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The urban hydrology and hydraulic engineering at the classic maya site of Palenque

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Abstract This research explores a new method for the study of urban hydrology and hydraulics at the ancient Maya site of Palenque in Chiapas, Mexico. The conceptual hydrologic framework together with modern digital terrain, landcover class and soils are used to create virtual assessments of how various climate and landuse scenarios may have impacted the long-term hydrology and streamflow conditions for the Palenque watershed and urban center. The utility of understanding how landscape alteration and climate affect a watershed's function and output is a critical component of modern and ancient water management studies. In this study we evaluate the hydraulic design of the water management features at Palenque against extreme meteorological events over 100 year periods during Maya occupation. We pose the question: How successful were the Maya in coping with droughts, floods and water supply that evolve from their own hydraulic designs and urban hydrologic manipulations? The hydroarchaeological method demonstrated here is shown to be a plausible strategy for evaluating the impact of Maya water manipulation strategies on urban development.

Keywords Maya · Palenque · Water management · Hydrology · Hydraulic engineering · Watershed modeling · Human/environmental impact

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Introduction

The ancient Maya of Central America are renowned as great builders, but are rarely regarded as great engineers. Their constructions, though often large and impressive, are generally considered unsophisticated in terms of engineering techniques and knowledge, as we understand them today. Most large Maya constructions required only basic building techniques as well as a good supply of unskilled laborers. One major exception to this 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.

An inherent problem with many water management studies in an archaeological setting is the lack of a quantitative approach to watershed impacts. However, modern watershed modeling is now possible and can provide "hydrologically" plausible scenarios where terrain, landcover, landuse and climate conditions can be represented. We refer to the implementation of watershed models using projections of landcover, terrain and climate regimes as the *hydroarchaeological method* (French et al. 2012). The application is the Palenque watershed (7.21 km^2) surrounding the Classic Maya site at Palenque. The strategy is the evaluation of the hydraulic design of the water management features against simulated extreme meteorological events, distributed hydrologic response and subsequent appraisal of how successful the hydraulic engineering of the Maya was in coping with droughts, floods and water supply.

This study starts with the development of a 100-year daily climate scenario for precipitation and temperature, applied as input to a distributed watershed model. The watershed model then simulates the hydrology of all stores (e.g. canopy interception, soil moisture, groundwater storage, etc.) and fluxes (e.g. throughfall, transpiration, evaporation, recharge and runoff) within the watershed. For a given climate scenario we wish to understand the hydrologic and water use implications for an ancient urban setting, assuming that the modern watershed features and reconstructed urban environment represents a reasonable basis for parameterizing the watershed model. After calibrating the model we develop a 100-year simulation and then examine the simulated annual flood and drought events on each management feature (aqueducts, channels) for the Otolum stream, Palenque's main waterway that initiates in the upland watershed and passes under the urban center.

Palenque is a Classic Maya center with what is arguably the most unique and intricate system of water management structures known anywhere in the Maya Lowlands. Years of archaeological research, including intensive mapping between 1997 and 2000, reveal that this powerful center, situated on a narrow escarpment at the base in northern Chiapas, Mexico (Fig. 1), began as a modest settlement about AD 100. During the seventh and eighth centuries, Palenque experienced explosive growth, mushrooming into a dense community with an estimated population of 6,000 and approximately 1,500 structures—residences, palaces, and temples—under a series of powerful rulers (Fig. 2) (Barnhart 2001). This process of urban construction and population growth led to significant changes in landcover and landuse that fundamentally altered the natural hydrology of the site.

In order to better understand the effects that land-use and climate change had on the scarcity, excess, and distribution of water in this ancient city, a new approach was investigated that integrates the urban water distribution with the larger watershed ecohydrologic conditions. This includes scenario of the downscaled impacts of climate and landuse change in a spatially distributed watershed framework. The approach, referred to as hydroarchaeology (French et al. 2012), utilizes paleoclimate data, distributed modeling

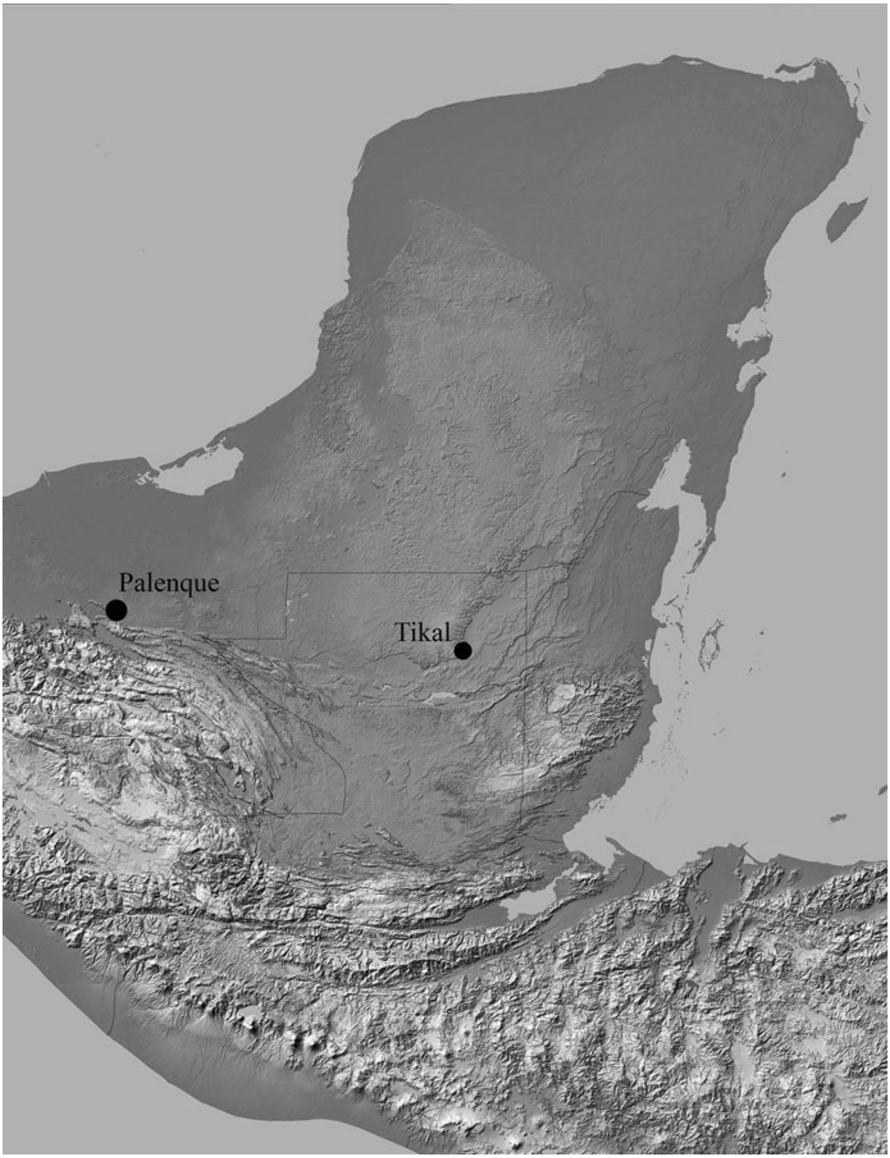


Fig. 1 Location map of Palenque

of the space–time dynamics of watershed hydrology, and traditional archaeological methods to reconstruct the response of the Palenque watershed to the varying degrees of ancient human impact. The method takes advantage of recently developed simulation tools for watershed models and climate scenarios (Qu and Duffy 2007; Bhatt et al.2008; Kumar et al. 2009) to present plausible projections of water use and supply, and the distributed effects of extreme flood, drought and average water supply conditions in an ancient urban environment. We note that the climate alone is insufficient indicator to assess the particular spatially and temporally varying impacts that may occur on this watershed coupled within

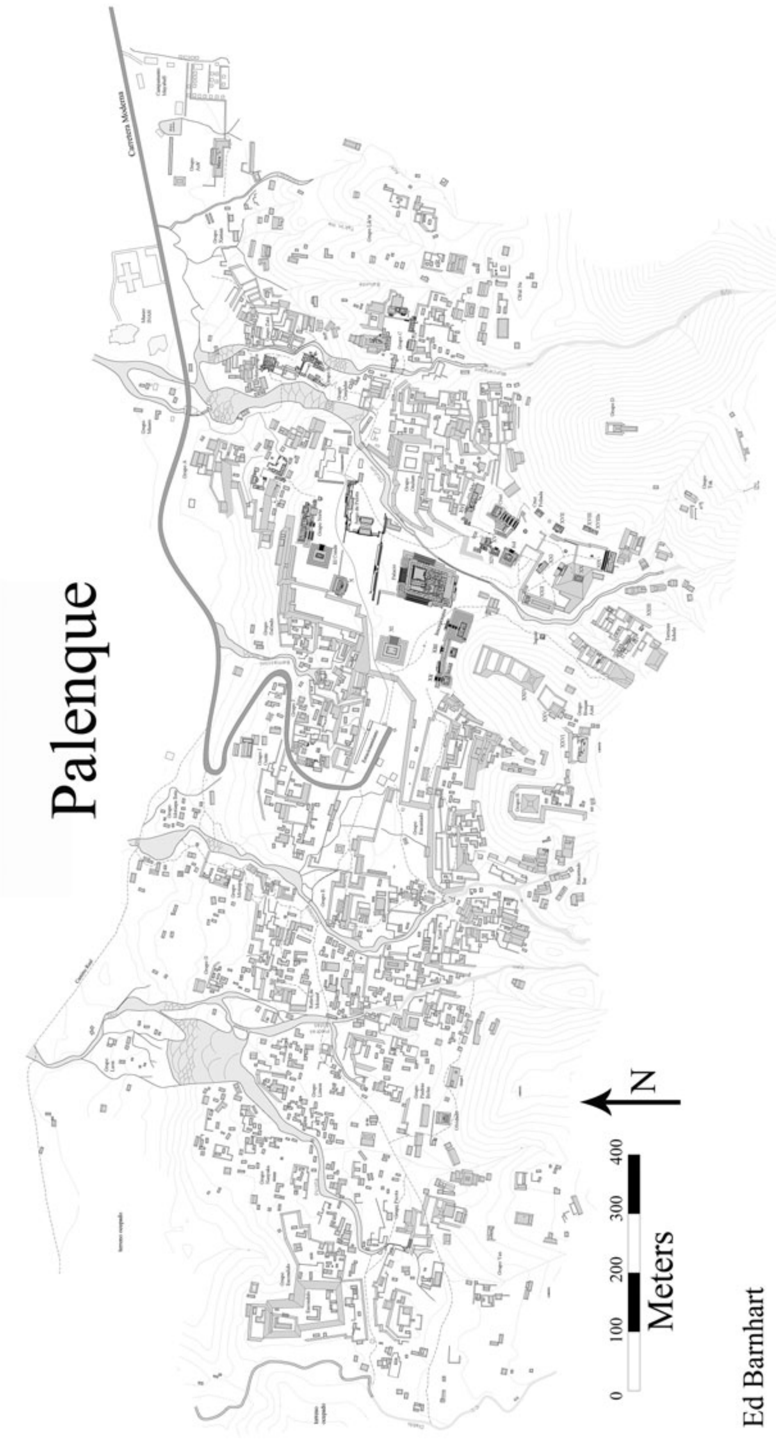


Fig. 2 Map of Palenque (Barnhart 2001)

urban environment. With recourse to modern use of spatially distributed watershed model, we use simulated climate inputs to explicitly assess the impacts of urban structures and landuse patterns on this ancient environment.

Methods and environmental setting

Major hydrological processes within the terrestrial hydrological cycle operate over a wide range of time and spatial 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. Penn State Integrated Hydrologic Model (PIHM) (Qu and Duffy 2007) represents a new strategy for watershed modeling where spatial details of the watershed are explicitly represented on numerical grids. Multi-state, multi-physics representation of processes including surface flow, groundwater flow, vegetation water and energy are represented in the model. Details of the model can be found in French et al. (2012).

The simulation environment

The estimated effects of climate change are now well recognized through IPCC projections (IPCC 2007) with potentially large impacts for global water resources. Climatic perturbations also play an important role in changing the ecosystem's structure and function (Westerling et al. 2006). Studies on ecosystem response to relatively short disruptions have indicated that species assemblages often recover rapidly from meteorological drought (Matthews and March-Matthews 2003), but quantitative assessments of ecohydrological impacts from extreme, decades-long wet or dry episodes have revealed more pervasive impacts than previously thought (Gray et al. 2006). Any strategy for understanding the historical cultural and political risks associated with past climate impacts requires an estimate of past hydrological variability and extremes (NRC 2007). Instrumental records of precipitation, temperature, and surface-water flow throughout Mesoamerica are rare to non-existent. This section outlines a novel method that combines simulated climatic records and distributed watershed modeling to produce estimates or scenarios of long-term streamflow for the Palenque Watershed (French et al. 2012).

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

Late Cretaceous (99.6–65.5 Ma) limestone covers most of the watershed. The model assumes that the hydraulic properties of the underlying geology are, like the soils, very permeable. The permeability of the soil and geologic materials is enhanced by macropores, or soil or rock fractures, cracks, weathering, root holes and bioturbation that tend to increase the hydraulic conductivity of the soil and rock. The near-surface limestone tends to weather along joints and fracture planes as is shown conceptually in Fig. 3.

Palenque is categorized as a "tropical moist forest" according to the Holdridge Life Zone classification scheme (Holdridge et al. 1971). Holdridge defines "tropical moist forest" as a tall, multi-stratal semi deciduous forest with many different species of

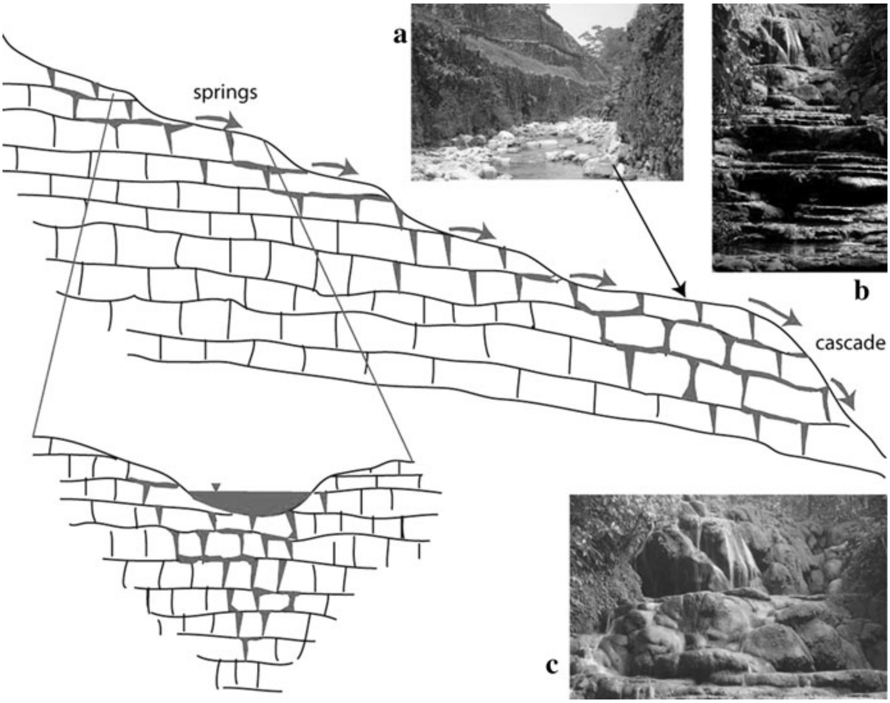


Fig. 3 Hydrologic conceptual model for the Cretaceous limestone watershed at Palenque showing the increased dissolution along bedding planes and fractures below the stream channel bed, a boulder channel (*top photo*) crossing the ruins, and two photos within the groundwater discharge zone showing the pool and ledge cascade and accreting tufa deposits

wide-crowned trees 40–50 m tall. The sub-canopy consists of trees up to 30 m tall, mostly with narrow crowns. Palms are generally abundant. The shrub layer is made up of dwarf palms and giant herbs with banana-like leaves. The ground is generally bare except for a few ferns, broad-leaved herbs, and tree seedlings. Abundant herbaceous vines hang throughout the forest.

The watercourses at Palenque generally run in a northerly direction. Beginning in the uplands along the first rise of the Chiapas Plateau to the south, the spring-fed streams flow north toward the plains of Tabasco. Fifty-six known springs supply nine separate watercourses, that generally flow through the urban center. These arroyos support ephemeral or seasonal streamflow, and are the object of Palenque's many different water management features (French 2002).

The urban environment

Palenque was one of the most highly urbanized centers of the Maya Classic Period (A.D. 250-900) with (1) a high settlement density; (2) monumental public works; and (3) public activity zones, such as plazas (Barnhart 2001). The spring-fed streams that dissected the landscape contributed to the dilemma of building on its confined plateau. George Andrews (1975) claimed that this irregular natural terrain caused problems for the city's builders, who were forced to reshape the existing landscape to maintain visual order in the overall layout of the city. To 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 subterranean aqueducts to guide the stream beneath plaza floors (French 2007; French et al. 2012).

Landuse and vegetation: past and present

Patterns of landuse and vegetation represent essential variables that determine how extreme events unfold at different locations. For example, a tropical rain forest may intercept 30–40 % of the rainfall that re-evaporates, short-circuiting the rainfall-runoff. On the other hand, urban plazas produce extremely rapid runoff with no chance to store and moderate extreme rainfall events. In this study two scenarios were developed that cover a plausible range of climate conditions and possible land cover settings (French et al. 2012).

For the model discussed below, nomenclature for describing the land cover classification in National Land Cover Database (NLCD 2001) was used. The most appropriate category, according to the NLCD (2001), was "forest/evergreen". They define "forest/evergreen" as "trees >3 m in height, canopy closure >35 % (< 5 % intermixture with deciduous species), of species that do not seasonally lose leaves" (www.epa.gov/mrlc/nlcd-2001.html).

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; Schreiner 2002). To make stucco limestone must be heated to 900 °C, a process called calcination or lime burning, to remove the carbon

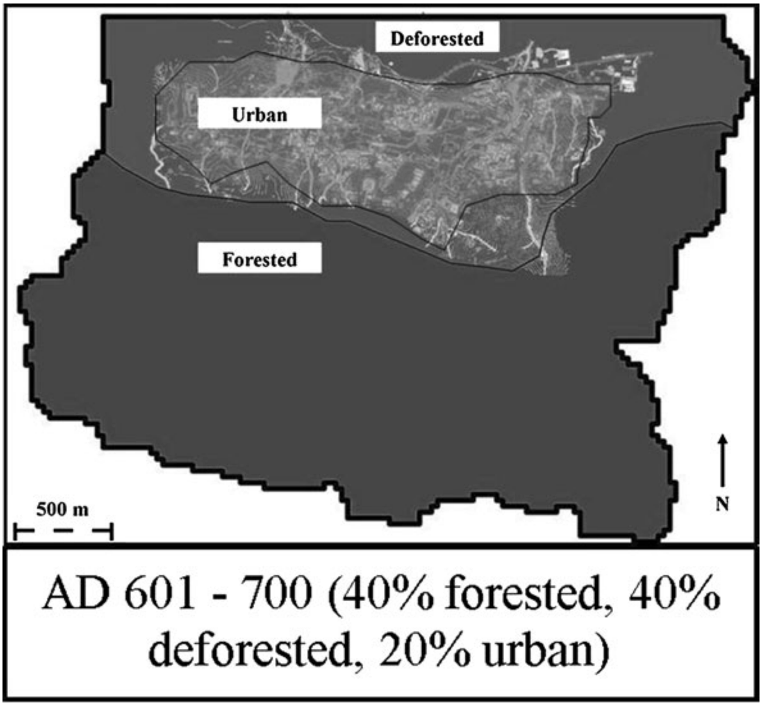


Fig. 4 Estimated landcover for the Palenque watershed from AD 601–AD 700

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 as well as for paving for their expansive plaza floors because it was a sign of wealth and prestige. The stucco had to be constantly maintained. The high temperature required for the calcination process coupled along with the high demand for aesthetics stimulated deforestation.

Reconstruction of a Maya kiln used for the calcination process revealed that 1 ha of forest with trees greater that 5 cm diameter will provide 444 kg of quicklime (Schreiner 2002). The quicklime contribution to a cubic meter of plaster is 325 kg. To conceptualize these numbers the pyramid of El Tigre, from the Preclassic (1000 B.C.–A.D. 150) site of El Mirador in northern Guatemala, required 2,200 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 1,630 ha (16.3 km^2) of forest trees (Schreiner 2002). It must also be noted that some portion of the trees used in the production of quicklime would have most likely come from the clearing of land for agricultural production.

Deforestation was most likely a side effect of Palenque's dense population due to its aggressive use of stucco (French et al. 2012). 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 and releasing it into the atmosphere through transpiration. Ironically, floods, aggravated by deforestation, can also lead to localized and complex ecohydrologic impacts. For example

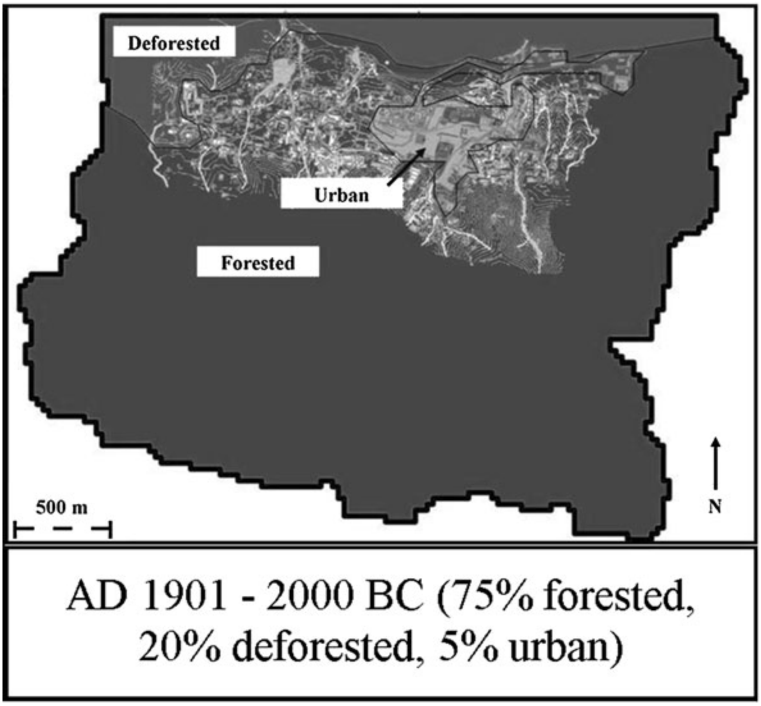


Fig. 5 Estimated landcover for the Palenque watershed from AD 1901–AD 2000

Table 1 Simulation results, showing mean annual precipitation (MAP), mean annual temperature (MAT) and mean annual flow (MAQ)

Time period	MAP (mm)	MAT (°C)	Otolum–MAQ (m^3/day)
AD 601–AD 700	3,017	25.9	12,468
AD 1901–AD 2000	2,958	27	11,102

extreme rainfall on denuded landscapes causes extreme runoff, which in turn causes excess erosion which reduces infiltration, and may impact recharge to groundwater and baseflow to streams and springs (French et al. 2012).

Palenque would have been highly susceptible to erosion caused by deforestation due to its steep terrain and shallow soils. The 16 non-contiguous kilometers of architectural terracing found in Palenque may very well have been a response to erosion caused by deforestation (Barnhart 2001).

The urban landcover scenario was difficult to parameterize because it is unknown to what extent the Palenque plazas and courtyards were made impermeable by application of stucco/plaster. In lieu of this information the hydraulic conductivity of the soil within the site boundary was reduced by 50 % in the developed regions to simulate compaction by urban traffic (Gregory et al. 2006; French et al. 2012).

The climate: landcover scenario

The period AD 601–AD 700 was the plausible peak of Palenque's population and urbanization. The reconstructed landcover for this scenario was estimated to be a mix of forested (40 %), deforested (40 %), and urban (20 %) land cover types (Fig. 4). A 100-year climate scenario was developed from the model of Bryson and DeWall (2007). This was used to develop the average climate (precipitation and temperature) input to the watershed model.

From satellite and aerial photos we estimate the current landcover as a mix of forested (75 %), deforested (20 %), and urban (5 %) (Fig. 5).

Results: two centuries of virtual watershed simulation

We compare the Maya urban maximum scenario AD 601–AD 700 to the modern period, AD 1901–AD 2000, for which we can ground our simulations with a regionally measured record of tropical climate observations. This span of time is also useful because of the opportunity to compare the model results for this scenario with descriptions from the local

Table 2 Estimated calendar for the Palenque summer growing season for maize

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

population of flood and drought events that have taken place in the last 50 years (French et al. 2012). The results from these simulations on Palenque's largest waterway, the Otolum, are shown in Table 1.

Comparison of watershed response to extreme events

Comparison of the seventh century Maya scenario to that of the 20th century points out the critical role of landuse and hydrologic shifts during climate change scenarios. We observed that climate change alone (e.g. increased/decrease in precipitation, decrease/increase in temperature) is insufficient to assess the expected degree of changes on the landscape.

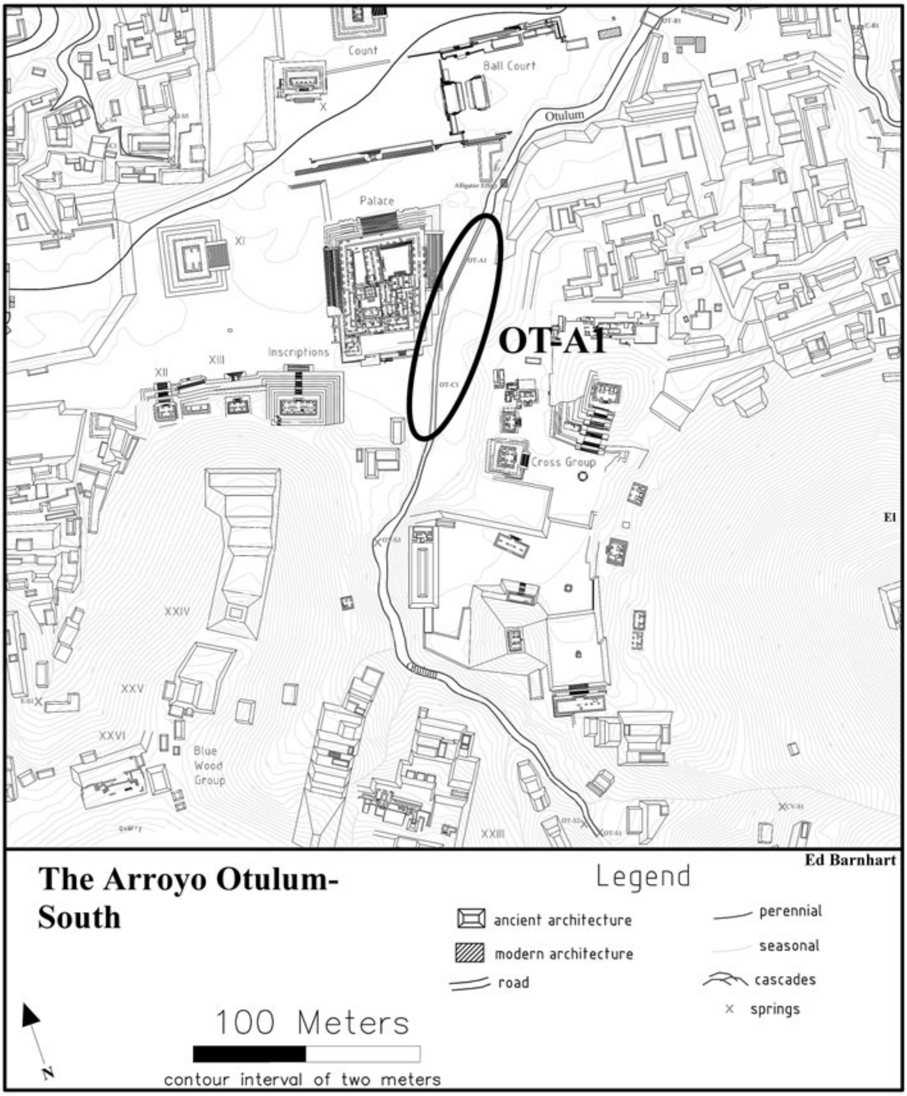


Fig. 6 The southern section of the Otolum stream

However taken together, the degree to which climate change leads to an amplification of the hydrologic regime can be assessed, such as the degree to which cooler–wetter conditions and increases in urban land cover leading to much larger runoff; and warmer–dryer conditions leading to deeper hydrological drought from lower runoff. Comparison of the relative change in climate-watershed response for seventh and 20th century simulations follows.

Overall, comparing the average climate simulations for the two centuries showed that the precipitation for the earlier time period was 2 % higher and temperature was 4 % cooler than the 20th century. The deforestation levels along with the presence of urban

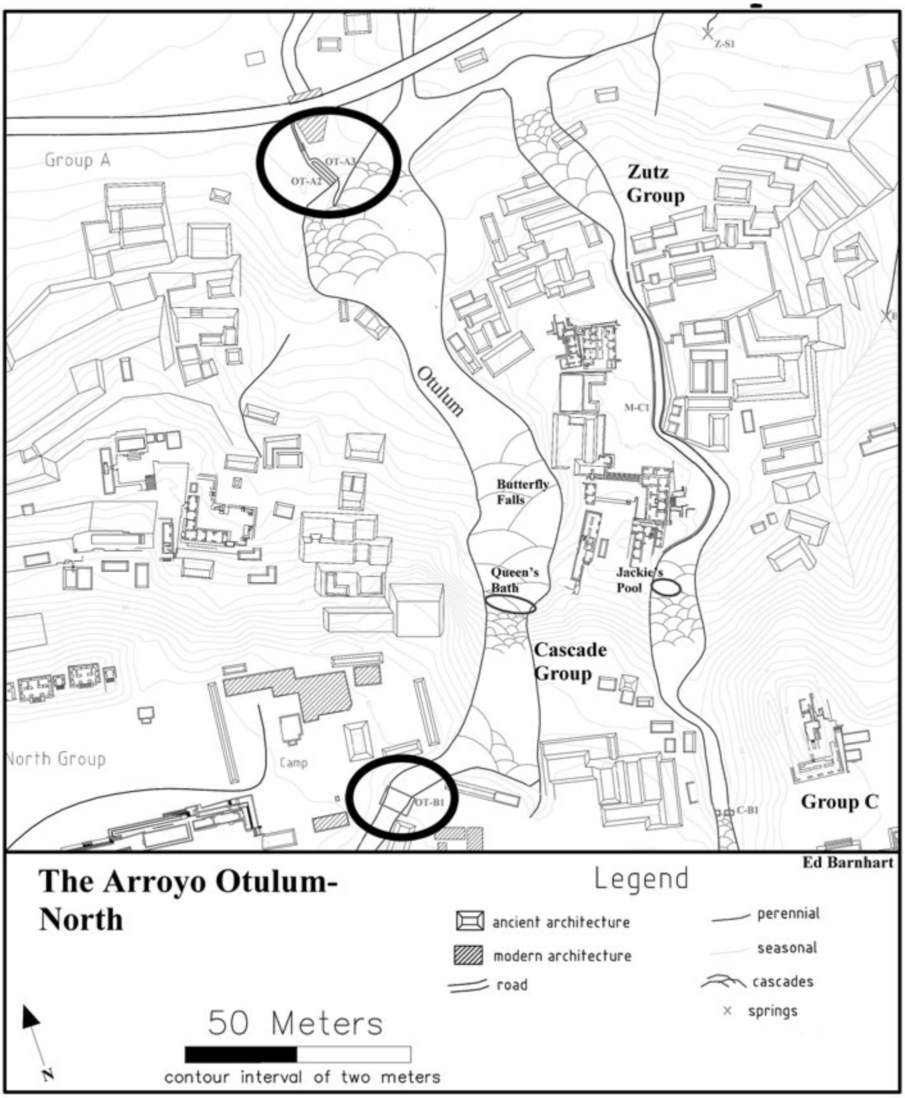


Fig. 7 The southern section of the Otolum stream. Note the *circled areas* delineating the bridge and the northern aqueducts

landcover (i.e. less permeable surfaces) and reduced evapotranspiration from the watershed are the main cause for this increase in runoff in the model simulations.

In the case of drought, the worst 7-day drought event during AD 601–AD 700 the Otolum was still flowing at 484 m^3/per day (484,000 l). By storing a mere 25 % of this daily flow would have provided an ample water supply (121,000 l) for a population of more than 20,000 based on 6 l/person/day (Back and Lesser 1981). 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 principle waterways, the Otolum. According to these 100-year projections, Palenque likely never experienced a hydrological drought severe enough to cause major disruptions in daily life, much less abandonment (French et al. 2012).

Analysis of the most severe simulated meteorological droughts in Palenque for AD 601–AD 700 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 (Table 2) dipped to as low as 650 mm, the streams continued to deliver water to the channelized fields in the plains to the north of the site.

The simulations for both centuries show that flood events in Palenque are closely linked to rainfall and landcover. The most severe 1-day flow for the Otolum was 106,232 m^3/day. Based on conversations with longtime residents of Palenque, we qualitatively estimate that this appears to be a much higher volume of discharge than has been observed for modern flood events. The model suggests that the present forest cover (75 %) dramatically reduces runoff, enhancing long-term canopy interception and short-term infiltration, which together

Fig. 8 The Otolum flowing through OT-C1, also referred to as Section *D*. Note that Sections *D* and *C* join together where the man is standing

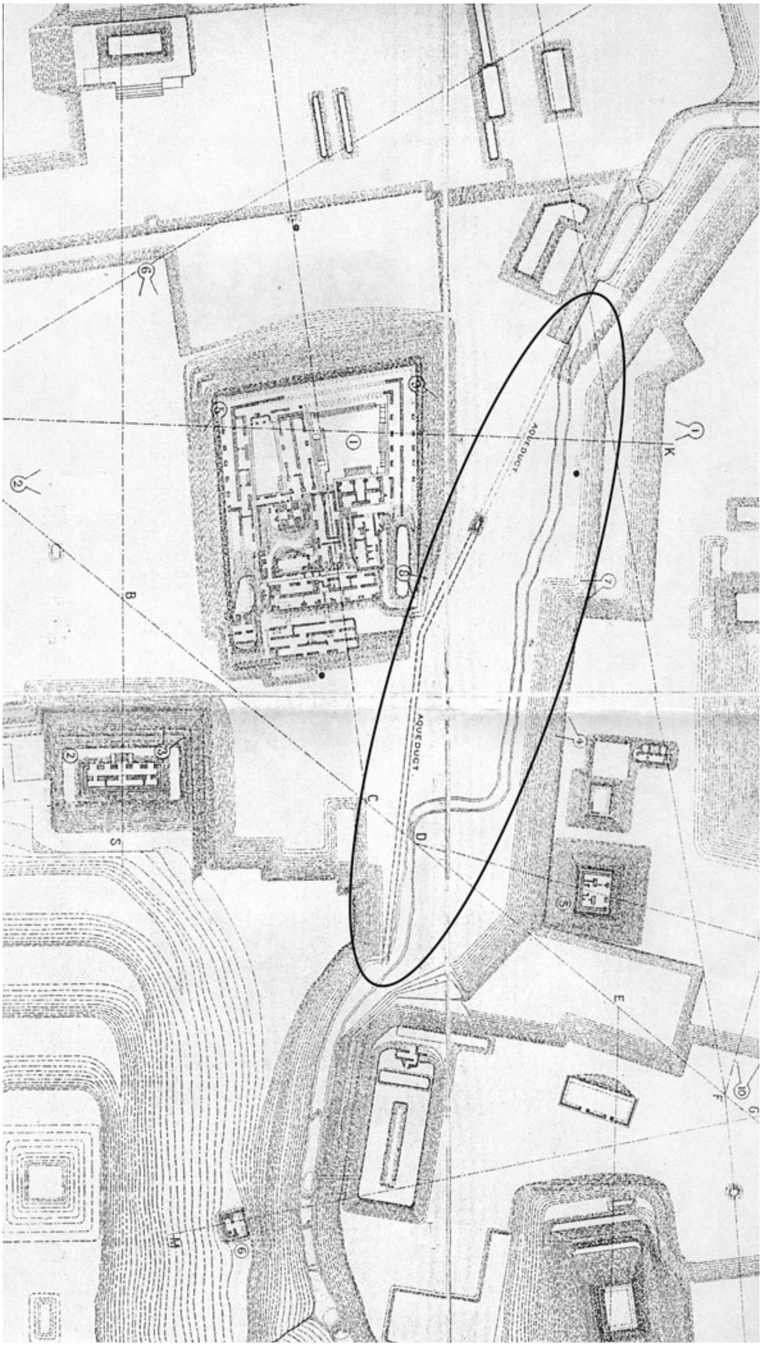


Fig. 9 Map of Palenque in 1891. Notice the stream bypassing and flowing parallel to the aqueduct (Maudslay 1889–1902)

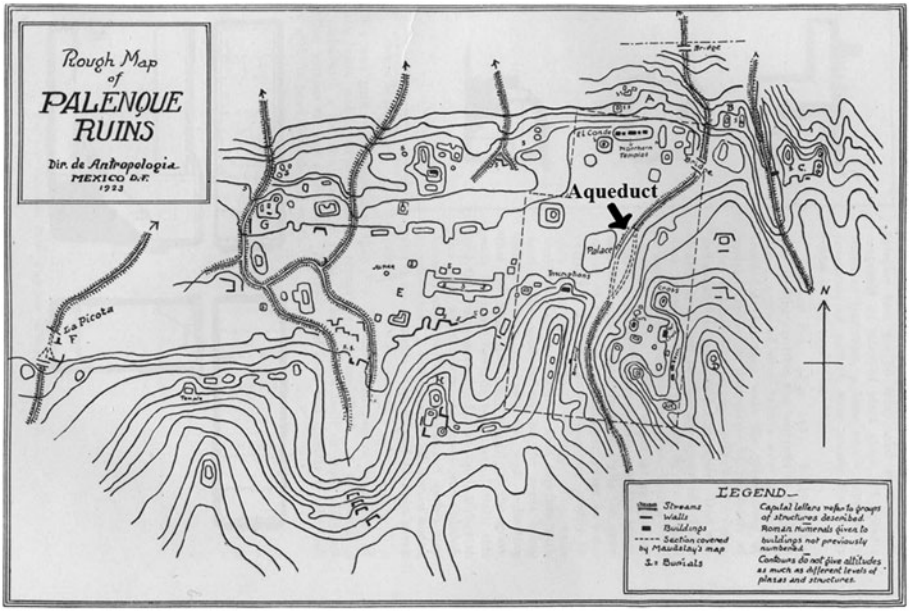


Fig. 10 An early map of Palenque by Frans Blom showing the Palace aqueduct (Blom 1925)

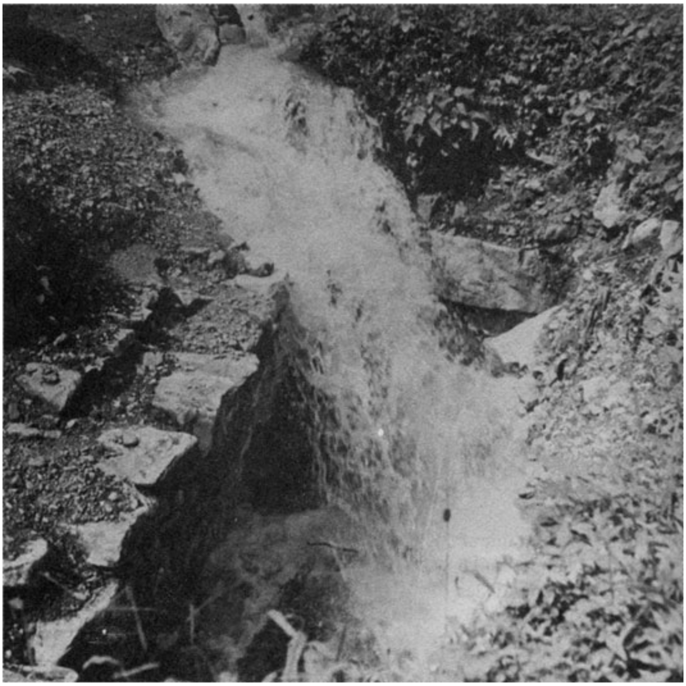


Fig. 11 The Otolum flowing back into OT-A1. This is at the northern end of Section *A* (Moll 2007)

reduces the relative impact of flooding. The landcover for AD 601–AD 700 was an estimated 40 % forest, 40 % deforested, and 20 % urban. The level of deforestation and impermeable cover amplified the flood events, which is a phenomena urban areas experience today. Next we examine Palenque's hydraulic designs for flood and drought events for one of the water management features on the Otolum Stream.

The Otolum urban hydraulic features

The distributed watershed simulations allowed a spatial analysis of urban hydraulic structures of the Otolum stream during flood and drought events. The Otolum represents the largest and most developed waterway in Palenque with the largest contributing watershed area. The Otolum is Palenque's longest and most managed stream (Figs. 6, 7). Its perennial waters flow through the site's center by way of a sophisticated aqueduct (French 2002).

Upstream (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.

Fig. 12 Collapse section of OT-A1 (Moll 2007)

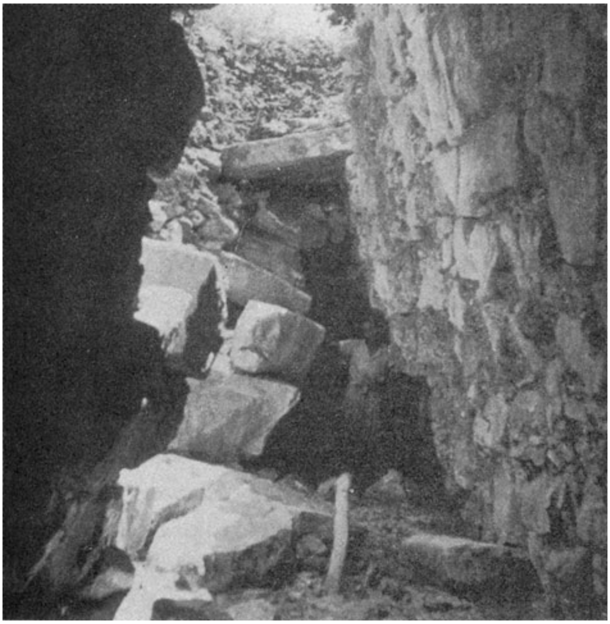


Fig. 13 Partial collapse of the southern end of Section *C* (Moll 2007)

Fig. 14 Interior of OT-A1, Section *A*

The stream collects more water at several other springs before entering the walled channel, OT-C1 (Fig. 8).

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

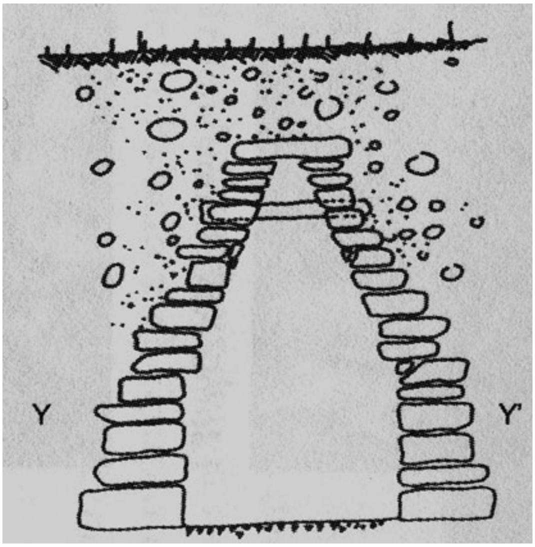


Fig. 15 Section *A* of OT-A1 (Moll 2007)

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 (Fig. 9). Franz Blom (1925, p. 173) stated that the aqueduct was "blocked by its fallen roof". The collapse forced the Otolum to flow just to the east of the aqueduct and cut a new streambed. Blom's map (Fig. 10) 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 (Fig. 11). During the 1950s archaeologists began to clean out the debris and rebuild the walls (Figs. 12, 13). 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 would have allowed the Otolum to flow through the channel beneath the floor of the plaza for 58.5 m (Fig. 14) 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 m (Figs. 14, 15, 16). This is OT-A1's best-preserved section, 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 a large stone crocodile effigy positioned 1 m above the flow of water (Fig. 17). It

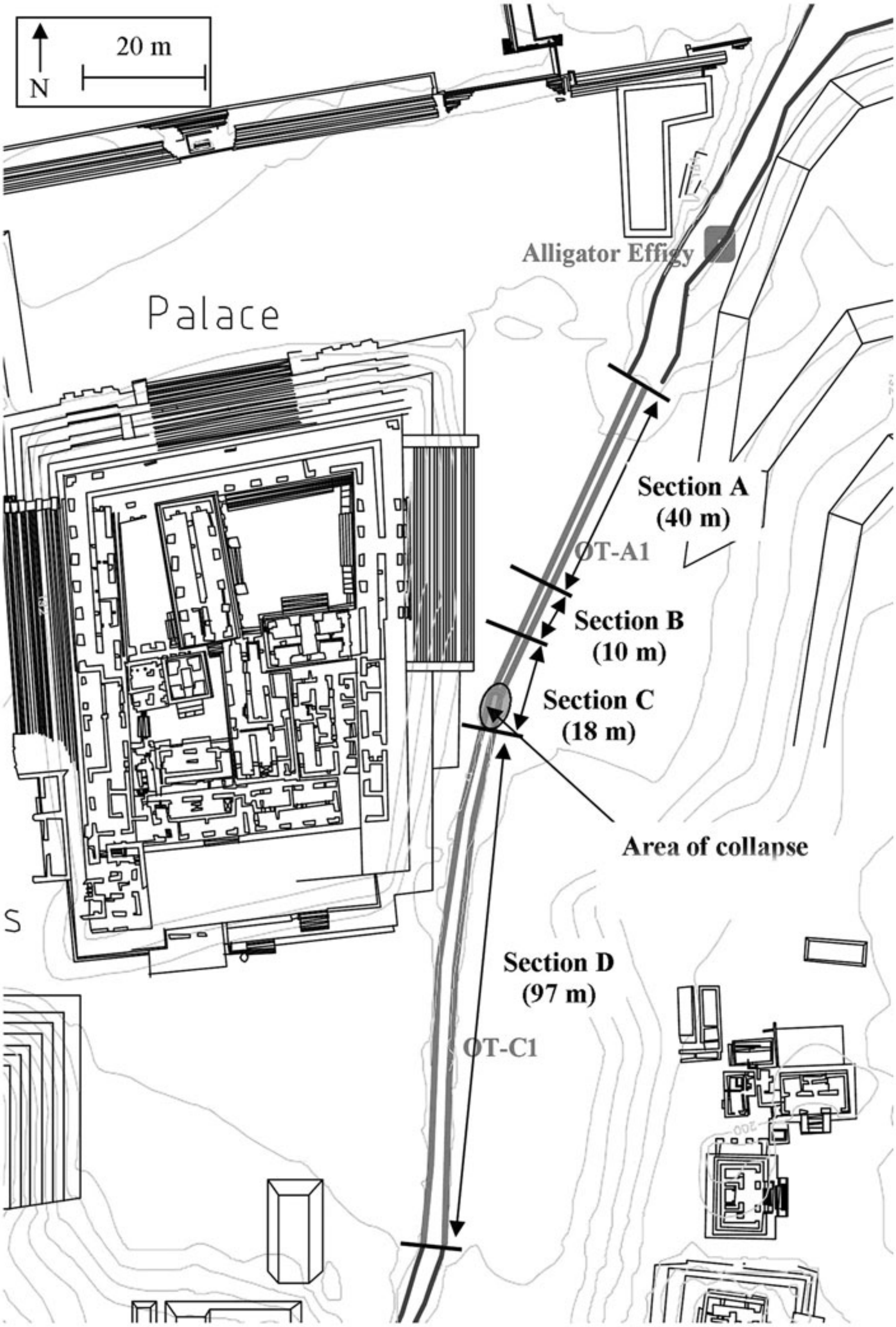


Fig. 16 The four construction phases of OT-A1

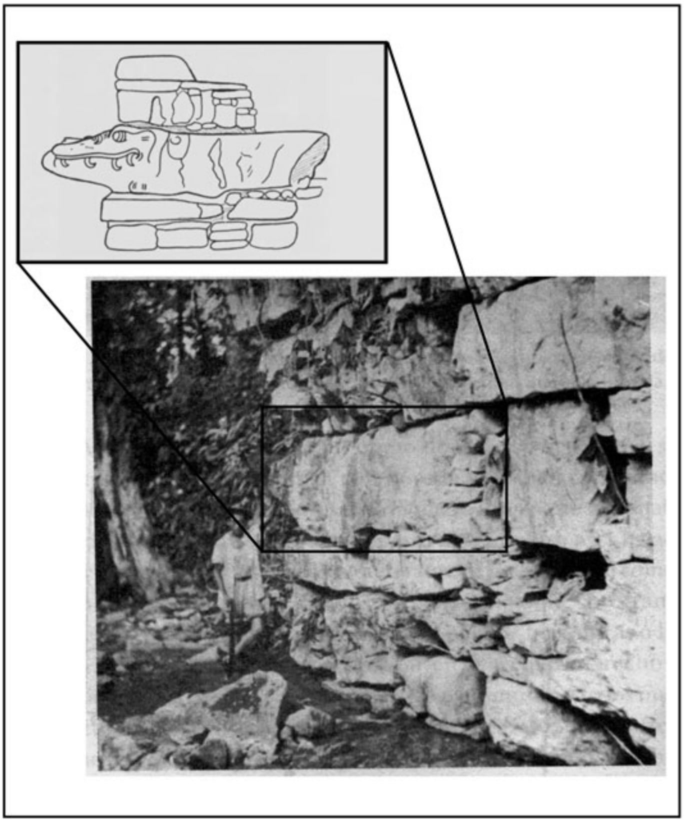


Fig. 17 Crocodile effigy

measures 3.44 m in length, 1.10 m in height, and 86 cm thick, or about 3.50 m^3. During times of high water, the crocodile would have appeared to be floating atop the waters of the Otolum (Stephen D. Houston, personal communication, 2000). This still occurs today during high flows in the rainy season.

The stream then meanders slightly eastward, passing the ball court and approaches OT-B1, the Otolum Bridge, which measures 10.25 × 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 arch 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 (Fig. 6). The water then topples through multiple small pools that have been nicknamed the Butterfly Falls.

At an elevation of 110 m the stream gathers in a small and shallow natural pool and then enters a set of parallel aqueducts (Fig. 18). 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 (Fig. 19). The second aqueduct, OT-A3, is heavily calcified and partially 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. One is located on the west wall, while the

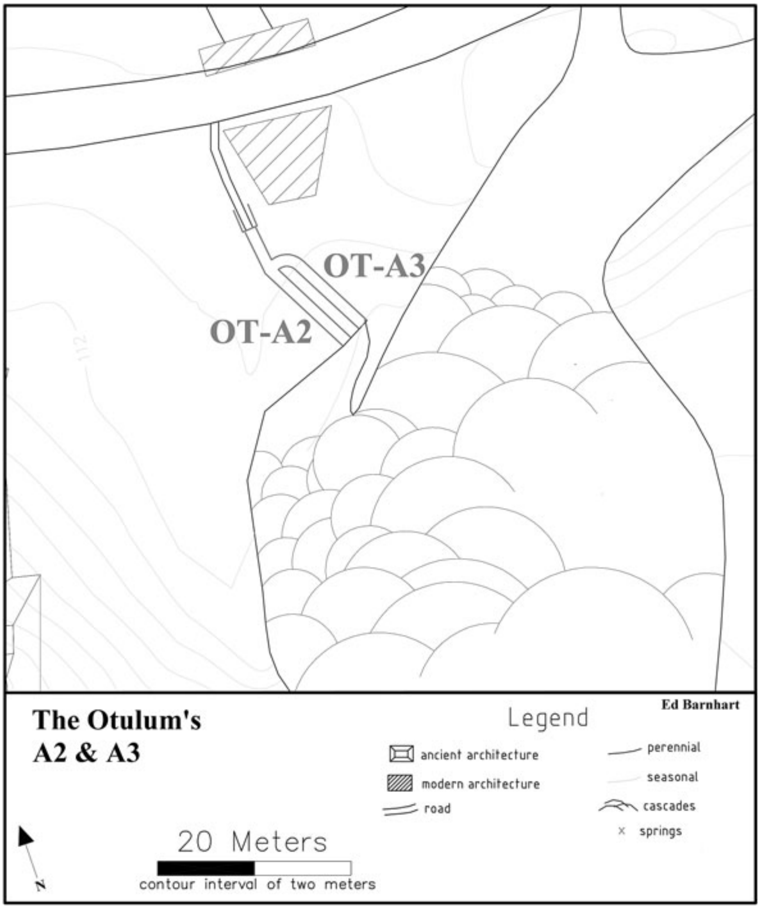


Fig. 18 Map of OT-A2 and OT-A3

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 is 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 a cluster of buildings referred to as Museum Group and eventually joins the waters of the Michol River. It is interesting to note that Palenque sits on a watershed divide between tributaries of the Grijalva and Usumacinta Rivers, two of the largest river systems in all of Mexico.

Results: distributed modeling urban hydraulic structures

OT-A1: flood response and hydraulic capacity

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

Fig. 19 The interior of OT-A2, showing the exit of OT-A3 on the *left*

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.

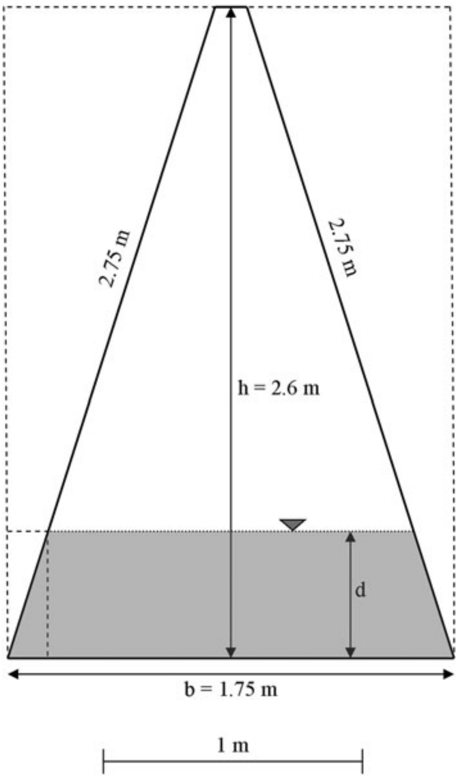
First, the *flow rate* (Q) of OT-A1 (a trapezoidal conduit) needed to be established. The flow rate is simply the volume of fluid that passes through a given cross-section per unit time (e.g. m^3/s.) (Linsley et al. 1982; Viessman and Lewis 1996).

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) (Fig. 20).

In order to better gauge the functionality 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. A design based on the probable maximum stormflow or maximum flood is called the *critical-event method* (Linsley et al. 1982). Table 3 is a flow chart containing the details of the estimated flood capacity (light gray) of the aqueduct and threshold for plaza flooding (dark gray) at OT-A1. There were ten instances within a 100-year period that OT-A1 exceeded capacity (>3.1 m in height), equating to a 10-year flood design.

The difference in over-capacity of the conduit (>2.6 m) and plaza flooding (>3.1 m) is the additional 0.5 m between the top of the aqueduct and the plaza floor (Fig. 21). The flow rate was calculated for the construction phase of OT-A1 with the smallest area. The dimensions of Section C (Table 3; Fig. 20), the third construction phase of OT-A1, were

Fig. 20 Hydraulic design of OT-A1



used to calculate the flow rate. The smallest section of a closed conduit is always used because it will cause the most restrictive flow conditions.

Although one cannot be sure that the Maya fully understood the consequences, the construction phase added to Section C was much wider. As a result during a critical flood event the wider entrance of Section D would allow significantly more water to enter the aqueduct. As the flood waters continued through the aqueduct the smaller entrance to Section C would have slowed and rapidly filled to beyond capacity. These unfavorable conditions at Sections D are the most likely cause of the collapse of the southern few meters of Section C and the entire length of Section D (Figs. 8, 12, 13).

It is useful to compare both the flow rate and flood response of the Otolum with and without the aqueduct, OT-A1. Figure 22 is an approximation of the Otolum in an open channel. Table 4 is a flow chart containing the details of channel capacity (light gray) and plaza flooding (dark gray) for the Otolum flowing assuming 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 height) five times and flooded the plaza (>0.50 m in height) on 16 separate occasions within a 100-year period.

OT-A1: drought response and low flow characteristics

The same extreme event analysis was used to examine the frequency of occurrence of the low-flows events in the record. Even during the worst simulated meteorological drought the Palencanos had substantial streamflow (0.006 m^3/s) according to the watershed model.

Table 3 Rating table for OT-A1

Depth (m)	Channel Slope	Flow Area (m^2)	Wetted Perimeter (m)	Hydraulic Radius (m)	Flow (m^3/sec)	Historic Flows (m3/sec)	Simulated Date
2.70	0.20%	2.363	7.448	0.317	1.639	1.654	AD 10/24/608
						1.665	AD 9/10/654
						1.675	AD 10/14/691
						1.682	AD 2/4/625
						1.688	AD 1/13/662
2.80	0.20%	2.450	7.659	0.320	1.710	1.710	AD 10/15/660
						1.741	AD 8/1/691
						1.749	AD 10/13/683
						1.763	AD 12/16/612
						1.765	AD 10/14/606
						1.765	AD 12/26/644
2.90	0.20%	2.538	7.870	0.322	1.780	1.788	AD 10/11/676
						1.795	AD 10/22/636
						1.797	AD 12/15/612
						1.800	AD 10/25/608
3.00	0.20%	2.625	8.081	0.325	1.851	1.856	AD 11/9/699
						1.864	AD 10/18/604
3.10	0.20%	2.713	8.292	0.327	1.921	1.928	AD 10/5/684
						1.929	AD 10/31/691
						1.938	AD 10/25/626
						1.959	AD 10/16/602
3.20	0.20%	2.800	8.503	0.329	1.992	2.037	AD 10/26/658
3.30	0.20%	2.888	8.714	0.331	2.063	2.073	AD 11/3/619
						2.077	AD 10/24/614
						2.079	AD 12/30/619
						2.092	AD 10/5/626
3.40	0.20%	2.975	8.925	0.333	2.134	na	na
3.50	0.20%	3.063	9.136	0.335	2.205	2.355	AD 12/25/653
						2.383	AD 10/29/671
						2.443	AD 10/5/609
						2.775	AD 10/15/684
						2.875	AD 10/29/630

At capacity (light gray); plaza flooding (dark gray)

Approximately 500,000 l of water per day were available through the Otolum Stream alone. It should be noted that archaeologists have always thought Palenque was unique in that there were a complete absence of water storage features. Although not a conventional storage feature when compared to other Maya sites (e.g. Tikal, Calakmul, or Caracol) with reservoirs, modified *aquadas/bajos*, etc., OT-A1 could have easily stored water during times of prolonged drought, by temporarily damming the outlet just 1 m in height and allowing the water to partially fill the aqueduct, the Maya could have stored at least 225,000 l of fresh water during low-flow periods. Given the continuous flow, the water would not become stagnant, because of the relatively steady spring flow from the upland

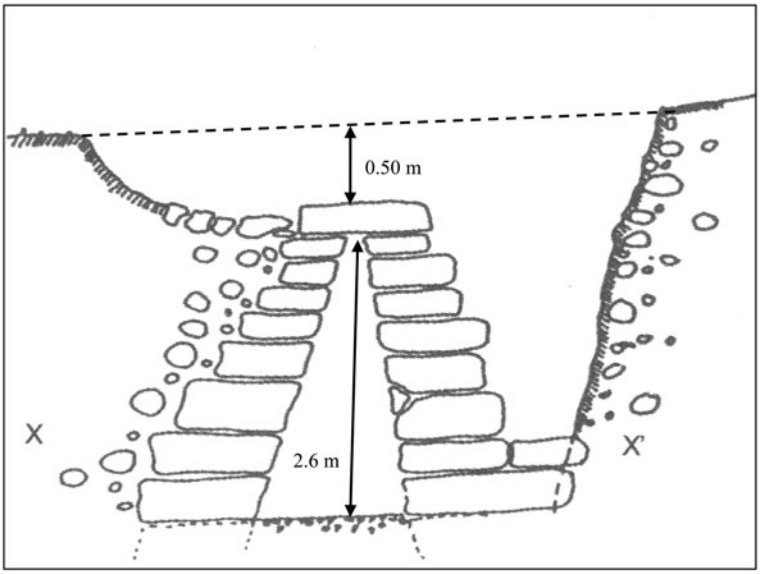


Fig. 21 Cross section of OT-A1's Section *C*. This is the section that was used to determine the flow rate

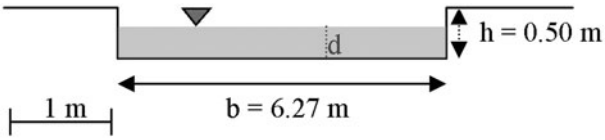


Fig. 22 The Otolum in an open channel

part of the watershed. This excess flow would also be important as it make its way over the cascades of the escarpment to be utilized for irrigating crops in the plains.

Conclusions

We see from the simulation results that the unique urban landscape of Palenque affected the hydrology of the Palenque Watershed. The hydrologic conditions set the stage for building hydraulic features such as aqueducts that increased the urban area at Palenque. In terms of modern engineering practice the hydraulic features seem to have been built to withstand a 10-year flood event as determined from the watershed model. It was found that the impermeable cover of the paved plazas along with deforestation produced much higher peak flows in the rainy season and lower flows during the seasonal drought. The latter occurred even though the actual input events for modern and historical conditions showed relatively small changes in precipitation and temperature. Thus small to moderate changes in climate coincident with moderate changes in landcover tend to amplify extreme events from floods and droughts, although the most extreme drought conditions did not dry up the channel.

Table 4 A flow chart for 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
0.50	0.20%	3.135	7.270	0.431	1.779	1.788	AD 10/11/676
						1.795	AD 10/22/636
						1.797	AD 12/15/612
						1.800	AD 10/25/608
0.51	0.20%	3.198	7.290	0.439	1.836	1.856	AD 11/9/699
						1.864	AD 10/18/604
0.52	0.20%	3.260	7.310	0.446	1.893	1.928	AD 10/5/684
						1.929	AD 10/31/691
						1.938	AD 10/25/626
0.53	0.20%	3.323	7.330	0.453	1.950	1.959	AD 10/16/602
						1.965	AD 12/27/619
0.54	0.20%	3.386	7.350	0.461	2.008	2.037	AD 10/26/658
						2.073	AD 11/3/619
0.55	0.20%	3.449	7.370	0.468	2.067	2.077	AD 10/24/614
						2.079	AD 12/30/619
						2.092	AD 10/5/626
						2.355	AD 12/25/653
						2.383	AD 10/29/671
						2.443	AD 10/5/609
						2.775	AD 10/15/684
						2.875	AD 10/29/630

At capacity (light gray); plaza flooding (dark gray)

Interestingly, the watershed's response to the simulated hydrological droughts are contrary to the great "megadrought" theory causing Maya abandonment put forth over the last 10 years (Curtis et al. 1996; Gill 2000; Haug et al. 2003; Gill et al. 2007). According to the scenarios presented here the Maya of Palenque would not have been 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. These results demonstrate the utility for watershed modeling to reconstruct hydrologic conditions under historical climate and landuse change. It seems clear that part of understanding the complexities of ancient water management systems requires a basic understanding of the site's watershed hydrology.

The utilization of the simulated landscape and climate scenarios allowed us to test the hydraulic design and response of Palenque's largest aqueduct, OT-A1, to extreme meteorological and hydrological events. This single urban feature could both limit plaza flooding during rain events and store water during times of hydrological drought, and furthermore lends credence to the idea that the Maya of Palenque had an empirical understanding of hydrologic and hydraulic urban engineering.

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