Water and sustainable land use at the ancient tropical city of Tikal, Guatemala

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The access to water and the engineered landscapes accommodating its collection and allocation are pivotal issues for assessing sustainability. Recent mapping, sediment coring, and formal excavation at Tikal, Guatemala, have markedly expanded our understanding of ancient Maya water and land use. Among the landscape and engineering feats identified are the largest ancient dam identified in the Maya area of Central America; the posited manner by which reservoir waters were released; construction of a cofferdam for dredging the largest reservoir at Tikal; the presence of ancient springs linked to the initial colonization of Tikal; the use of sand filtration to cleanse water entering reservoirs; a switching station that facilitated seasonal filling and release; and the deepest rock-cut canal segment in the Maya Lowlands. These engineering achievements were integrated into a system that sustained the urban complex through deep time, and they have implications for sustainable construction and use of water management systems in tropical forest settings worldwide.

archaeology | resilience | intensification | tropics | paleoecology

How human populations have used currently threatened environments in a sustainable and managed manner over time can be addressed through archeology and its multidisciplinary collaborations (1). Today, in the geographical core of Classic Maya civilization (A.D. 250–800)—the tropical forest of Petén, Guatemala (a subtropical moist forest in the Holdridge system) (2)—short-fallow slash-and-burn agriculture, logging, and cattle ranching have significantly affected portions of the ecosystem and limited access to potable water (3, 4). Nevertheless, within this biophysical context, one of the earliest and most long-lived tropical civilizations flourished. Maya water and land uses were significantly affected by highly seasonal precipitation and karst physiography, which accommodated little perennial surface water. In response, the ancient Maya developed a complex system of water management dependent on water collection and storage devices. The hydraulic system was cleverly tailored to the biophysical conditions and adaptively engineered to the evolving needs of a growing population for more than 1,000 y (5–7). By identifying how a tropical setting was altered using a Stone Age technology, methods and techniques associated with long-lived and sustainable landscape engineering are revealed. Establishing baseline assessments of human impact on an environment before the extraction and depletion of resources by recent technological advancements may allow an evaluation of current technology's effects and the origins of unintended ecological as well as social consequences.

The ancient low-density urban community of Tikal, Guatemala, was recently examined by way of water and landscape assessments (8–10).* Our intent was to document the evolution of a tropical wet–dry engineered landscape (11) and the manner in which the site was altered from its initial colonization (Middle to Late Preclassic, 600 B.C. to A.D. 250) to the community's apogee (Late Classic, A.D. 650–800) followed by its rapid near abandonment in the late ninth century (12, 13). Six ancient reservoirs associated with four separate topographical catchment areas were examined within the 9-km^2 core, referred to as Central Tikal, previously mapped by the University of Pennsylvania Tikal Project (14)[†] (Figs. S1 and S2). As is typical of many of the largest Maya centers located in the heartland of present day Petén, Guatemala, Tikal was positioned some distance from major perennial stream or lake access and dependent on sizable reservoir construction associated with elevated catchments (5–7).

The longevity and resilience of the ancient Maya over a 1,500-y period reveal significant cultural and environmental adaptations to a seasonally wet–dry tropical ecosystem beset by a sizable population—a condition with contemporary implications. Population estimates for the southern Maya Lowlands at A.D. 700 suggest as many as 5 million people or a density one full order of magnitude greater than supported in the region today (7, 10); ironically, this setting is under environmental siege by a much reduced contemporary population—one organized very differently than in the past (3, 4). Early colonization of the ridge on which the subsequent site of Tikal resides was spurred by springs at the head end of a natural ravine that was subsequently widened and dammed. Architectural construction and paving accompanying a population boom in the Classic period required large water storage tanks in the site's central precinct filled by directed seasonal runoff, but the pavements unintentionally prevented the normal recharging of the springs that had originally attracted colonists. Although the recharge and filtering of the pure water source was significantly curtailed, many more times the amount of water available to the growing population was now contained in the formal reservoir system.

Results

Our investigations concentrated on the water management features on the southern side of central Tikal. At the summit of the north-to-south–oriented ridge defining the upraised central precinct of Tikal, three prominent arroyos cut west to east through the site area (Fig. 1). The southernmost arroyo was deeply incised and displays significant human alteration, although each of these drainages was dammed or had their flow redirected. The Temple, Palace, and Hidden Reservoirs represent a descending chain of artificially dammed tanks that were markedly widened to increase storage capacity as well as provide necessary construction fill for

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*Low-density urbanism contrasts with highly nucleated definitions of city identified with many archaic states in semiarid settings elsewhere in the world. Population estimates range from 60,000 to 80,000 people within a 120-km^2 area.

[†]A dry core from Inscription Reservoir yielded four radiocarbon dates, and the most recent was contemporanous with the core from the Tikal Reservoir and likely pre-Maya. The small residential Madeira Reservoir was not further explored, although previous excavators indicate Early Classic to Late Classic usage.

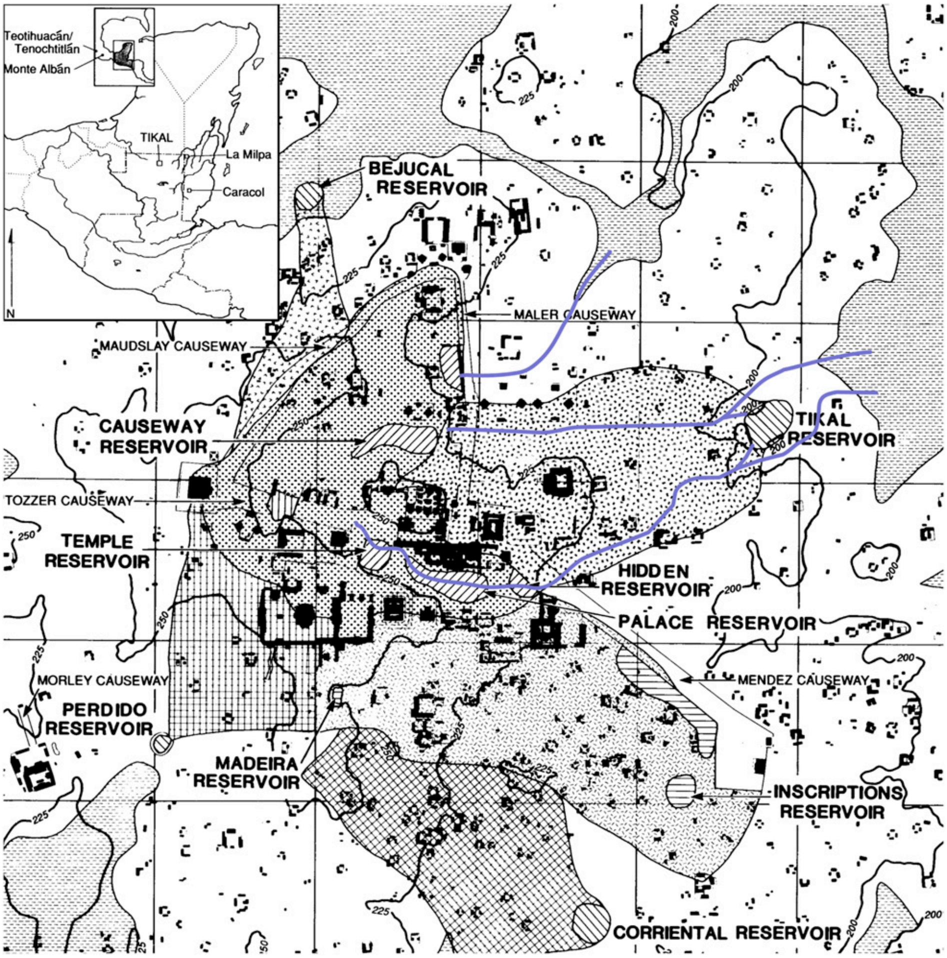

Fig. 1. Map showing the main catchments and associated reservoirs at Tikal, Guatemala. We focused on six reservoirs in the southern one-half of the area—Temple, Palace, Hidden, Corriental, Perdido, and Terminos Reservoir (not shown) to the east of Central Tikal (Fig. S2*B*). Three prominent arroyos are shown in blue. From ref. 15. Reprinted with permission from AAAS.

building massive pyramids and palace-like structures in immediate proximity (Figs. 2 and 3). Expansive plaster surfaces covering plazas and courtyards sealed the otherwise fractured limestone bedrock and were canted to direct runoff into these tanks, an adaptation that prevented the natural percolation of surface moisture into the porous substratum and concentrated seasonal precipitation for ameliorating annual drought (15). Two other low-lying bajo- or swamp-margin reservoirs—Corriental and Perdido—separated by two independent but adjacent catchment areas were examined through a program of extensive coring and formal excavation (Figs. 1 and 3), although Perdido Reservoir datasets will not be developed here. The Inscription and Tikal Reservoirs, also part of the southern catchment system, received limited attention in this study (14).

Temple Reservoir. Temple Reservoir is the most elevated but smallest public tank, with a conservative volume of 27,140 m^3 (16). Surrounded by some of the most impressive pyramidal structures at the site, together with the feature's circular symmetry and associated silting tank, it was a ritual place (Figs. 2 and 3). Fourteen excavation units were systematically positioned, principally in the upper silting tank, with two dry cores taken from the basal reaches of the silting tank and the low-lying main tank body (Fig. S3*A*) —the latter featuring a poorly preserved clay lining (Fig. S3*B*). Excavation results indicate that the ancient Maya expanded the head end of the natural arroyo by creating an elevated silting tank to the south and west of the original shallow headwater drainage before quarrying the deeper main tank body to the north and east off the original course of the increasingly incised eastward-flowing arroyo. Based on present-day contours and subsurface testing, the Temple Causeway, which separated the Temple Reservoir from the larger Palace Reservoir, was engineered from exposed bedrock with added construction fill to prevent the natural movement of water out of the arroyo head. Four radiocarbon samples (Fig. S3*B*) were taken from the main tank body and indicate a Late Classic (eighth century) remodeling. Another three samples were retrieved from the silting tank (Fig. S3*C*), and both contexts indicate a Late Classic use (Fig. 3 and Table S1). One sample from the main tank excavation unit (OP 7C) (Fig. S3*A*) was associated with a Late Preclassic date; sediments were trapped between the floor of the tank and subsequent matrices, and the former was introduced from earlier activities flanking a late enlargement of the Temple Reservoir (Fig. S3*B*).

A substantial berm separated the silting tank from the main Temple Reservoir, with a constricted 2-m-wide plastered spillway sealing an underlying Late Classic dedicatory burial and an overall vertical drop of 3 m before cascading into the lower-lying basin 8 m below the base of the silting tank (Fig. S3*A*). Of special interest was the amount of water that percolated from one of our test units during the dry season (recharge rate of 7.5 liters/h in April of 2009, the driest month of the year; workmen routinely filled their canteens from this source while it was exposed, preferring it to water available in their village). At 1.6 m below the surface and all cultural deposition, potable water seeped through the profile wall of fine silty sediment—a condition not repeated from our excavations in other reservoirs at Tikal at significantly lower elevations and associated with much larger catchments and tanks (Fig. S3*C*). The Temple Reservoir area positioned at the head end of the ravine may tap a fault spring (17), a source of freshwater available all year and a focused initial attraction for Preclassic settlers. A date of 521–216 B.C. was obtained immediately above the seep interface (all dates recorded by way of a 2-σ calibrated range). Earlier excavations along the exterior

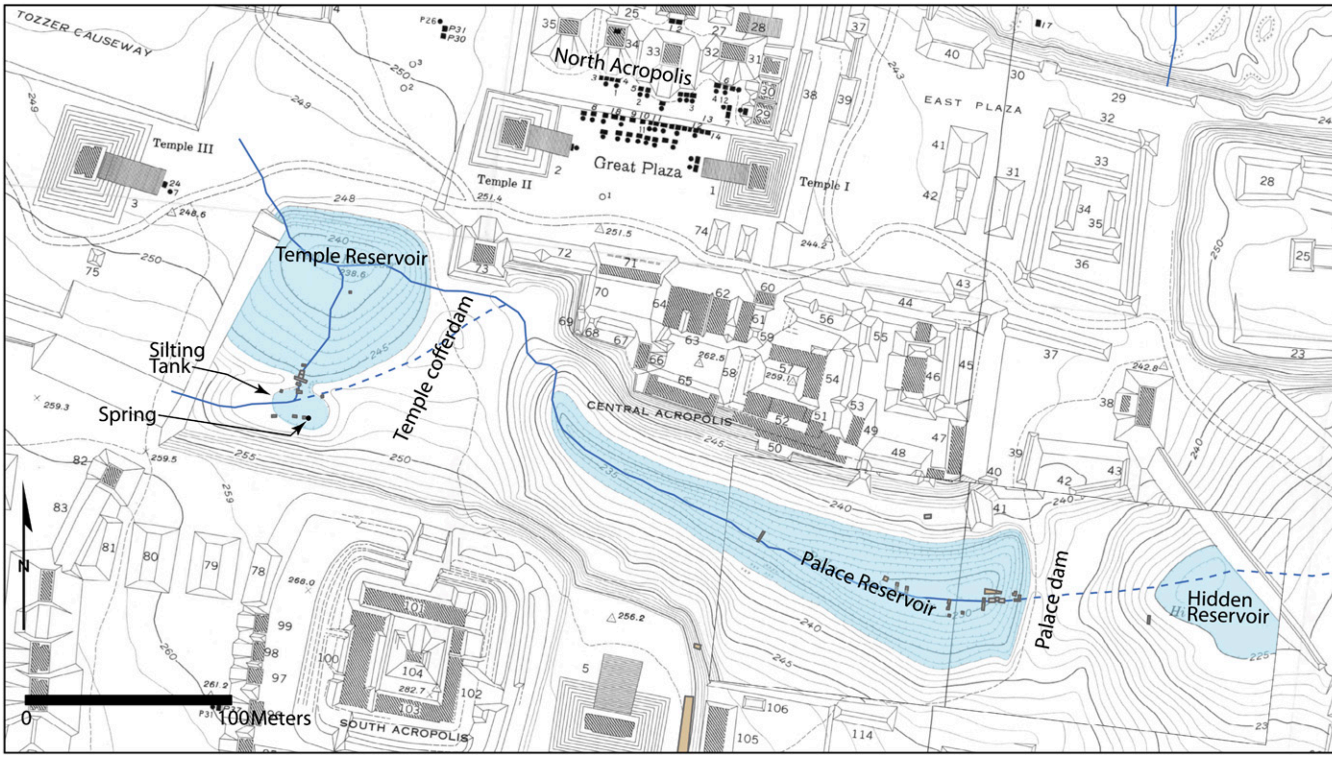

Fig. 2. Temple, Palace, and Hidden Reservoir chain with location of excavations and ancient arroyo drainage. The spring in the silting tank feeding Temple Reservoir and the cofferdam separating the Temple and Palace Reservoirs are indicated. The release sluice gates run through the Palace dam into Hidden Reservoir. A patch of the Palace Reservoir map has been locally georeferenced based on project Total Station and global positioning system measurements. The base map is courtesy of the Penn Museum (16).

western margins of the reservoir revealed an elaborate ramp dating to the Late Preclassic (18), contemporaneous with the North Acropolis (19) and the Mundo Perdido complex (20) that wraps around the head end of the arroyo and spring (Fig. S1). Ironically, with the continued growth in population and the built environment, water demands increased markedly, resulting in extensively paved surfaces designed to direct and retain seasonal runoff (14). This condition, however, capped the recharge potential of the elevated spring and significantly altered the amount and kind of filtered groundwater issuing from the elevated margins of the arroyo.

Palace Reservoir. The Palace Reservoir extended from the lower margins of Temple Reservoir to the well-defined Palace Causeway or Dam, and it once contained an estimated water volume of 74,631 m^3 (21). Thirteen discrete excavations and one dry core (Fig. S4*A*) revealed a diminutive basal channel ~1-m deep associated with the original arroyo drainage and filled with thin

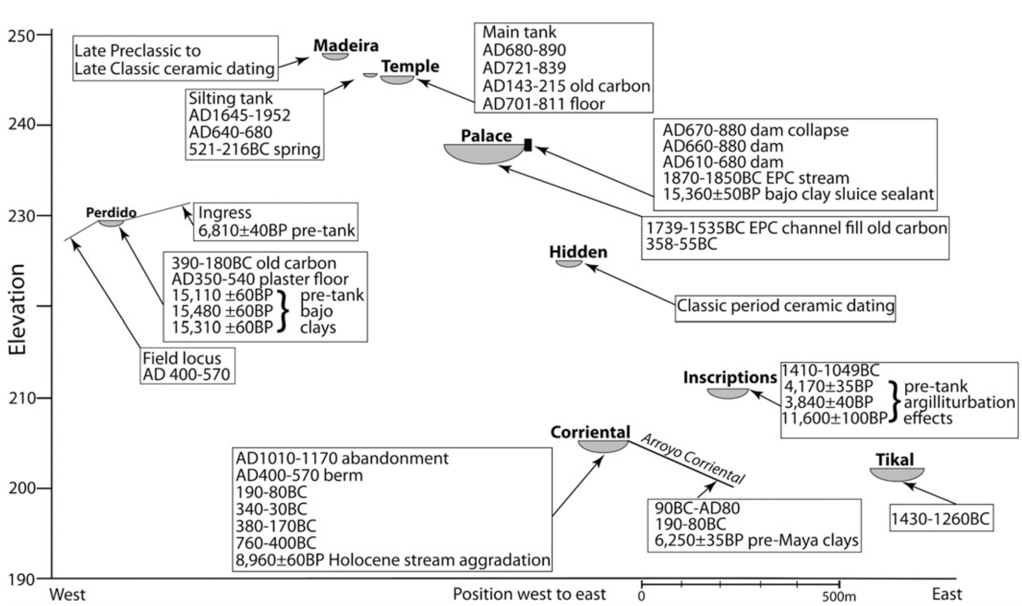

Fig. 3. Cross-sectional schematic profile of southern one-half of the Tikal hillock, with reservoirs positioned by elevation and associated with dated stratigraphic sedimentational histories (Table S1).

alternating lenses of granular sand and silty clays, interpreted as episodes of seasonal storm flows followed by less energetic deposition (Fig. S4 *B* and *C*). Stratigraphically dating to the initial colonization of the Tikal hillock or sculpted plateau in the Middle to Late Preclassic, the bedrock channel was modified by way of a carved limestone bench or landing (Fig. S4 *B* and *C*) on the immediate northern bank below the precipitous 10-m climb to the upper crest of the ancient ravine. The modified channel bottom dated to 358–55 B.C., although a more elevated stratum yielded a 1739–1535 B.C. date—the latter reversal interpreted as an earlier matrix eroding from the adjacent slope and associated with the original unaltered arroyo (see below). Because banded sediments filled the ancient channel and covered the carved landing without signs of dredging, seasonal access to the flow of water through the ancient ravine was neglected at some point.

By the Classic Period, the Palace Dam was constructed to contain the waters that were now directed from the many sealed plaster surfaces in the central precinct. With sloping basal dimensions of 80 × 60 × 10-m high and a conservative volume approximated at 14,000 m^3, this gravity dam represents the largest hydraulic architectural feature known in the Maya area, and it is second only to the huge Late Preclassic/Early Classic Purrón Dam in Mexico's Tehuacán Valley for greater Mesoamerica (22). Given the narrow course of the incised prequarried arroyo (Fig. S4*C*), it is likely that portions of the original escarpment were left in place to form part of the dam. Trenching efforts into the feature suggest an early cut-stone building effort followed by a massive wall of rubble and earthen construction, the latter sealed with cut veneer stone (Fig. S5). Sluice gates through the massive feature were poorly preserved, but there are evidential suggestions of vertically stacked openings no more than 30 cm in diameter defined by slab stones secured with plaster and imported dark viscous bajo clays (Figs. S5 and S6). These clays were dated to 15,360 ± 50 C14 y BP (Fig. 3 and Table S1), and they were likely sourced to Pleistocene surfaces found deeply buried in the nearby Bajo de Santa Fe.

Water discharge through the dam did not entail massive openings—gates were subject to intense erosion pressures but gradually released near the ponded surfaces associated with dropping water levels (Fig. 4*A*).[‡] Dating of the dam comes from matrices sealed by elongated cut-stone collapse debris both toward the end and immediately after the use life of the feature (the three contexts sampled providing the same A.D. 670–880 dates; OP 6L and Op 6Q) (Figs. S4*A* and S5). Excavations revealed a 10-cm-thick sediment deposit with 11 distinct microstrata sealed beneath dam collapse (Fig. 4*B*); darker strata were deposited during the annual dry season when water levels dropped, concentrating organic matter, whereas lighter strata were calcite clay bands laid down by runoff moving across plaster in the rainy season. Predictably, partial dam collapse took place during a rainy season inundation. A 1-m-thick apron of fine silty clay was heaped over the collapse debris, suggesting a subsequent crude Late or Terminal Classic period repair attempt. The Early Preclassic (1870–1850 B.C.) arroyo channel (OP 6L) (Fig. S5) was likely buried by sediment backed up by a small interior dam built in the Early Classic given ceramic associations and evidence for an initial diversion feature (OP 6U) (Fig. S5). Sometime thereafter, the present Palace Dam was constructed, falling into disrepair and partial collapse by the end of the Late Classic period. A flagstone pavement lining was found immediately above the reservoir floor on the southern slope of the tank to aid in seepage control (Fig. 4*C* and Fig. S4*A*) and is likely associated with Late Classic expansion of the reservoir.

The isolation of the elevated Temple Reservoir from the more voluminous Palace Reservoir suggests that the dam dividing these two tanks functioned as a coffer when dredging—or repairs were needed in the lower reservoir—as indicated by the overall paucity of sediment in the huge Palace tank. After routine maintenance, the collected waters from Temple and Palace Reservoirs were subject to a controlled release into the low-lying Hidden Reservoir before dropping a total of 45 m into and around the bajo margin Tikal Reservoir (15) (Fig. 1 and Fig. S2*B*). One wet core was taken from the lowest lying Tikal Reservoir (Fig. S2*B*), yielding only an Early Preclassic date (1430–1260 B.C.) (Fig. 3 and Table S1). The apparent integration of this tank with the above chain of reservoirs, however, suggests a contemporaneous date, with the overall system well-defined by the Late Classic (15, 16, 21).

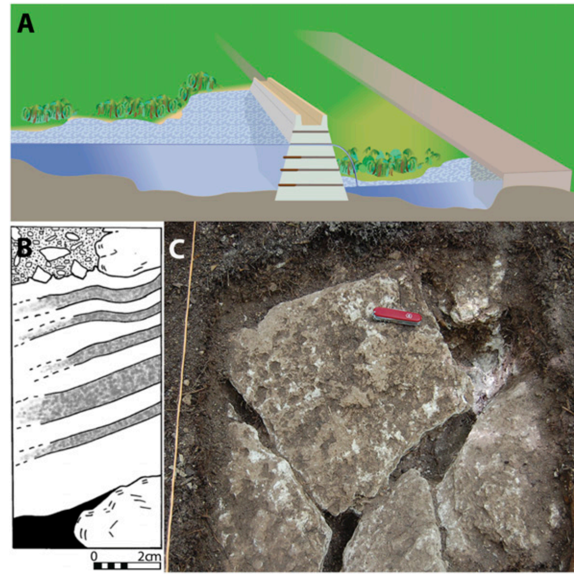

Fig. 4. Palace Reservoir depictions. (*A*) Schematic of dam function showing vertically stacked sluice gates (prepared by R. Weaver). (*B*) Microstratigraphy beneath dam collapse debris (OP 6Q) (Fig. S5). (*C*) Flagstone pavement lining reservoir floor (northernmost flagstone) (Fig. S4*A*).

Corriental Reservoir. Another water catchment and reservoir system was positioned south of the chain of reservoirs detailed above (23) (Fig. 5*A*). The Corriental Reservoir is one of four bajo-margin tanks within Central Tikal, situated just above isolated, seasonally inundated depressions (pocket bajos) that were likely the foci of intensive farming (21). Corriental was circumscribed by a 4- to 7-m-high berm with two ingresses or gates and a complex egress. Thirty dry cores and nine trenches (Fig. S7*A*) revealed the feature's shape, an estimated maximum capacity of 57,559 m^3 (21), and the tank's sedimentation history (Figs. 3 and 5 *A* and *B*). A basal date of 8,960 ± 60 C14 y B.P. underlies the reservoir at 4-m below surface datum (BSD) and was associated with a buried soil identified by a very low δ^{13}C signature indicative of a natural drainage having coursed through this forested area before Maya colonization (Tables S1 and S2). Wetter conditions in the Holocene generated subsequent erosion within the natural catchment and an initial aggradation of sediment by the Middle Preclassic (760–400 B.C.). Evidence from the interface between the built berm and bedrock indicates a date of A.D. 400–570 (core 17) (Fig. S7*A* and Table S1) for this construction, a feature at this northern upstream margin of the tank's circumference established as much for diverting and directing flow as containment. Excavation results and X-ray diffraction (XRD) analysis of both the berm and reservoir sediments indicate limited dredging and a source other than the infilling reservoir matrices for the berm's construction (23).

The sediments in the reservoir show stratified layers of quartz sands interbedded with laminated organic clays (Fig. 5*B* and Fig. S7*B*), the latter indicating slow-moving recharge. Given the lack of natural quartz sand sources within the greater Tikal region and their frequent identification in strata within several of the reservoirs (Fig. 5*B* and Figs. S3*B* and S4 *B* and *C*), deliberately

[‡]Logs used as grand bottle brushes are posited to have allowed the removal of silt accumulation with possible vertical inspection by way of limited access manholes at the summit of the dam. Causeway surface excavations by our teams were not possible.

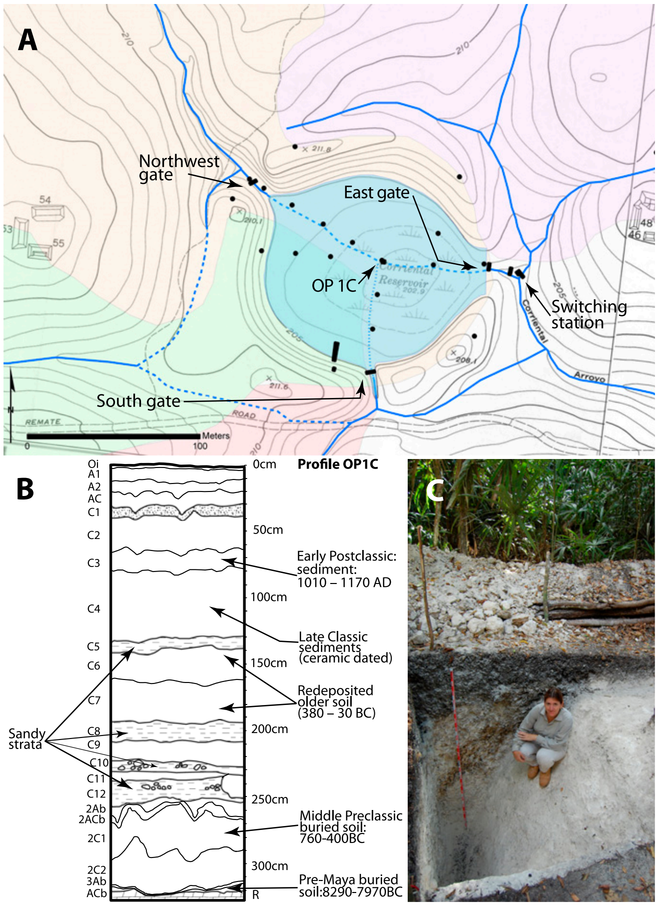

Fig. 5. Corriental Reservoir depictions. (*A*) Plan map. The principle catchment is to the northwest, with the northeastern catchment diverted away from the reservoir during the Classic Period. (*B*) Profile of the sediment control unit for correlating coring operation; dates in the brackets are from core 8 (Fig. S7*A*). (*C*) Canal exposure (OP 1G) (Fig. S7*A*). The base map is courtesy of the Penn Museum (16).

positioned sand boxes are suggested to have been located above several of the ingresses, directing catchment runoff into a tank and acting as a form of filtering to create degrees of potable water (24). Low δ15N isotopic signatures suggest an absence of algal blooms related to pollutants in reservoir waters (23) (Table S2). Such features may have been replaced frequently, given the caprice of storm flow from hurricanes and related tropical depressions as well as seasonal variations in rainfall. A terminal date of A.D. 1010–1170 (Fig. 5*B*) for reservoir use is recorded at 65 cm BSD, indicating some Early Postclassic occupation of the catchment area (12, 13). Given the steepness of the catchment gradient with its associated erosional rates and a reservoir use life of over 1,000 y, the amount of sedimentation into the depression was minimal, with little evidence of dredging—a condition unlike that apparent in the summit arroyo tanks. Although only the Temple Reservoir manifests a well-defined silting tank, negative evidence suggests that shallow silting tanks were located above the inflow gates of all reservoirs (25, 26).

Of special note were two unusual features identifying an East Gate ingress and egress posited as a seasonally adjusted switching station or control point for one of the inflowing catchments recharging the Corriental Reservoir (Fig. 5*A* and Fig. S7*A*). A 2-m-deep canal was sectioned immediately above the ingress, revealing a V-shaped channel excavated through the indurated bedrock and believed to date to the Late Preclassic, with inflowing catchment waters directed into a shallow and early version of the tank (Fig. 5*C*). The end of the Late Preclassic has been frequently associated with an intensified drought cycle (27). Water recharge into the reservoir was closed from this source by way of an expedient though substantial earth-moving effort in damming the East Gate, only to resume infilling with runoff from the other major catchments entering from the Northwest and South Gates (Fig. S7*A*).[§] During the dry season, waters are posited to have been incrementally released by dismantling the earthen dam and switching the flow out of the tank at this East Gate location. Sometime after the Late Preclassic, a period of greater precipitation (27), the deep V-shaped ingress canal was carefully infilled and sealed with a dense composite of crushed limestone cement, not unlike the matrices used in plaza floors or portions of the most elaborate weight-bearing wall sections at uptown Tikal, thus preventing the redirection of waters into the tank (the decommissioning of the canal segment into the reservoir corresponds sequentially with the water diversion function of the northern berm construction). A postulated plug or dam (Fig. S7*A*) was added to complete the circumscribing berm at the former East Gate switching station, although it has since eroded out as a result of the area's natural contours and the present-day corriental or rushing movement of rainy season waters from this quadrant of Central Tikal [the work by Carr and Hazard (16) noted the incidence of construction stone found below the East Gate drainage and suggest a post-Maya collapse of the plug].

Discussion

Ancient climatic instability is recorded in the region, with several researchers suggesting drought peaks during the Terminal Preclassic period in the second century (27, 28) followed by conditions more like today or until the 9th and 10th centuries, when a series of droughts (29–31) aided in severely fragmenting the established political and social order (32). Our work suggests that the system of reservoirs and early water diversion features were established at the onset of a Terminal Preclassic drying trend, an adaptation that likely helped Tikal and some other centers survive, whereas many others were abandoned (27). Subsequent periods of water redirection indicate the decommissioning of the Corriental Reservoir switching station and the infilling of the carved bedrock canal leading into it, a reflection of the greater abundance of water during the Classic period. To accommodate the need for potable water, sand filtration beds were built at the inflow gates of several of the reservoirs. The water management system was highly resilient and adaptable in the face of both natural and human deranging forces until about A.D. 900.

Coring operations have revealed an elevated presence of minerals derived from volcanic ash and ejecta in the reservoirs (23). Originating hundreds of kilometers away, ash enriched the region's soils and likely provided the temper for a huge investment in ceramic production throughout the Maya region (33). The frequency of these volcanic events and their short-term negative effects suggest the need for a social mechanism to mobilize labor to remove as much of this material as possible from the surficial water catchment system. Nevertheless, the most persistent water quality concern was quotidian excreta and the human-affected, organic waste that influenced water potability within the engineered microwatershed (24). Although silting tanks and sand filters helped in controlling both inorganic and organic pollutants, respectively, water may have been boiled or more likely, combined with carbohydrates, such as maize gruel, and fermented to accommodate thirst (34).

Isotopic assessments of bulk carbon in reservoir sediment reveal significantly lower $\delta^{13}C$ values in Central Tikal and higher $\delta^{13}C$ values on its periphery during most periods of occupation (Tables S1 and S2). These findings suggest less maize agriculture or presence of other C4 plants immediately within the site center, with potential garden plots farther away. Although the use, variety, and abundance of tree species through time are currently

[§]Excavations at the East Gate revealed an elevational drop from the bottom of the V-shaped canal into the upper edge of the Late Preclassic tank of 30 cm. The drop from this East Gate lip or elevated margin to the basal Late Preclassic reservoir depths was at least 1 m.

being studied, previous research indicates that the ancient Maya of Tikal—at least leading up to the Late Classic period—were conservative in their forest management practices (35). Given the steepness of Tikal's topography and the near absence of terracing, whatever vegetation covered the drainages surrounding the reservoirs seems to have anchored soils and slowed erosion—a condition apparent in the relatively slight amount of sediment infilling into the bajo-margin reservoirs for over a millennium.

Hydraulic and potability studies are crucial for understanding urban centers, especially areas where little precipitation is available during 3–5 mo of the year (2, 15). The low-density urban conditions at Tikal (8, 9) were accommodated by the adaptation sustained for more than a millennium. The hydraulic system accretionally developed dependent on the interplay between the evolving built environment and the biogenic demands of an increasingly anthropogenic forest and soilscape. These relationships were complicated by climate change, the distribution of reservoirs throughout the site, and the clever modification of the drainage system; a highly resilient urban landscape may have hastened reservoir construction at the end of the Late Preclassic during extended drought conditions, changes that subsequently resulted in a different set of water diversion practices associated with greater rainfall. The system was resilient and sustainable based on a Stone Age technology, which prevented an overexploitation of the biophysical resources undergirding water access.

Although the current intent for creating a more productive use of natural resources is driven by improved technologies for extracting and distributing water, other pathways to enduring longevity exist. Returning to past life ways is not a sought or viable option, but a deeper understanding of simple technologies and associated labor allocations on an engineered landscape could curb some of the unintended consequences affecting today's environs. Archeology is in a position to recognize low-technology adaptations—as assessed by current measures of technology—systems noted for their resilience and sustainability over deep time and based on their reduced impact on the biophysical environs. Today, these simple systems are consistent with conservation efforts (36) and warrant attention in situations less accommodating of Western technological breakthroughs or access to limited—even unobtainable—energy sources. Perhaps by assessing the adaptive behaviors of our distant human ancestors and their engineered landscapes, we can better inform our own suite of environmental options and degrees of resilience for the future.

Materials and Methods

Our work reveals a representative sample of the water catchment and reservoir system through time at Central Tikal (15, 21). Other tests were conducted beyond the core, principally along an existing eastward transect (37), but they are not discussed here (Fig. S2). This research involved several methods and approaches inclusive of both dry and wet coring of ancient reservoirs and natural depressions, conventional excavation and surveying techniques, and a suite of paleoenvironmental analyses. Both previous studies and ongoing botanical assessments of past and present ecosystems complement the water management investigations described (35). To date, 45 accelerator mass spectrometry radiocarbon dates from key strata within reservoirs and related contexts provide our principle chronological control, although redeposited ceramics of known ages provide terminus postquem assessments of human use. Because of the extensive and exclusive use of wood for cooking fires, field clearance, kiln firing, and lime plaster production during the construction and maintenance of Tikal, slight but continuous charcoal rain on the surfaces of the often undredged tanks provides useful dating contexts.

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