season supply of water or for display during the rainy-season. Up to 6 m of hydraulic head might have been utilized to lift water from the pressurized conduit.

As mentioned in previous chapters, water management at Palenque involved the construction of subterranean aqueducts that were multi-functional, with flood and erosion control being two of their primary functions. As water descended in several streams from the steep uplands and entered the level plaza, flooding, along with erosion, were frequent. By forcing the streams below plaza floors, the aqueducts acted as storm drains. In times of prolonged hydrological drought, the aqueducts could have stored over a million liters of water by impeding the flow at their outlets with removable stone or wooden blocks. Stucco was plastered along the interior walls of the aqueducts to reduce leakage.

Figure 6.2 illustrates a conceptualization of the hydrologic setting and the inferred relation of surface water to groundwater for a typical limestone stream reach. An important feature of the watershed is that along lines of surface drainage, the near- and subsurface exhibit enhanced weathering of limestone along natural bedding and fracture planes. The rock beneath natural channels allows relatively simple manual excavation, and the weathered limestone blocks are readily re-used for construction of the enclosed channel.

CREATING WATER PRESSURE

In general, the simplest strategy for constructing a water distribution network in steeply sloping settings is to construct lateral open-channel diversion of the upland stream directed along topographic contours away from the main channel. The laterals are constructed with a relatively flat slope to slow the rate of flow and to maximize flexibility to do useful work away from the main stream (e.g. irrigation, stormwater, supply). The main drawback to upland lateral diversion at Palenque is the loss of urban area and the fact that surface channels saturate adjacent land, eliminating even more civic/living space. The limited space within the site makes lateral diversion undesirable.

The method of subsurface construction is common in Palenque due to its shortage of flat civic terrain. Building subterranean conduits beneath the natural channel would be convenient for ease of construction and readily available materials (Figure 6.2). There are over a dozen examples in Palenque where subterranean channels were created by excavating the bed of a pre-existing stream, constructing limestone conduits and then covering them with fill.

The spring-fed Piedras Bolas – Aqueduct 1 (PB-A1) (Figure 8.0) has a unique design when compared to the other aqueducts recorded within the site. The other subterranean conduits vary in overall size, but they each maintain a constant cross-section from inlet to outlet with a relatively flat bed slope (<1/100). The main closed-conduit of

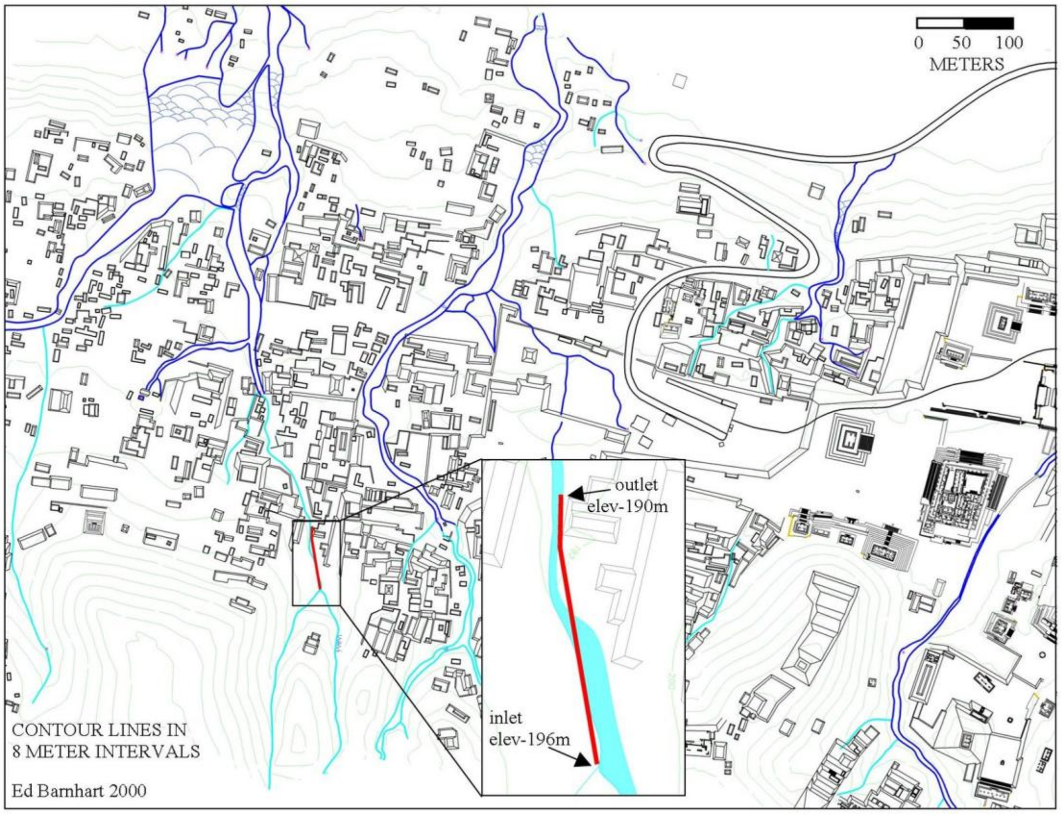


Figure 8.0 – Palenque site map. The area surrounding PB-A1 inset.

PB-A1 is 1.2 m X 0.8 m, is at least 66 m in length, and maintains a topographic slope of ~5/100. Near the end of the existing conduit there is an abrupt decrease in size to a much smaller section measuring approximately 20 cm X 20 cm. This reduction in cross-section continues for another 2 m before the aqueduct re-emerges in the channel. Today, due to partial collapse and subsequent erosion, very little water passes through PB-A1.

Although only a short segment of PB-A1's original subsurface channel is extant, it is fortunate that the remaining segment is the terminus of the conduit. We know it is the terminus because a reduction in cross-section (~1 m^2 to 0.2 m^2) would be necessary to maintain hydraulic pressure within the upstream buried conduit (Figure 8.1).

In this example the upstream flow is the springflow or streamflow diverted into the conduit. Head loss coefficients were estimated from reference experimental data for rough stone channels and smooth masonry channels to establish a range of effects (Young et al. 2007).

There is no evidence that the Maya plastered the walls of the conduit at the Piedras Bolas site, but there is evidence of this practice at other locations within Palenque. A hydraulic evaluation was conducted for an assumed channel length of 68 m, the distance from the convergent section to an upstream tributary. The pressure head along the conduit would have been higher with a smoother finish. For relatively small discharges $Q<1$ m/sec, the pressure head is the same as the elevation change between the outlet and inlet (~6 m). Thus, up to 6 meters of hydraulic head were available to lift water from the outlet of the pressurized conduit depending on the losses acquired within the conduit (Figure 8.2).

PB-A1 was capable of multiple uses and although the full range of functions are unknown it did create approximately 200 m^2 of civic terrain by allowing the preexisting stream to flow underground and simultaneously bridged together several household groups. The conduit could have also been used to store an estimated 68,000 liters of fresh water by capping the outlet during low flow. Another possibility, depicted in Figure 8.3, is that PB-A1 created the pressure necessary for an aesthetically pleasing fountain, and could have aided in the filling of water jars (Davis-Salazar 2003).

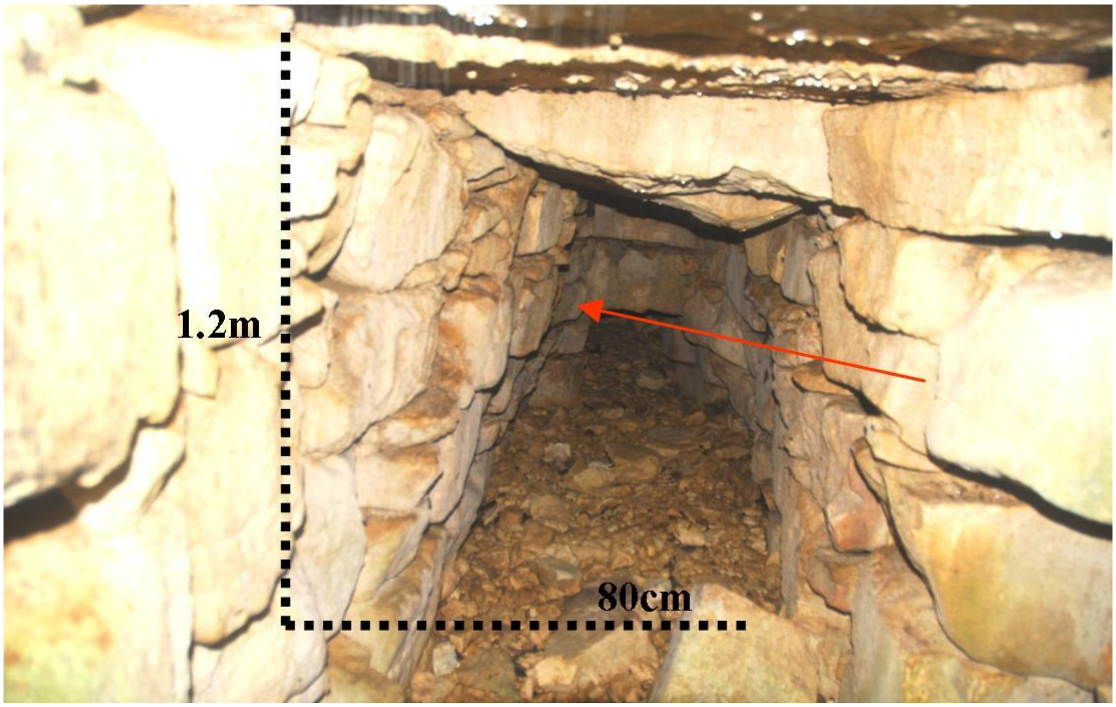


Figure 8.1 – Interior of PB-A1. Note the abrupt reduction in conduit size.

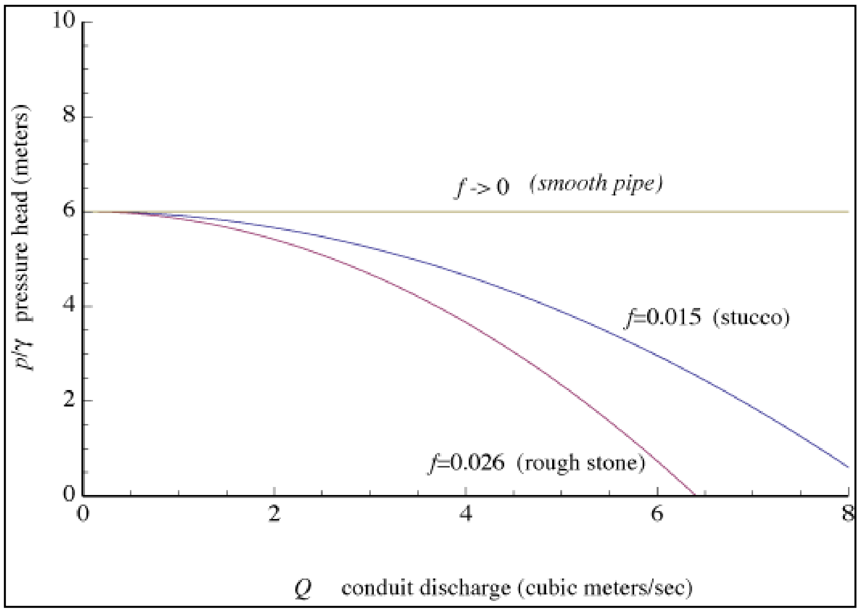


Figure 8.2 - Pressure versus discharge for rough stone, stucco, and very smooth conduits. For a given discharge the pressure is greater for a smooth finish (less friction) than for a rougher surface (greater friction) (Viessman and Lewis 1996).

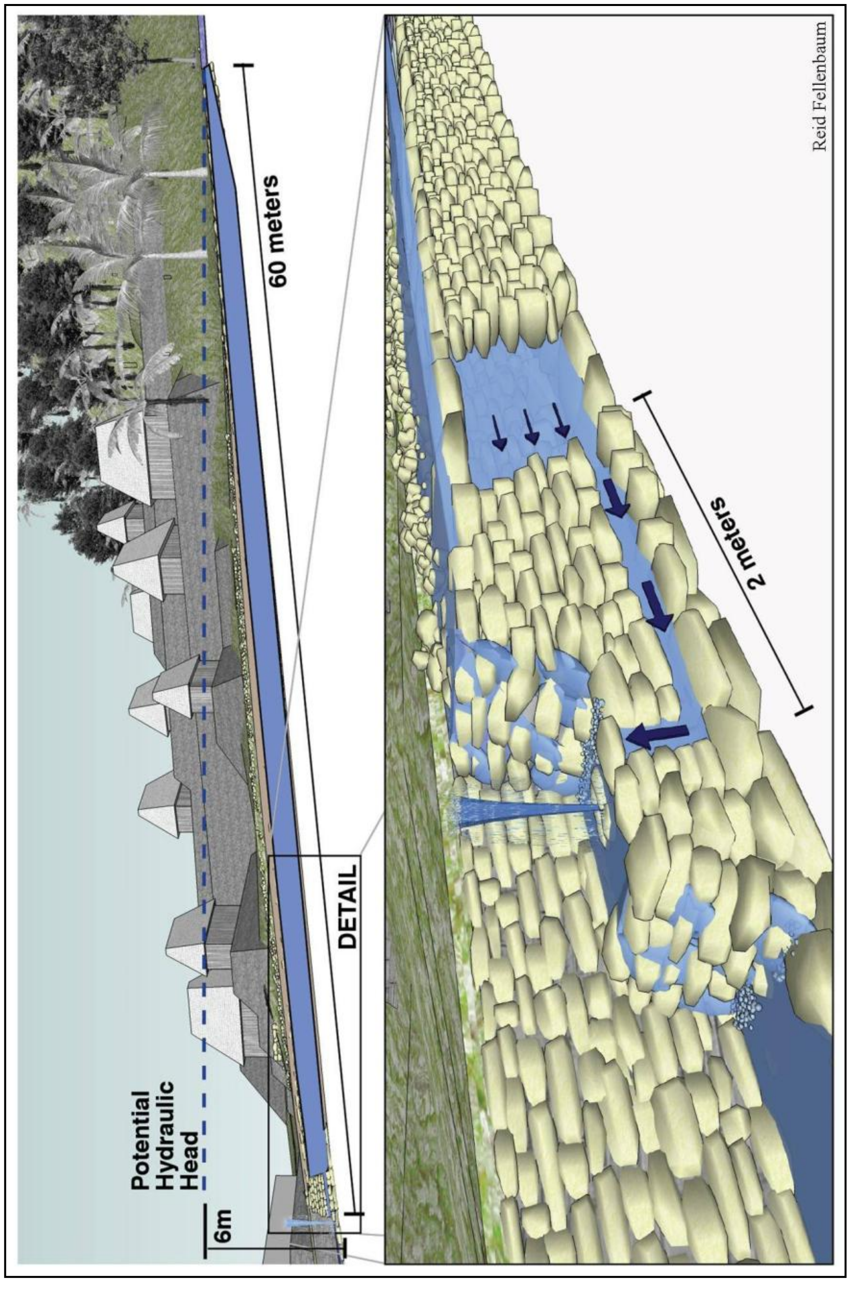


Figure 8.3 - A depiction of PB-A1 functioning as a fountain. This illustrates one plausible explanation of how the feature utilized water pressure. Details of the use of the pressurized conduit have long been destroyed. Note that during the monsoon excess runoff simply flows over the feature while the buried conduit continues to function (drawing by Reid Fellenbaum).

Finally, a basic and impressive aspect of any water pressure system is the control of nature's most fundamental resource. Under natural conditions it would have been rare or difficult for the Maya to witness examples of water pressure in conduit flows. But with their experience in constructing aqueducts for diversion of water (PB-A1), the rulers of Palenque would have had the skills and technology to "lift" water, hence use it to their advantage. This method for displaying power through knowledge is similar to approaches used by the ancient Greeks and Romans.

The archaeological data, combined with simple hydraulic theory, clearly supports the theory that the Maya of Palenque had empirical knowledge of closed channel water pressure. It is likely that there are other examples of Precolumbian water pressure throughout the Americas that have been misidentified or unassigned. The most promising candidate being the segmented ceramic tubing found at several sites throughout central Mexico (Saville 1899, O'Brien et al. 1975, Hirth 2006). These ceramic pipes are tapered, with one segment fitting into the large end of the next, and cemented tightly together (O'Brien et al. 1975, Hirth 2006). Although these tubes appear to be for drainage they represent the technology necessary to utilize closed conduit water pressure.

I would be remiss if I did not point out the need for new excavations, including test pits of the surrounding residential groups, to better understand the extent and purpose of this unique hydraulic feature.

Chapter 9

Conclusions

The ancient Maya center of Palenque was once a major player in the Usumacinta River Basin and politically significant throughout much of the Maya Lowlands. It was also distinctive for its architectural layouts and for the cleverness its people showed in the manipulation of water. Palenque was incredibly small, both geographically and in population, when compared to other Maya centers with similar influence, such as Tikal, Calakmul, or Caracol. Due largely in part to the lack of geographical confinement, these major centers held sway over areas upwards of 50 - 100 km^2 and populations of 50,000 – 100,000. The geographically limited shelf on which Palenque was built was so confined that the "center" and its "polity" were essentially one in the same.

We know of Palenque's influence because the emblem glyph that bears its ancient, and highly appropriate, name *Lakamha'* (Big Water) is expressed in hieroglyphic texts at many other Maya centers, some as far away as Copan (Marcus 1976). Around AD 800 the Palencanos began to leave their city for reasons that are still unknown – a process that is mainly known from a dated inscription. This collapse of the political system was accompanied by an eventual demographic decline. The forest began to reclaim the area, although how fast the whole region was depopulated remains unknown because of the lack of extensive household excavations. Seven hundred and fifty years later the ruins were rediscovered by a Spanish priest and were christened Palenque. Several hundred more years passed before the arrival of early explorers, followed soon after by the archaeologists. Since the beginning, archaeological research at Palenque has focused almost exclusively on the site's center and its dynastic history. In 1998 I began assisting the team that produced the first complete structural and topographic map of Palenque. Soon after the completion of the mapping project I initiated the Palenque

Hydroarchaeology Project (PHAP) with the goal of developing a better understanding of the site's peculiar and complex water management system.

The goals for PHAP were initially geared toward obtaining a pre-Maya view of the landscape. Although I knew nothing of hydrology at the time, I was aware that monitoring stream flow was essential to the study. I wanted to see what the first Maya villagers witnessed as they first stepped onto the Palenque Shelf circa 100 BC. Were the steams spread out across the escarpment like the unmanaged waterways in the area today? I also wanted to reconstruct a view of the site at the height of its urbanism (ca. AD 600 – 800) but devoid of all water management features. I believed this analysis would demonstrate the necessity of the hydraulic engineering, particularly the aqueducts. Could the Maya have developed an urban environment at the current location without the implementation of monumental public works? In addition, I was interested in testing the available stream flow against varying amounts of human waste. Was there enough streamflow to flush out the human refuse produced in an urban environment in a sanitary fashion?

As the project continued some of these goals became unattainable, at least for inclusion into this dissertation. The objectives of this dissertation consisted mainly of testing the hydroarchaeological approach, especially as related to the issues of the several forms of drought outlined in Chapter 1. I wanted to know if this new cross-disciplinary method can provide insight into the success and failures of Palenque. I also wanted to find out if drought was a reasonable cause for Palenque's abandonment. Did the Maya abandon Palenque because of deficiencies of water, as some paleoclimatologists and archaeologists have asserted? In addition, I wanted to test the hydraulic design of the water management features against extreme meteorological events. How successful was the hydraulic engineering at Palenque in coping with droughts and floods?

The first logical step toward answering these questions and to obtaining a clearer picture of the Palenque water system was, at the very least, to gain a basic knowledge of hydrology. Like most archaeologists, the only thing I knew about hydrology was that water naturally flowed downhill. I soon began collaboration with Penn State hydrologist, Dr. Christopher Duffy. It is through this relationship that I began to understand the utility of watershed modeling for developing plausible scenarios of water use, supply and the effects of extreme conditions (flood and drought), which cannot be fully represented by atmosphere-based climate and weather projections.

In order to model the watershed and simulate stream flow a paleoclimatic record was needed. 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 simulations revealed a great deal of climatic consistency from AD 400 – AD 900. It was during the period of AD 500 – AD 800 that most of the Maya Lowlands experienced an enormous amount of prosperous development. Often, long periods of predictable climate equate with the reproductive, demographic, and political success of a regional population (Demeritt 1991).

The paleoclimatic simulations were then entered into PIHM (Penn State Integrated Model) (2007 Qu and Duffy). PIHM represents a new strategy for watershed modeling. 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. PIHM modeled the Palenque watershed for three key time periods with three differing landcover scenarios: 1) 500 BC – 401 BC, prior to Maya settlers, with a 100% primary forest landcover; 2) AD 601 – AD 700, the plausible height of Palenque's population and urbanization, with a landcover consisting of 40% forested, 40% deforested, and 20% urban; and 3) AD 1901 – AD 2000, used as a comparison to the measured record of tropical climate observations, with 75% forested, 20% deforested, and 5% urban. The conclusions from these three scenarios produced drastic distinctions when the percentages of change in climatic conditions are compared to that of the total discharge. The definitive leading factor driving the rise in stream flow is the difference in landcover. The amplification effect of the slight increases or decreases in precipitation or temperature on the watershed from landcover change is dramatic.

The combination of paleoclimate and stream flow simulations provides a plausible view of Palenque's response to major flood events and prolonged hydrological drought. The simulated flood events reveal that OT-A1 reached capacity once every twenty-five years. Though when filled to capacity flooding would have been unlikely because the aqueduct is far enough below the surface of the plaza. Without the construction of OT-A1, Palenque's Main Plaza would have most likely flooded once every 50 years and erosion would have been both inconvenient and destructive.

Interestingly, the 25-year flood design is still used today on culverts and storm drains for small streams the world over. A quarter-century is a span of time that a person in the previous generation (an elder) could recall and pass down as event/information (a flood event) to the current generation. Without the aid of complex formulas or written records, the ancient hydraulic engineer could know the highest water levels in observed history.

As a student of Maya water management, one of the more unique aspects of Palenque has always been the apparent absence of water storage features. In previous publications (French 2006, 2007) I claim that Palenque's water management features were designed for moving an abundance of water through the site in an efficient manner and had nothing to do with storage. Writing this dissertation has changed my mind about this issue. The simulations presented earlier reveal several occasions throughout the seasonal meteorological drought (January – April) where the stream flow is at such a low level that retrieving it with water jars would prove difficult. In times of extreme low flow the outlets of the aqueducts could have easily been temporarily dammed to allow for partial filling. The stucco applied on the interior walls of the aqueduct would have drastically reduced seepage. The damming of OT-A1 (the Palace Aqueduct) could have stored over 225,000 liters of fresh water per day and still allowed enough overflow for crop irrigation in the plains to the north of the site. That is more than ten times the amount of water necessary to sustain the population of Palenque. If the watershed simulations presented in this dissertation are even remotely accurate, it is safe to say that Palenque was not abandoned because of drought, either with regard to drinking, household use, or food production. The worst simulated droughts repeatedly show more than sufficient levels of fresh water for the population. Why the inhabitants of Palenque abandoned their city is still unknown, but they did not leave to quench their thirst or because their agricultural production seriously failed.

The paleoclimate data from lake cores throughout much of the Maya Lowlands suggests that four major droughts occurred at AD 760, 810, 860, and 910 (Gill 2000, Haug et al 2003, Gill et al 2007). This fits neatly into the estimated time of the abandonment for many Maya centers. One thing we are fairly certain of is that the Maya left these polities and moved on. There is little evidence of mass starvation, escalation of warfare, or disease. It is as if the Maya "disappeared". But we as archaeologists know that they didn't. They most likely moved back into the jungles in small-extended family groups and continued to farm. Surely they became disillusioned with the old Classic political system, with its dominant kings who claimed the ability to keep chaos at bay and guarantee plenty. Richard Gill provides a hyperbolic description of what he envisions (2000:1):

> "One by one and by the millions, the people died of starvation and thirst. They died in their beds, in the plazas, in the streets, and on the roads. Their corpses, for the most part, lay unburied and were eaten by the vultures and varmints who entered the houses to eat the bodies of people who didn't die in the open.
>
> There was nothing they could do. There was nowhere they could go. Their whole world, as they knew it, was in the throes of a burning, searing, brutal drought. Their fields and woods were paper dry and on fire. The smell of smoke was everywhere. There was nothing to eat. Their water reservoirs were depleted, and there was nothing to drink."

This dramatic narrative would make Mel Gibson proud, but I am under the firm belief that this vision of Maya abandonment is nothing more than silliness. I give the Maya, and all mankind for that matter, a little more credit than Gill. One does not wait until he is dying of thirst to go look for water. As the drought began to set in people would have slowly trickled out of the densely populated centers and settled in the jungle, where many still live today. The Maya did not disappear, they are still with us, but are just called Mexicans, Guatemalans, Belizeans, and Hondurans.

It might be overzealous for me to claim that Palenque was not abandoned because of drought. As I have shown in the previous chapters, Palenque was never without sufficient supplies of water, even during the worst simulated droughts. Yet it could have been the unending supply of fresh water that led to its demise. If Palenque were the only center in the region to have a supply of fresh water and productive agriculture during a "megadrought" then it would be a prime target for "drought refugees".

Usually when prolonged hydrological drought takes place people are forced to leave. These drought refugees place undue stress on wherever it is they end up. Famine, government repression, and conflicts with insurgents in the Horn of Africa were all stemmed from the prolonged drought during the early 1980s. This crisis caused 2.5 million people to flee their homes and seek asylum in neighboring countries.

Eastern Syria is currently experiencing a major drought. According to the United Nations, over the past three years, 250,000 Syrian farmers and their families have abandoned their homes and villages, moving to cities in search of work. The city of Damascus is feeling the stress of these refugees with groups of 50 – 100 people living in squalid encampments under bridges and on the sides of the road (Sands 2009).

From 1934 – 1940, 2.5 million Americans from the Great Plains abandoned their homes and farms. Over 200,000 of those Dust Bowl refugees descended into California (Figure 9.0). This placed an enormous burden on the Californian government. So much so, that for several months in 1936, the Los Angeles Police Department sent 136 deputies to the state lines to turn back migrants who didn't have any money. Bordering states like Arizona were angry that California was trying to "dump hoboes" back on them (Worster 1979). These hard times felt by so many during this period of American History have become a part of our culture. The stories grabbed the attention of the American public with John Steinbeck's novel *The Grapes of Wrath* and through many songs by folk musician, Woody Guthrie.

> Lots of folks back East, they say, is leavin' home every day,
> Beatin' the hot old dusty way to the California line.
> 'Cross the desert sands they roll, gettin' out of that old dust bowl,
> They think they're goin' to a sugar bowl, but here's what they find
> Now, the police at the port of entry say,
> "You're number fourteen thousand for today."
>
> Oh, if you ain't got the do re mi, folks, you ain't got the do re mi,
> Why, you better go back to beautiful Texas, Oklahoma, Kansas, Georgia, Tennessee.
> California is a garden of Eden, a paradise to live in or see;
> But believe it or not, you won't find it so hot
> If you ain't got the do re mi.
>
> -*Do Re Mi* by Woody Guthrie

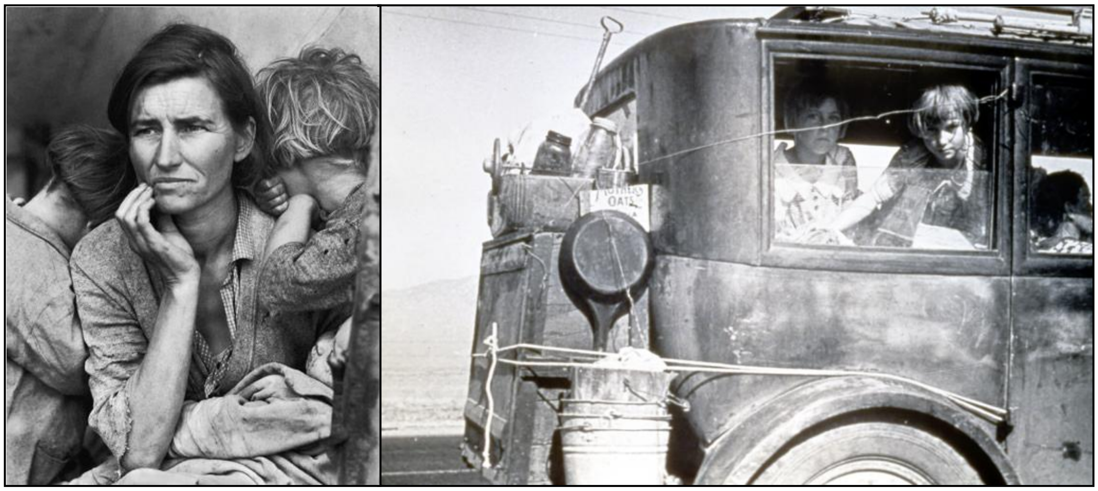


Figure 9.0 – Photographs of “drought refugees” from the American Dust Bowl (by Dorothea Lange).

The situations mentioned above give me reservations about definitively 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 in the periphery, evident by tightly spaced housing with no platform, concentrations of pottery made elsewhere, or human remains with evidence of famine. Although difficult to detect archaeologically, this scenario remains plausible.

THEORETICAL IMPLICATIONS

Vernon Scarborough is by all accounts the authority on Maya water management studies, and I had the distinct pleasure of being his student for my Masters degree. In his book, *The Flow of Power: Ancient Water Systems and Landscapes*, he discusses the process by which resources are managed and consumed and the rate at which this occurs. To explain the types and degrees of land alteration and water management practices adopted by ancient state-level societies, Scarborough creates three categories – *labortasking*, *technotasking*, and *multitasking*.

According to Scarborough (2003), *labortasking* maintains a cultural logic that invests in highly efficient labor divisions which are generally the case for "*still-water systems*" like that of the Lowland Maya and Sinhalese. *Technotasking* tends involve "*moving-water systems*" and invests in novel laborsaving technologies and include the ancient highland Mexicans, the Harappans, the Hohokam, and the Mycenaeans. The *multitasking* occurs when people diversify the tasks necessary for survival in a less measured routine and without a great demand for technology (e.g. portions of Africa and indigenous Latin America today).

Many Lowland Maya centers developed in areas without permanent water sources but with high seasonal precipitation. Such environments necessitate a focus on reservoir construction, which then increased the potential for political control over water resources. Many of the Maya in this environmental setting had to rely on peripheral *bajos* and *aguadas* that were dispersed over the landscape. This lack of opportunity to concentrate water resources led centers to have a dispersed urban structure (e.g. Tikal, Calakmul). As a result communities became more independent and relied heavily on the hinterlands.

Palenque presents a different set of environmental restrictions than the rest of the Maya Lowlands. Urban concentration dominated the landscape. Precipitous growth followed an exploitative pace of *technotasking*. The water resources concentrated into a nucleated urban setting enabled a degree of intense landscape manipulation rarely seen in the Maya Lowlands. Inventive ways of controlling water protected against centennial droughts and provided irrigation for year round maize production. Access to water would have been difficult, if not impossible, to control at the from the point of view of kings and elites.

PRACTICAL 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 the early summer of 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 stream flow 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. In addition, I would like to install an online/interactive kiosk for weather and watershed budgets in the Palenque Museum. The kiosk will provide real-time data from the weather station and streams, as well as explain how humans, past and present, impact the water and ecological-human environment.

BROADER IMPLICATIONS

This dissertation validates the hydroarchaeological approach, a new method for measuring the degree of human impact on an environment through paleohydrological modeling of a watershed. Hydroarchaeology can be applied to any archaeological site worldwide. The approach is relatively simple:

1) Gather either preexisting local paleoclimate data or, in the case of Palenque, simulated data
2) Developing varying landcover scenarios.
3) Enter the paleoclimate date and landcover scenarios into PIHM.
4) Retrieve and analyze the streamflow data.

The possibilities for this non-invasive method are many, including detecting periods of stress within a community, estimating population by developing caps based on the availability of water, understanding settlement patterns, as well as assisting local populations in areas where monetary resources are lacking. As with most new methods, there are always applications and conclusions the author never imagined. Most importantly, landcover emerged as the "big actor" in the watershed.

FUTURE WORK

As mentioned earlier, we know very little about Palenque's development through time. Few projects have even stepped outside of the site's core. Most deal exclusively with the excavation of monumental architecture and deciphering the glyphic texts to determine dynastic history. Continuing Barnhart's survey in the periphery in conjunction with a test-pitting program is dire. It is disheartening that a site as important as Palenque has so little ongoing research – research that is geared toward understanding its development, not just who built a particular temple.

My research priority for the immediate future is retrieving and testing speleothem cores for paleoclimate data from the cave in Palenque. Speleothems have shown promise in providing very localized paleoclimate data (Frappier et al 2007). Next I want to apply the hydroarchaeological approach to a much larger watershed and different environment. I am currently working with Ken Hirth on applying the method to the Basin of Mexico. I also believe there is a need for the development of a website with an accessible template so that other researchers can develop scenarios, enter their data, and obtain results. And lastly, invest time into public outreach with the Palenque townspeople regarding watershed monitoring.

Appendix A

MarkSim: 100-Year Simulations

MarkSim Monthly Precipitation (mm)										
Month	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**
Jan	0	299.2	275.2	94.8	205.2	133.2	76	540.5	317.5	336.5
Feb	46.5	136.8	121.9	277.4	9.5	83.8	190.9	32.6	200.6	64
Mar	18.4	0	44	22.7	15.8	17.5	61.9	35.9	54.8	33.1
Apr	16.1	1.8	5.7	18.6	31.5	12.8	15.4	31.6	40.6	19.1
May	32.9	81.1	68.2	247.1	147.6	43.9	167.1	154.8	54.2	98
Jun	226.7	278.4	275.9	692.3	196	368.3	170.4	266.3	440.7	155.9
Jul	303.1	378.5	472.8	108.5	165.1	285.2	412.8	135.3	526.7	278.7
Aug	564.9	392.6	229.8	320.5	455.7	358.1	444.6	379.1	349.6	514.8
Sep	428	569.3	630.9	420.5	336.4	457.7	543.6	454.2	539	347.2
Oct	352.1	1052.7	576	608.2	322.6	750.7	857.6	751.4	1169.3	498.7
Nov	433.4	347.9	402	7.8	326	122.2	199.9	88	197.1	183.4
Dec	230.8	253.2	156.3	170.2	269.3	34.7	101.5	85.4	113.1	141.4
Yearly Totals	**2652.9**	**3791.5**	**3258.7**	**2988.6**	**2480.7**	**2668.1**	**3241.7**	**2955.1**	**4003.2**	**2670.8**

Month	**Year 11**	**Year 12**	**Year 13**	**Year 14**	**Year 15**	**Year 16**	**Year 17**	**Year 18**	**Year 19**	**Year 20**
Jan	179.7	295.6	95.8	208.7	212.4	54.6	364.3	601.3	169.3	246.5
Feb	197.2	257	145.8	82.9	102.7	99.9	51.7	72.9	3.7	58.8
Mar	82.9	22.1	93.7	63.9	16.5	11.9	19.8	172.1	6.6	211.6
Apr	17.8	5.9	15.7	1.8	21	18.8	6.7	13.9	36.8	16.8
May	211.1	343.1	73.1	42.1	82.4	229.2	80.4	72.6	74.1	31.3
Jun	302.4	173.5	159.6	438.4	349.6	315.4	391.6	444.9	263.6	367.5
Jul	271.3	380	232.1	224.1	324.2	181.8	311.8	426.4	397.7	330.7
Aug	296.3	576.1	188.7	295.2	393.8	343.2	532.9	508.4	424.8	342.3
Sep	523.4	304.7	710.4	457.5	546.5	575	267.4	498.8	374.9	409.8
Oct	445	277.3	420.8	532	643.7	609.3	700	377.7	721.2	593.9
Nov	392.6	183.9	82.3	241.3	72.4	347.9	332.6	68.9	402.5	28
Dec	66	466.8	118.7	86.6	63.1	110.9	22.7	261.9	717.2	352.3
Yearly Totals	**2985.7**	**3286**	**2336.7**	**2674.5**	**2828.3**	**2897.9**	**3081.9**	**3519.8**	**3592.4**	**2989.5**

Month	**Year 21**	**Year 22**	**Year 23**	**Year 24**	**Year 25**	**Year 26**	**Year 27**	**Year 28**	**Year 29**	**Year 30**
Jan	358.4	371.4	73.2	578.8	127.7	385.1	35.3	119.8	260	512.7
Feb	179.9	131.2	21.7	298	350.9	115.8	134.3	134.4	152.1	81
Mar	15.2	28.8	44.3	10.5	2.8	126	28.5	67.6	96.9	38.3
Apr	54.8	0	39.5	11.5	13	0	2.1	5	40.3	2.2
May	319.5	138.9	14.7	220.9	94.9	89.2	68.7	119.9	88.2	94.7
Jun	264	258.5	211.3	412.7	289.1	370.6	400.5	533.4	314.3	299.9
Jul	294.8	379.4	305.1	525.7	364.3	299.2	201.6	129.8	258.1	296.4
Aug	143.1	291.3	297.4	167.6	102.5	161.9	213.7	262.5	371.1	335
Sep	250.4	624.3	685.2	407.2	618.1	550.3	533.8	560.1	429.1	381.2
Oct	898.9	422.4	667.7	264.9	590.7	960	526	351.8	402.2	794.6
Nov	162.7	67.6	46	206.1	218.6	225	426.8	41.9	367.8	278.4
Dec	20.2	91.3	169.5	328.1	139.6	161	267.3	194.9	368.3	621.2
Yearly Totals	**2961.9**	**2805.1**	**2575.6**	**3432**	**2912.2**	**3444.1**	**2838.6**	**2521.1**	**3148.4**	**3735.6**

MarkSim Monthly Precipitation (mm)

Month	Year 31	Year 32	Year 33	Year 34	Year 35	Year 36	Year 37	Year 38	Year 39	Year 40
Jan	164.2	187	121.7	288.5	286	364.6	183.2	33.5	267.8	198.2
Feb	57.5	21.7	82.2	154.5	113.7	82.1	38.6	52.7	302.4	73.6
Mar	33	36.9	32.8	168.1	17.3	53.4	109.9	0.6	52.2	10
Apr	3	16.6	9.4	9.1	0	0.1	40	0	22.6	1.1
May	10.3	32.4	22.7	149.2	186.9	130.4	95.3	88.9	51.8	234.7
Jun	316.1	452.1	266.1	300.4	676.1	198.8	466.9	355.7	432.7	379.8
Jul	366.4	397.2	107.7	337.9	227.3	295.4	248	438.6	235.5	171.4
Aug	545.9	140.1	189.4	451.6	290.7	225	284.1	360.5	155.5	400.9
Sep	414.8	540.1	486.2	426.2	710.4	563.9	418	435.4	541.9	95.9
Oct	322.4	598.1	277.9	344.7	599.6	505.3	464.1	435.3	848.4	657.1
Nov	139.6	112.6	210.7	0.3	212.1	403.1	145.5	130.8	389.4	233.7
Dec	37	141.4	140.5	52.2	329.8	121.1	93.7	12.4	165.9	251.8
Yearly Totals	**2410.2**	**2676.2**	**1947.3**	**2682.7**	**3649.9**	**2943.2**	**2587.3**	**2344.4**	**3466.1**	**2708.2**

Month	Year 41	Year 42	Year 43	Year 44	Year 45	Year 46	Year 47	Year 48	Year 49	Year 50
Jan	482.3	76.5	173.1	256.7	11.1	202.1	90.4	18.9	339.1	315
Feb	160.9	42.7	165	87.5	63.7	43.2	126.8	90.9	139.5	38.4
Mar	58.6	119.1	34.2	6.3	162.2	92.5	96.4	126.1	18.3	66.3
Apr	17.2	26.5	0.1	0	4	4.1	1.4	34.1	6.5	1.6
May	106.6	56.3	140.2	130	156.3	208.4	111.3	87.5	73	267.3
Jun	520.9	105.2	132.8	119.1	449.3	361	214	88.9	246.6	326.1
Jul	213.6	319.7	310.3	397.5	416.1	326.7	281.1	385.7	189	388.9
Aug	370.3	211.9	374.4	488.8	410.9	257.8	195.6	112	270	264.6
Sep	448.9	475.3	308.3	499.6	545.5	552.2	529	378.8	527.1	503.9
Oct	509.9	303.9	430.7	659.3	659.5	571.6	717	172.4	693.5	727.3
Nov	220.1	110.3	280.3	259.2	292.9	299.9	177	214.3	45.9	174.2
Dec	212.5	155.9	272.8	331.6	217.6	309	0	138	289.5	70.5
Yearly Totals	**3321.8**	**2003.3**	**2622.2**	**3235.6**	**3389.1**	**3228.5**	**2540**	**1847.6**	**2838**	**3144.1**

Month	Year 51	Year 52	Year 53	Year 54	Year 55	Year 56	Year 57	Year 58	Year 59	Year 60
Jan	174	92.6	257.6	223.9	175.3	156.1	454.2	509.3	2.5	249.8
Feb	142.3	126	66.6	22.8	65.6	198.1	192.5	130.8	92.9	29.9
Mar	219.7	107.1	269	23	25.3	39.3	5.7	23.5	15.1	37.6
Apr	20.1	1.6	25	0.4	27.1	23.5	11.8	17.9	7.6	4.6
May	34.6	229.7	219.6	132.6	32.3	202.5	139.6	78.1	110.5	415.9
Jun	197.4	268.9	475.5	433.7	318.8	280.2	316.6	420.1	361.2	266.4
Jul	173.7	301.8	149	498.4	309.7	235.7	255.9	235.7	256.7	438.4
Aug	437.9	424	117.1	147.5	299.5	290.4	209	368.7	228.9	397.7
Sep	419	328.4	495.2	514.3	349.4	392.2	492.6	773.8	323.6	582.5
Oct	335.2	662.7	342.4	409	319.1	512.4	552.4	914.5	770.9	796.8
Nov	119.5	71	332.7	135	220.9	164	111.3	463.2	332.4	139.2
Dec	217.9	312.6	390.9	99.3	101.4	149	177.8	668.5	92.1	53
Yearly Totals	**2491.3**	**2926.4**	**3140.6**	**2639.9**	**2244.4**	**2643.4**	**2919.4**	**4604.1**	**2594.4**	**3411.8**

MarkSim Monthly Precipitation (mm)

Month	Year 61	Year 62	Year 63	Year 64	Year 65	Year 66	Year 67	Year 68	Year 69	Year 70
Jan	287.2	532.7	136.3	164.2	419.1	11.6	97.2	151.7	124.9	24.1
Feb	146.6	238.6	63	145.1	140.3	53.6	85.1	57.8	78.5	125.8
Mar	84.8	13.2	71	18	114.6	72.6	72.2	52.6	65.3	38.3
Apr	15.7	38.6	27.6	4.9	0.4	1.7	27.5	5.5	18.9	5.9
May	224.9	39.2	269.9	49.9	56	33.6	35.2	96.7	22.8	104.2
Jun	388.6	205.8	285.4	452.8	324	191.5	273.1	262.7	199.2	333.3
Jul	310.5	351.4	254.4	377.4	108.6	150.6	348.3	409	404.9	241.1
Aug	282.4	522.1	573.3	286.6	359.9	346.5	173	250.9	344.4	143.4
Sep	692	553.2	472.8	369.1	450.6	176	612.6	534.5	578.1	427.9
Oct	315.7	540.9	421.7	651	710.1	363.1	370.7	441	425.9	359.2
Nov	75.3	41.5	372.9	306.7	241.9	193.2	37.2	327.9	247.6	28.7
Dec	145.7	545.2	107.6	283.6	136.9	59.2	88.3	220.3	177.5	128.1
Yearly Totals	**2969.4**	**3622.4**	**3055.9**	**3109.3**	**3062.4**	**1653.2**	**2220.4**	**2810.6**	**2688**	**1960**

Month	Year 71	Year 72	Year 73	Year 74	Year 75	Year 76	Year 77	Year 78	Year 79	Year 80
Jan	301.5	202	314.9	179.6	95.6	259.1	131.9	492.9	344.7	110.1
Feb	146.9	213.9	248.9	226.9	127.1	64.3	37.4	0	190.2	257.4
Mar	44.4	15.2	80.9	34.5	11.5	0	36.9	5.6	105.6	67.5
Apr	5.2	33.5	28.9	21.6	0	15.5	46.3	9.6	20.5	26
May	121.5	112.2	162.2	99.3	82.5	89.3	100.5	0.9	93.3	65.4
Jun	458.6	509.7	311.6	157.5	289.6	169.5	338.7	427	392.7	422.4
Jul	82.6	444.1	352.9	528.7	367.5	281.6	187.9	248.1	526.2	396.8
Aug	188.7	343.7	327.1	372.9	393.1	501.3	408.4	368.4	448.8	304.5
Sep	754.5	302	565.1	720.4	560.1	478.9	252.2	526.4	151.5	684
Oct	895.5	344.2	622.6	904.6	729.7	831.6	405.7	151.6	713.1	624.2
Nov	178.7	170.7	290.9	66.6	203.9	158.3	192.3	164.6	285.1	132
Dec	12.5	234.4	370.3	222.5	307.4	54.8	112.2	304.3	187.2	224.2
Yearly Totals	**3190.6**	**2925.6**	**3676.3**	**3535.1**	**3168**	**2904.2**	**2250.4**	**2699.4**	**3458.9**	**3314.5**

Month	Year 81	Year 82	Year 83	Year 84	Year 85	Year 86	Year 87	Year 88	Year 89	Year 90
Jan	181.8	448.8	227.1	239.4	158.7	378.5	73.3	9.2	128.4	71.4
Feb	369.9	149.6	177.9	44.3	248.3	21.6	0	68.1	185.2	16.9
Mar	46.1	84.4	68.9	13.2	24.9	18	140.1	0	123.7	56.9
Apr	5.3	14	3.2	0	9	57.3	0	37	5.2	20.6
May	120.4	202.3	15.7	345.9	245.3	167.1	92.6	181.8	68.5	173.2
Jun	282.4	306.2	130.6	246.6	166.8	270	359.1	104.5	327.7	234.3
Jul	218.1	273.6	258.8	368.8	152.8	415.9	296	158.8	350.5	119.6
Aug	506.3	478.4	345	240.7	453.2	479.3	176.9	367.4	250	187.7
Sep	391.2	353.8	499.2	657.9	483.1	420.1	563.5	249.6	465.2	396.9
Oct	805.4	668.9	939.3	1061.8	576.4	459.2	326.6	248.7	287.3	581.8
Nov	186.8	277.1	271.3	152	156.2	112.9	313.8	154.6	24.5	126.2
Dec	93.9	119	328.2	73.4	148.2	82.8	157.4	267.5	407.3	34.4
Yearly Totals	**3207.6**	**3376.1**	**3265.2**	**3444**	**2822.9**	**2882.7**	**2499.3**	**1847.2**	**2623.5**	**2019.9**

MarkSim Monthly Precipitation (mm)										
Month	**Year 91**	**Year 92**	**Year 93**	**Year 94**	**Year 95**	**Year 96**	**Year 97**	**Year 98**	**Year 99**	**Year 100**
Jan	120.5	306.7	519.1	248.8	342.2	316.2	503.6	456.2	247.1	0
Feb	53.4	259	266.5	3.2	94.4	208.9	248.2	171	77.4	46.5
Mar	159.8	47.1	141	139.1	106.6	89.5	190.7	67	124.8	18.4
Apr	15.5	34	4.5	9.4	26.6	11.5	7.6	0	1.2	16.1
May	229.3	115.5	59.9	82.6	72.1	42.3	92.4	211.1	121.1	32.9
Jun	485.6	286.9	185.5	265	531.6	272.1	229.1	355.5	393.1	245.2
Jul	383.1	236.8	192.2	203.1	176	363	497.9	217.6	366.4	284.6
Aug	462.1	238	338.6	415.7	568.4	426.3	368.8	453	379.1	573.4
Sep	486	205.2	606.9	505.5	349.9	505.1	511.2	223.8	493.8	428.4
Oct	998.8	706	573.9	746.5	687.7	525.1	323.8	770.7	391.5	365.1
Nov	226.3	127.2	284.4	134.9	204.3	235.7	218.3	172.2	666.1	458.8
Dec	156.3	287.3	169.5	390.1	111.8	311.8	526.5	454.1	193.3	183.5
Yearly Totals	**3776.7**	**2849.7**	**3342**	**3143.9**	**3271.6**	**3307.5**	**3718.1**	**3552.2**	**3454.9**	**2652.9**

Month	**Avg.**
Jan	**232.42**
Feb	**121.99**
Mar	**61.89**
Apr	**14.86**
May	**120.50**
Jun	**314.51**
Jul	**300.16**
Aug	**338.26**
Sep	**471.66**
Oct	**571.19**
Nov	**208.62**
Dec	**202.08**
Yearly Totals	**2958.13**

MarkSim Montlhy Temperature (°C)										
Month	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Jan	22.07	24.32	23.51	21.62	24.05	25.89	24.32	20.01	23.77	23.99
Feb	25.55	25.66	27.52	26.38	25.07	24.46	25.03	27.36	26.88	25.88
Mar	27.47	25.74	26.77	27.10	26.16	27.45	26.01	27.95	26.31	26.84
Apr	28.00	28.03	27.80	27.73	26.53	29.21	29.59	28.26	28.14	27.95
May	29.47	29.75	29.84	29.44	30.52	31.54	29.78	28.77	29.53	30.71
Jun	29.73	31.45	31.17	28.23	29.25	27.81	29.80	30.06	29.97	30.00
Jul	27.10	28.71	29.74	28.18	27.13	28.10	29.08	29.35	28.28	30.29
Aug	27.31	27.39	29.17	30.38	27.59	26.21	27.04	29.86	29.37	28.51
Sep	26.86	26.79	27.12	27.43	28.53	26.80	27.53	27.02	27.76	26.86
Oct	26.44	26.37	27.16	27.50	25.48	26.04	26.81	26.35	26.71	27.12
Nov	25.11	24.76	25.97	26.07	24.22	24.98	24.98	23.08	24.39	25.91
Dec	23.99	23.45	24.30	23.38	25.32	23.72	25.79	23.29	25.08	21.91
Yearly Averages	**26.59**	**26.87**	**27.51**	**26.95**	**26.65**	**26.85**	**27.15**	**26.78**	**27.18**	**27.16**

Month	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20
Jan	24.77	24.88	23.70	22.34	21.83	23.83	23.98	25.31	24.36	25.20
Feb	24.93	24.94	26.14	24.01	23.89	27.00	25.15	25.47	26.46	26.94
Mar	28.92	25.83	25.91	26.08	27.05	26.28	26.63	25.60	26.51	27.67
Apr	26.67	26.98	28.78	28.97	28.73	27.15	28.50	26.64	28.55	28.05
May	29.99	27.89	31.52	28.92	30.83	29.49	29.05	30.80	30.02	30.07
Jun	28.16	30.27	28.98	30.02	29.96	30.41	29.86	27.44	29.87	28.96
Jul	29.06	29.41	29.82	29.22	30.37	29.25	28.31	30.40	29.53	29.76
Aug	24.52	27.50	28.46	27.48	27.38	28.71	27.18	27.91	27.60	29.38
Sep	26.78	28.20	26.43	29.01	28.54	26.80	26.46	28.97	28.96	27.48
Oct	27.72	27.17	25.90	27.53	27.48	25.37	25.10	27.03	28.25	26.82
Nov	22.90	24.24	25.19	26.71	25.43	21.81	24.37	25.24	25.52	22.55
Dec	24.68	22.62	24.04	24.38	23.58	23.15	23.50	26.43	23.21	25.31
Yearly Averages	**26.59**	**26.66**	**27.07**	**27.05**	**27.09**	**26.60**	**26.51**	**27.27**	**27.40**	**27.35**

Month	Year 21	Year 22	Year 23	Year 24	Year 25	Year 26	Year 27	Year 28	Year 29	Year 30
Jan	23.15	23.56	23.22	22.36	22.77	23.81	25.47	24.06	24.94	23.47
Feb	25.28	23.48	25.35	26.48	24.73	25.73	24.48	23.92	23.96	25.05
Mar	26.74	25.71	25.74	26.14	25.64	27.26	24.69	26.01	26.33	25.41
Apr	26.18	26.05	27.30	26.90	28.09	27.55	28.47	27.95	27.23	28.54
May	29.64	28.49	30.33	28.06	29.98	29.08	29.25	29.86	29.42	29.84
Jun	30.06	29.65	30.07	30.76	29.42	30.12	29.69	29.13	29.32	30.22
Jul	28.59	29.48	29.48	29.60	30.57	28.81	29.15	29.99	30.02	29.30
Aug	28.78	27.57	27.26	27.74	30.25	29.23	27.59	27.79	27.68	28.01
Sep	28.48	27.73	28.10	27.76	26.60	28.65	28.99	27.76	28.72	28.47
Oct	26.64	26.45	27.15	26.13	26.95	27.39	24.77	27.45	27.53	25.63
Nov	25.28	25.33	24.82	25.00	26.48	23.47	24.68	25.05	24.70	24.40
Dec	24.93	27.26	23.78	24.37	25.37	24.13	23.72	23.94	23.82	24.22
Yearly Averages	**26.98**	**26.73**	**26.88**	**26.77**	**27.24**	**27.10**	**26.75**	**26.91**	**26.97**	**26.88**

MarkSim Montlhy Temperature (°C)

Month	Year 31	Year 32	Year 33	Year 34	Year 35	Year 36	Year 37	Year 38	Year 39	Year 40
Jan	22.67	22.95	23.63	22.84	22.39	22.84	24.27	23.50	24.25	24.59
Feb	24.63	25.49	25.67	26.34	26.00	25.43	26.46	26.68	25.35	25.26
Mar	26.95	28.23	27.76	27.85	26.53	26.89	26.04	25.31	26.49	27.13
Apr	27.38	26.79	28.68	27.59	27.83	27.57	27.97	26.01	27.49	26.68
May	29.86	30.49	29.11	29.17	30.28	29.45	30.46	30.94	30.79	29.75
Jun	28.95	29.11	27.99	29.47	29.27	30.01	29.87	29.33	28.33	29.30
Jul	28.21	29.97	30.27	28.84	28.34	29.40	28.93	28.84	29.37	28.93
Aug	27.85	27.90	27.42	27.93	29.21	27.09	28.75	27.16	27.60	27.21
Sep	28.18	26.73	27.78	28.45	27.62	28.02	27.62	24.57	28.59	27.08
Oct	27.35	25.90	26.88	26.19	25.37	25.75	25.81	27.61	26.32	26.25
Nov	26.24	25.90	25.42	24.24	25.44	26.57	24.01	26.07	25.92	24.62
Dec	24.19	24.65	25.39	25.50	23.71	23.02	25.05	23.30	24.31	24.04
Yearly Averages	**26.87**	**27.01**	**27.17**	**27.03**	**26.83**	**26.84**	**27.10**	**26.61**	**27.07**	**26.74**

Month	Year 41	Year 42	Year 43	Year 44	Year 45	Year 46	Year 47	Year 48	Year 49	Year 50
Jan	23.96	22.99	23.51	21.97	21.14	22.37	24.15	25.37	24.90	21.97
Feb	26.64	25.87	25.92	26.92	25.10	26.86	24.16	26.10	26.38	25.01
Mar	26.66	27.06	26.70	27.04	26.64	27.66	25.93	27.31	26.54	26.46
Apr	28.78	28.91	28.28	28.16	27.43	28.70	28.90	27.60	27.39	26.69
May	30.39	29.06	30.28	28.78	30.28	29.85	29.96	30.40	29.07	29.55
Jun	29.17	28.51	29.50	29.58	28.58	29.96	28.77	30.65	29.06	28.97
Jul	30.04	29.01	29.17	27.95	28.87	28.99	29.00	27.97	28.63	28.76
Aug	27.15	27.85	28.55	28.86	28.02	28.26	28.00	29.37	26.79	28.49
Sep	28.30	28.53	28.10	29.15	28.23	28.14	26.36	29.00	27.55	27.86
Oct	25.43	27.99	27.65	26.28	26.89	27.19	26.95	27.60	26.61	26.10
Nov	26.68	24.76	25.69	24.70	26.46	24.49	23.78	24.58	25.00	25.08
Dec	25.33	22.75	24.87	23.84	26.56	23.81	23.85	26.09	24.25	25.09
Yearly Averages	**27.38**	**26.94**	**27.35**	**26.93**	**27.02**	**27.19**	**26.65**	**27.67**	**26.85**	**26.67**

Month	Year 51	Year 52	Year 53	Year 54	Year 55	Year 56	Year 57	Year 58	Year 59	Year 60
Jan	22.67	24.74	23.50	23.38	21.05	22.71	22.23	23.88	24.18	22.74
Feb	25.98	24.97	25.88	27.29	25.60	25.89	25.88	26.06	25.61	25.44
Mar	27.83	25.37	27.35	26.54	25.19	27.72	27.60	26.85	26.97	26.80
Apr	26.67	30.09	27.51	25.80	27.11	28.68	27.42	27.44	27.72	26.11
May	31.08	29.89	29.64	29.97	29.75	29.30	28.56	29.65	29.32	27.88
Jun	29.13	28.18	28.96	29.37	28.83	29.36	29.11	28.97	28.53	29.89
Jul	27.85	30.42	29.58	26.72	28.97	29.47	30.10	29.23	29.12	28.56
Aug	26.63	27.41	27.71	28.15	28.69	29.50	27.76	28.47	27.01	27.87
Sep	28.15	27.11	26.99	28.16	27.33	26.21	28.11	28.87	29.32	27.84
Oct	26.05	26.06	27.07	28.05	26.61	26.16	27.24	27.32	25.98	26.24
Nov	26.45	25.40	26.18	23.28	25.48	26.93	23.76	25.45	24.51	26.55
Dec	23.12	23.81	24.55	24.37	24.19	24.38	24.71	23.79	24.60	24.27
Yearly Averages	**26.80**	**26.96**	**27.08**	**26.76**	**26.57**	**27.19**	**26.87**	**27.16**	**26.91**	**26.68**

MarkSim Montlhy Temperature (°C)										
Month	**Year 61**	**Year 62**	**Year 63**	**Year 64**	**Year 65**	**Year 66**	**Year 67**	**Year 68**	**Year 69**	**Year 70**
Jan	21.80	22.98	22.91	24.03	22.01	24.90	24.04	22.14	24.75	24.95
Feb	24.81	26.18	25.57	25.48	26.44	25.81	26.18	26.52	26.04	22.60
Mar	26.81	26.78	25.32	26.30	25.77	26.48	25.14	27.58	27.60	26.31
Apr	29.26	28.48	27.43	27.83	27.81	27.31	27.68	29.09	26.99	29.45
May	30.30	29.51	30.09	29.13	31.05	28.24	28.80	31.14	29.97	30.65
Jun	30.18	29.63	29.49	28.54	30.98	29.47	29.97	30.13	29.94	28.78
Jul	29.70	30.29	28.06	29.09	30.38	27.97	27.68	28.73	29.50	29.10
Aug	29.32	26.57	28.42	28.17	27.34	26.91	30.23	29.41	27.88	27.52
Sep	26.95	26.80	26.68	27.68	27.61	28.16	29.03	28.35	28.17	27.57
Oct	26.68	28.10	27.59	25.86	26.42	24.78	25.74	27.78	26.73	27.88
Nov	24.99	25.70	23.71	26.49	24.37	24.80	25.68	25.22	25.39	25.40
Dec	25.48	25.13	25.48	23.73	21.87	23.54	23.06	24.31	25.30	25.63
Yearly Averages	**27.19**	**27.18**	**26.73**	**26.86**	**26.84**	**26.53**	**26.93**	**27.53**	**27.36**	**27.15**

Month	**Year 71**	**Year 72**	**Year 73**	**Year 74**	**Year 75**	**Year 76**	**Year 77**	**Year 78**	**Year 79**	**Year 80**
Jan	24.26	24.43	22.22	24.69	23.81	23.66	25.50	22.62	24.04	23.48
Feb	24.96	25.81	26.52	24.84	26.21	26.24	23.92	27.72	24.90	26.26
Mar	24.29	26.73	26.15	25.27	27.27	27.13	25.50	25.74	26.56	26.49
Apr	29.90	27.90	26.34	28.39	28.22	29.53	28.67	26.07	29.79	27.93
May	28.95	28.83	30.47	29.04	29.82	31.40	29.19	29.37	29.78	28.91
Jun	30.17	29.02	29.67	31.57	29.84	28.74	30.00	30.69	29.88	30.06
Jul	29.82	29.79	28.71	29.77	28.49	29.92	28.29	29.15	30.21	28.42
Aug	27.38	28.57	28.23	27.55	28.72	27.76	28.57	27.40	28.82	28.47
Sep	26.23	27.97	27.79	28.02	28.76	26.82	27.85	28.36	28.50	26.52
Oct	26.50	25.87	28.16	26.33	25.89	26.00	27.00	26.55	26.12	26.55
Nov	23.62	24.94	26.06	25.61	23.44	26.04	24.76	24.87	26.81	25.68
Dec	24.22	23.15	26.03	22.93	25.23	23.65	24.71	25.01	24.66	24.73
Yearly Averages	**26.69**	**26.92**	**27.20**	**27.00**	**27.14**	**27.24**	**27.00**	**26.96**	**27.51**	**26.96**

Month	**Year 81**	**Year 82**	**Year 83**	**Year 84**	**Year 85**	**Year 86**	**Year 87**	**Year 88**	**Year 89**	**Year 90**
Jan	22.18	25.30	24.52	23.64	23.39	23.81	26.73	23.57	23.69	24.28
Feb	26.32	26.80	27.23	25.27	26.01	24.79	26.07	24.16	24.68	25.35
Mar	26.59	27.35	28.41	26.00	28.39	25.43	27.94	26.35	25.19	28.20
Apr	28.42	27.33	28.12	26.99	28.67	27.23	26.67	27.12	27.26	26.93
May	29.74	29.62	29.75	30.05	30.75	30.50	28.47	29.11	28.28	29.46
Jun	28.91	29.59	31.10	29.67	29.40	29.06	30.14	29.81	31.05	29.99
Jul	29.39	29.94	29.72	27.94	29.36	27.31	29.24	29.64	29.04	28.00
Aug	27.17	29.86	29.20	27.55	28.88	28.30	27.43	27.36	27.94	28.43
Sep	26.69	28.51	27.00	25.72	28.53	28.60	28.33	27.58	28.47	27.26
Oct	26.17	25.60	24.96	26.01	25.89	26.62	25.96	26.65	26.95	26.35
Nov	24.75	24.25	25.10	26.04	24.65	25.75	24.96	24.89	26.37	25.76
Dec	24.85	22.84	23.29	24.11	23.46	25.79	25.53	25.19	24.25	24.70
Yearly Averages	**26.76**	**27.25**	**27.37**	**26.58**	**27.28**	**26.93**	**27.29**	**26.78**	**26.93**	**27.06**

MarkSim Montlhy Temperature (°C)										
Month	**Year 91**	**Year 92**	**Year 93**	**Year 94**	**Year 95**	**Year 96**	**Year 97**	**Year 98**	**Year 99**	**Year 100**
Jan	24.95	24.27	21.97	24.19	23.30	24.23	21.96	24.94	22.58	22.07
Feb	24.29	24.49	23.69	25.73	25.28	26.56	25.28	24.98	26.88	25.62
Mar	27.81	24.42	26.47	25.67	27.95	25.61	26.74	26.44	27.35	27.47
Apr	27.09	26.94	28.20	27.01	28.54	29.42	26.51	27.66	27.75	28.08
May	30.04	30.67	30.30	31.15	30.84	29.31	30.01	29.29	29.13	29.38
Jun	30.40	29.20	29.84	29.19	29.23	29.55	30.19	28.93	29.62	29.83
Jul	27.53	29.81	27.72	28.82	27.87	30.59	28.26	27.15	28.94	26.98
Aug	28.95	28.82	27.78	27.68	29.21	28.28	28.34	28.31	27.77	27.41
Sep	28.38	29.12	26.94	27.22	29.05	26.81	28.56	28.31	26.71	26.88
Oct	26.78	24.93	27.02	25.33	26.35	27.90	27.36	27.45	25.94	26.31
Nov	25.34	25.21	24.62	24.39	24.91	26.98	26.72	26.80	25.98	25.14
Dec	25.14	24.12	23.47	23.80	24.44	24.84	24.88	26.19	25.39	23.95
Yearly Averages	**27.22**	**26.83**	**26.50**	**26.68**	**27.25**	**27.51**	**27.07**	**27.20**	**27.00**	**26.59**

Month	Avg.
Jan	**23.57**
Feb	**25.61**
Mar	**26.60**
Apr	**27.80**
May	**29.75**
Jun	**29.56**
Jul	**29.02**
Aug	**28.07**
Sep	**27.74**
Oct	**26.58**
Nov	**25.14**
Dec	**24.36**
Yearly Averages	**26.98**

Appendix B

Bryson: 2,500 Year Climate Simulations

Bryson Precipitation (mm) - 2,500 Years

DATE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
500 BC	249.55	124.18	64.97	42.3	152.27	294.76	274.13	313.28	483.94	547.72	241.07	193.87	2982
400 BC	272.63	116.68	72.19	41.01	159.31	288.28	258.29	279.48	499.14	550.1	241.4	193.35	2971.8
300 BC	288.38	115.51	76.33	36.65	163.49	286.12	249.86	262.46	507.69	551.47	241.62	193.17	2972.7
200 BC	272.78	115.95	73.28	41.02	157.71	289.83	263.48	291.03	494.96	549.53	241.41	193.44	2984.4
100 BC	253.74	118.15	69.54	41.91	151.02	297.85	281.98	324.15	480.44	547.21	241.16	193.96	3001.1
100 AD	269.59	115.08	77.44	39.15	157.04	291.39	268.88	301.9	492.12	549.23	241.55	193.49	2996.9
200 AD	250.28	114.85	71.8	41.24	148.95	302.84	294.12	334.01	476	546.4	241.19	194.16	3015.8
300 AD	252.08	121.72	63.91	38.48	142.08	322.86	332.42	334.39	467.54	543.61	240.81	195.67	3055.6
400 AD	258.05	114.07	74.93	41.33	150.94	299.73	288.83	329.38	479.23	547.1	241.34	193.92	3018.8
500 AD	277.96	117.25	79.27	38.19	156.26	292.84	273.54	309.64	489.65	548.93	241.62	193.54	3018.7
600 AD	302.97	125.26	82.1	32.2	161.88	288.25	259.95	285.3	501.52	550.78	241.88	193.3	3025.4
700 AD	302.58	126.37	82.73	32.02	161.56	288.59	261.3	288	500.61	550.66	241.89	193.32	3029.6
800 AD	284.7	122.59	82.49	35.2	157.7	291.99	272.13	306.98	491.99	549.37	241.77	193.48	3030.4
900 AD	266.19	116.69	81.17	39.36	152.72	298.23	288.06	327.05	481.72	547.67	241.57	193.77	3034.2
1000 AD	248.82	111.11	77.44	40.21	146.27	311.75	318.46	338.83	471.29	545.3	241.26	194.44	3045.2
1100 AD	274.56	120.9	83.43	37.09	154.8	295.67	282.44	320.79	485.55	548.37	241.7	193.64	3038.9
1200 AD	303.34	134.17	85.82	29.9	161.74	289.02	263.43	292.3	500.03	550.67	242.01	193.34	3045.8
1300 AD	307.07	135.72	86.15	29.32	162.31	288.64	262.11	290	501.21	550.86	242.04	193.32	3048.7
1400 AD	273.46	122.49	84.49	36.57	154.65	296.2	284.35	322.53	484.97	548.3	241.73	193.65	3043.4
1500 AD	256.06	114.94	82.55	39.96	149.83	304.14	303.55	335.98	476.17	546.61	241.51	194	3045.3
1600 AD	250.69	107.05	76.35	38.75	142.66	324.75	345.83	332.1	467.69	543.78	241.11	195.14	3065.9
1700 AD	300.09	105.95	65.24	36.41	136.82	357.32	363.6	297.38	466.87	540.69	240.64	198.55	3109.6
1800 AD	292.22	142.92	88.34	27.59	162.82	288.72	262.94	291.76	501.52	550.98	242.15	193.33	3045.3
1900 AD	315.23	102.09	65.01	36.18	136.46	360.46	360.99	293.93	467.07	540.44	240.62	198.96	3117.4
2000 AD	326.03	99.48	64.81	36.02	136.23	362.55	358.74	291.67	467.22	540.27	240.6	199.24	3122.9
Average	277.96	118.45	76.47	37.12	152.70	304.51	290.94	307.77	485.45	547.44	241.43	194.40	3034.63

Bryson Temperature (°C) - 2,500 Years

DATE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
500 BC	21.14	24.15	25.16	26.32	28.80	28.04	27.42	27.10	26.80	25.23	24.16	22.61	25.58
400 BC	21.36	24.38	25.39	26.57	29.07	28.33	27.71	27.39	27.08	25.50	24.40	22.84	25.84
300 BC	21.51	24.53	25.54	26.72	29.21	28.47	27.85	27.53	27.22	25.64	24.55	22.99	25.98
200 BC	21.37	24.39	25.39	26.54	29.01	28.25	27.62	27.30	27.00	25.45	24.38	22.84	25.79
100 BC	21.21	24.22	25.20	26.31	28.74	27.94	27.30	26.99	26.71	25.20	24.17	22.66	25.55
100 AD	21.48	24.49	25.46	26.56	28.98	28.18	27.53	27.22	26.95	25.44	24.42	22.93	25.80
200 AD	21.24	24.25	25.19	26.26	28.64	27.81	27.14	26.83	26.59	25.12	24.14	22.67	25.49
300 AD	20.97	23.97	24.89	25.93	28.26	27.39	26.71	26.40	26.18	24.75	23.81	22.38	25.14
400 AD	21.34	24.35	25.29	26.36	28.73	27.89	27.23	26.92	26.68	25.21	24.23	22.77	25.58
500 AD	21.53	24.53	25.49	26.56	28.95	28.12	27.46	27.15	26.90	25.42	24.43	22.96	25.79
600 AD	21.70	24.71	25.66	26.75	29.15	28.33	27.67	27.36	27.10	25.62	24.62	23.14	25.98
700 AD	21.71	24.72	25.67	26.75	29.14	28.31	27.65	27.34	27.09	25.61	24.62	23.15	25.98
800 AD	21.63	24.64	25.58	26.64	29.00	28.16	27.48	27.18	26.94	25.48	24.51	23.06	25.86
900 AD	21.50	24.50	25.43	26.47	28.81	27.94	27.26	26.96	26.73	25.29	24.35	22.92	25.68
1000 AD	21.29	24.29	25.20	26.20	28.51	27.61	26.91	26.61	26.41	25.01	24.10	22.70	25.40
1100 AD	21.59	24.59	25.52	26.55	28.89	28.02	27.34	27.04	26.81	25.38	24.44	23.01	25.77
1200 AD	21.79	24.80	25.73	26.79	29.14	28.29	27.62	27.31	27.08	25.62	24.66	23.22	26.00
1300 AD	21.81	24.82	25.75	26.80	29.16	28.31	27.64	27.33	27.10	25.64	24.68	23.24	26.02
1400 AD	21.61	24.62	25.53	26.56	28.89	28.01	27.32	27.02	26.80	25.38	24.45	23.03	25.77
1500 AD	21.47	24.47	25.37	26.38	28.68	27.79	27.09	26.79	26.58	25.18	24.27	22.87	25.58
1600 AD	21.19	24.19	25.07	26.03	28.30	27.37	26.65	26.36	26.18	24.81	23.95	22.58	25.22
1700 AD	20.84	23.83	24.68	25.61	27.82	26.85	26.12	25.83	25.68	24.35	23.54	22.21	24.78
1800 AD	21.89	24.89	25.81	26.84	29.18	28.31	27.62	27.32	27.10	25.67	24.73	23.30	26.05
1900 AD	20.82	23.81	24.66	25.58	27.78	26.81	26.07	25.78	25.63	24.31	23.51	22.18	24.74
2000 AD	20.81	23.80	24.64	25.55	27.75	26.77	26.03	25.74	25.60	24.29	23.49	22.17	24.72
Average	21.39	24.40	25.33	26.39	28.74	27.89	27.22	26.91	26.68	25.22	24.26	22.82	25.60

Appendix C

Bryson/MarkSim: Daily Simulations

Due to its size it was necessary to have Appendix C as a separate file. For a copy of Appendix C please contact the author at kirkdfrench@gmail.com. Thank you.

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Publications

Review	**French, Kirk D.** and Duffy, C. - Prehispanic Water Pressure at the Classic Maya Site of Palenque. *Journal of Archaeological Science,* March 2009.
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