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Ertsen, Maurits; Wouters, Kyra

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OVERVIEW

The drop that makes a vase overflow: Understanding Maya society through daily water management

Maurits W. Ertsen | Kyra Wouters

Water Resources Management, Delft University of Technology, Delft, The Netherlands

Correspondence

Maurits W. Ertsen, Water Resources Management, Delft University of Technology, Stevinweg 1/PO-Box 5048, 2628 CN Delft/2600 Delft, The Netherlands.

Email: m.w.ertsen@tudelft.nl

Water is an important key to understand Maya society, especially water availability within a context of climatic changes. Increasing drought would have pushed the Maya water systems into collapse. This paper studies the Maya water systems from an action-oriented perspective, in order to understand what challenges the Maya had to overcome when dealing with water. The systems found at Tikal serve as main example, allowing comparisons with other Maya sites. In this analysis, hydraulic- and agent-based elements are combined in a model to investigate the performance of the water system within extreme weather conditions and changing human agency. The results suggest that the Tikal water system was able to cope with most of the extreme situations. Furthermore, model results allow proposing that the Maya did not anticipate on short-term changes in external conditions. Generally, in Tikal surpluses of water may have been as important as shortages of water. The extensive system of drains and canals present at Tikal may have been built to move water from the center of the city rather than to supply water to lower situated reservoirs during the dry season. Such a water-removal system could be less centrally orientated and organized than is often argued. This could also mean that organizational structures of water systems of different city centers (Tikal, Calakmul, and Caracol) were more similar than usually assumed.

This article is categorized under:

Human Water > Water as Imagined and Represented

Engineering Water > Planning Water

Science of Water > Water Quality

KEYWORDS

actions, agency, material properties, Maya, modeling

1 | INTRODUCTION

As for other ancient civilizations, water was vital for the Maya. Many have studied the water systems in the Southern Maya lowlands, with varying results (Braswell et al., 2004; Chase & Chase, 1998; Crandall, 2006; Folan et al., 1995; French & Duffy, 2014; French, Duffy, & Bhatt, 2013; Gallopin, 1990; Gill, 2000; Lentz, Dunning, & Scarborough, 2015a; Lentz, Dunning, & Scarborough, 2015b; Lucero, 2006; Lucero & Fash, 2006; Scarborough, 1998, 2006; Scarborough et al., 2012; Scarborough & Gallopin, 1991; Scarborough & Lucero, 2010; Wyatt, 2014). This paper can only reference a subset of the huge number of water-papers for the Maya, but it is obvious that in general water in the Maya area must have been associated with power relations. The shape of the power relations—to which extent elites controlled the water sources more centrally or

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whether households could arrange their own water supply—is still open to debate. A shared (explicit or implicit) assumption in many Maya studies is the suggestion of a close relation between the organizational structure of a water system and the layout of that same system (actually the remnants of structures that have been recovered). System shapes would predict power relations, as suggested by Wyatt (2014). Without suggesting that size, shape, and or another physical dimension of a water system are not informative about possible power relations, we argue that understanding of material properties and their relations to power and control needs to go beyond the built infrastructure. We argue that the actions needed to manipulate the water flows within infrastructure are key to understand (non)emergence of certain political realities. To put it very simple: actual flows matter (Ertsen, 2010).

We are certainly not the first that study how water movements may be relevant for ancient societies. However, available studies on the Maya—and many other studies for other regions—tend to focus on annual water balances, within which volumes are exchanged without actually studying how these volumes would have to be brought to users. Again, we do not disqualify such larger-scale studies. Hydrological processes that dominate entire regions are certainly relevant when studying water systems—as they are expressions of materiality. Our argument is that such observations of regional patterns should not be too readily associated with specific modes of social arrangements, for example, when relating differences between small-scale (local) and imperial (large) systems to wetness and dryness—in terms of rainfall—of their environment. In dry zones, imperial systems would build on “techno-tasking,” whereas in the wet zones, smaller-scale ‘labour-tasking’ realities would emerge (Scarborough, 2000, 2003, 2005). Basically, the Old world would have yielded technology-based empires, whereas the New world did not go beyond local labor-based communities. We argue that wet labor and dry technology require the same methodological approach, as all worlds are built on local interactions between human and nonhuman agents (Berry, 2014; Dobres & Robb, 2000; Ertsen, 2012, 2016a, 2016b; Gardner, 2007; Hodder, 2012; Knappett, 2011; Latour, 2000, 2005; Martin, 2005; Verbeek, 2006).

We elaborate this notion below in a set of subsequent discussions. First, we take a brief dive into the world of complex societies and relate complexity to infrastructure. Second, we suggest that any societal situation—small-scale, large-scale, hierarchical, or other—would require a similar short-term base for understanding why that situation would (not) become or stay stable. Third, we apply the notions from these two discussions in a first, relatively simple modeling effort for a subset of the many Maya water situations that are available. This model allows us to review what could be done with available data on Maya water systems and suggests some preliminary answers to pertinent questions. After some general observations on Maya water studies, we reflect on the question how to study social complexity.

As such, our paper presents a review of what we know about the Maya water systems by developing an action-based model. In addition, we offer a broader review on the current state of affairs in the field of understanding changes in societies through modeling.

2 | COMPLEX SOCIETY

The issue of water-dependency in the ancient world can provide very useful comparative histories of social complexity and associated water systems (Mithen, 2012). The concepts of “complex society,” “societal complexity,” and “social complexity” are closely related. A complex society is usually defined as a society with hierarchical decision making—typically with a ruling elite supported by bureaucrats—and associated phenomena as administrative and elite buildings in urban settings. Such society—or a society that has signs of societal complexity—is typically described in terms of higher numbers of (unequal) interactions through formalized institutions equaling higher social complexity (Barton, 2014; Contreras, 2017; Flannery & Marcus, 2012; Latour & Strum, 1986; Maisels, 2012; Schwartz & Nichols, 2006; Strum & Latour, 1987; Ur, 2010). A complex society could sustain itself—actually the elites and their administrators—because nonelite groups in society provided the food surplus required to feed the elite.

The close (perceived) relation between (urban) elites and water control has led to water becoming a topic under rather over-arching models such as the “archeology of power,” of which Wittfogel’s model of hydraulic civilizations remains without doubt the most famous attempt (Wittfogel, 1957; see Davies, 2009; Harrower, 2009; Wilkinson & Rayne, 2010). Wittfogel’s large state creating large irrigation works—mainly based on southern Mesopotamia—no longer finds much support. For southern Mesopotamia, gradually developing water systems would have been fundamental to the development of Mesopotamian society in the fourth and third millennium BC (Ertsen & Wilkinson, 2014; Wilkinson, Rayne, & Jotheri, 2015). Within a flat landscape, productive water systems would have developed from a series of small flood recession systems along low-gradient channels on higher-level levees. Mesopotamian elites would have developed from agents that were able to exploit transport connections between communities (Rost, 2015).

Although Wittfogel may not have provided a convincing analysis of ancient Mesopotamia, his linking water, infrastructure, and power still makes sense. As the first author argued in a recent paper on colonial Sudan, power relations are typically channeled through infrastructural media and material agents such as canals, roads, and gold (Ertsen, 2016a, 2016c;

Schouten, 2013). However, Wittfogel neglects to consider that centrally controlled water systems may have developed over many decades or centuries and central control may be less uniform in shape than a single entity would suggest. Even in those systems where we might have a central state that could exert water-related power over larger areas—like the Neo-Assyrian state (Altaweel, 2008; Ur, 2005; Wilkinson, Wilkinson, Ur, & Altaweel, 2005) or the Maya regional centers—we need to study how that power and the associated state-controlled systems were realized on the ground by agents every day. Power or any social structure is not a force out there on its own to be manifested in matter. Social structures like power relations and institutions like states or elites needed to engage with the material to exist, whether with a canal or a text.

When social complexity was “shaped” by different agents, designs, or material realizations were options for human agents to “delegate” certain human desires to artifacts (Van de Poel & Verbeek, 2006; Verbeek, 2006). For actors only having their bodies as resources, building stable societies—in terms of predictable relations to other agents—is rather difficult (Schwartz & Nichols, 2006). In each encounter, group members need to decide who is actually a member, what membership means, what the group might be, how to interact, etc. Age, gender, and kinship are often considered as given (Algazi, 2010), but are object of negotiations between actors: a very “complex” setting. Increasing stability and predictability is acquired through additional resources (Strum & Latour, 1987): certain dress codes that show gender or age, certain symbols that show, and/or claim kinship. With material resources and symbols, negotiation outcomes—of what it means to be member of a group, with a certain gender of a certain age—become equivalent to what society is.

Building social life with the material produces a shift away from complexity to “complication” (Strum & Latour, 1987). A setting is complicated when it is produced in a succession of simple operations, like with computers or water systems. The material allows a certain degree of standardization of negotiations when human actors meet. The symbols one wears, the location one meets the other, the number of gates one needs to pass for such a meeting, all structure the (ongoing) negotiations between actors. Such material arrangements need support, however, in terms of maintenance investment, repair, or redesign. Maya water systems would have required much routine maintenance, and possibly management activities on a regular basis.

As such, in these terms we can study changes in societies over time as a move from complex sociality to complicated sociality—with such a “complicated social situation” being what traditionally is called a complex society (see Figure 1). Realizing infrastructures brings in future users as well (Verbeek, 2006). No one encounters a clean sheet when coming into the/a world. The material represents the relations that predate our arrival, whether we like these relations or not (Ertsen, 2016a, 2016b). Mobilizing matter allows changing weak and renegotiable associations into strong and unbreakable units (Ertsen, 2016c; Schouten, 2013; Strum & Latour, 1987). The water systems of the Maya and their symbols may have been important power structures and indeed deserve closer attention (Lucero, 2002).

3 | ENGAGING THE EVERYDAY

Water and irrigation can bring wealth and stability to communities and nations, but can also harm landscapes and food production on the long term. A narrow environmental threshold may separate stable, irrigated landscapes from unstable,

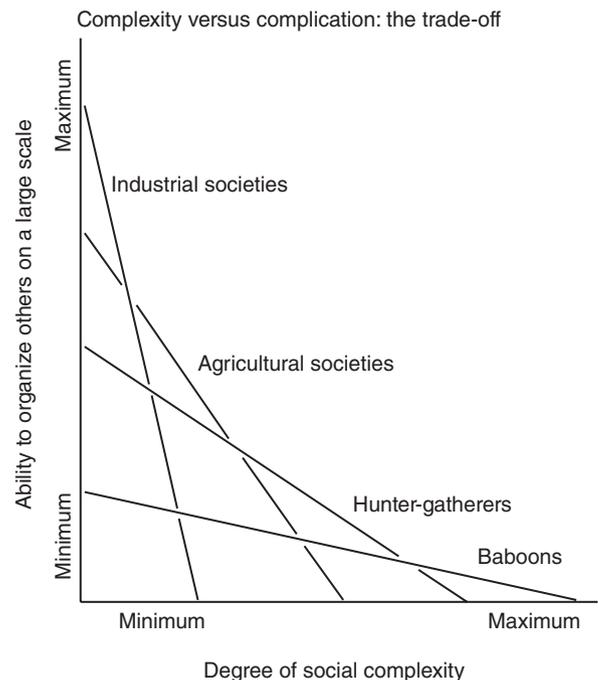


FIGURE 1 Trade-off between complexity and complication (Strum & Latour, 1987). Please note that the definition of complexity is different from the standard discourse; see text for explanation

over-used ones. The archeological record is filled with irrigation-related disasters, many of them related to climatic change—including the Maya themselves (Iannone, 2014; Marcus & Stanish, 2005; McAnany & Yoffee, 2010). Ancient Mesopotamia, one of the earliest examples of socially complex society (in the standard meaning of the concept), would have “collapsed” because of salinization due to over-irrigation. However, this “disaster” unfolded over centuries. Any discussion of societal collapse should incorporate time or rate of change. Many civilizations collapsed or disappeared over the course of centuries; over such long terms societies should be allowed to change without being labeled as unsustainable or as having collapsed. Our understanding of the past would have to be based on the way(s) that agents created the certainty so that their society would not collapse everyday. Creating certainty is directly related to social complexity, as the way in which engagements with other agents are scaled, influences how certainty is created and perceived.

In order to understand how certainty was strived for, traditionally archeology often focused on elite infrastructures, building on the assumption that elites ruled closely over their territories. This elitist focus has been challenged by “archeology of the everyday” and similar notions, with good reason. Societies are realized by all agents, not just by elites. We argue that we need to take just one more step in such focus on the everyday: elite agents also performed their respective agencies on an everyday basis. Realizing solutions—realizing the power to do so—require effort, whether from elites or nonelites. In 20th century Sudan, an intricate conglomerate of colonial rulers, staff of a private British firm, and Sudanese local tenants, changed the Sudanese Gezira plain into a large-scale irrigation scheme. Some 3,000 years earlier, the Assyrian empire shaped its imperial landscape in what is now modern Iraq. These two examples show how “imperial development” was shaped by daily agencies in government offices and muddy fields (Ertsen, 2016c).

Production of imperial space was not stamped out just like that onto the landscape. Creating lasting institutions is hard work for all agents, elite and nonelite (Doolittle, 2010; Marcus, 1989; Robin, 2013; Smith, 2010). States that have shown strong abilities to control the agencies of humans and materials have done so by mobilizing the power to do this continuously. We still would need to explain that observation, though, and study how empire was (re)produced in a process of cooperation, struggle, conflict, and contradiction. Sustaining an (ancient) central state was extremely hard work, which—among others—could result in less uniform irrigation systems in terms of construction, water use, and daily management efforts (Ertsen, 2016c). Irrigated landscapes did not necessarily yield social complex societies either. The south-western USA Hohokam culture, which occupied the lower Salt and Gila basins between 0 and 1450 AD, has signs of increasingly centralized societal control, reflected in settlement structures and ceremonial buildings, but Hohokam society would still not have the hierarchical and elitist structure associated with a complex society (Abbott, 2003; Woodson, 2016). The same may go for the Maya: perhaps there was too much work required to realize all elements assumed to be in complex societies (Wyatt, 2014).

We will not go into detail whether the Maya would qualify to be a “true” complex society. Given the importance of water infrastructure, however, we argue that we need to understand how the different Maya water systems functioned over time, in order to think about their organization, the different engagements that may have been required and other characteristics of Maya society. Given the large diversity in ecology and geology, differences in organizational structure could have been present in the Maya lowlands, but the degree to which these organizational structures varied in terms of what needed to be done to sustain Maya life is still unclear, despite some impressive (modeling) efforts. The MayaSim model is one of the most prominent models available (Heckbert, 2013; Heckbert et al., 2016; Heckbert, Baynes, & Reeson, 2010). It relates population growth, agricultural production, soil degradation, climate variability, primary productivity, hydrology, ecosystem services, forest succession, and the stability of trade networks. The model allows settlements to develop and expand within a landscape, represented as a spatial grid with properties for climate variation and anthropogenic impacts. The model can reproduce spatial patterns and timelines found in Maya archeology.

Within the IHOPE-network (Integrated History and Future of People on Earth), within which many Maya studies have been drafted, a recent modeling effort focused on information networks within the central Maya lowlands (Gunn et al., 2017). With a focus on ceramic influences reflecting decision-making practices of Maya elites over 3,000 years and with pollen analysis providing ecological boundary conditions, six cities were studied. Between 400 BCE and 800 CE, interior cities dominated in the Late Preclassic and Classic periods. Coastal cities became more powerful in the Terminal and Postclassic periods (800–1500 CE) as they could exploit their central position within marine navigation. In the Classic period, a shift in coastal power from east to west seemed to have related to Tikal gaining dominance over the Calakmul-Caracol alliance after 695 CE. The results of the modeling are impressive and provide a clear base for further studies. What we argue, however, is that the study does not engage with the decisions themselves, but with the results of decisions over a long time. Furthermore, as for example can be seen in its recommendations, the study assumes that societies change based on the decisions of the ruling elite.

A third study we like to discuss comes from the community of hydrologists (Kuil, Carr, Viglione, Prskawetz, & Bloeschl, 2016). The study builds on the hypothesis that modest drought periods played a major role in Maya society’s collapse. A major assumption in the model is that the Maya reservoirs were built to support food production—which is not totally certain. The different processes and feedbacks are captured in a mathematical model with nonlinear differential equations that relate the state variables water storage, population density, reservoir storage, societal memory, and vulnerability. It is

precipitation that drives the model. With this stylized model, the authors suggest that a modest reduction in rainfall may have led to an 80% population collapse. Furthermore, the model results indicate that reservoirs could indeed mitigate drought impacts, but also would “postpone” problems, as when reservoirs would run dry, actual drought impact may have been much more severe. Again, the modeling efforts are impressive, but our main comment is that the model setup does not really allow any surprises. Unraveling feedbacks is rather difficult, as the feedbacks have been predefined in the equations. Basically, the paper’s approach shows that it can mimic results that were expected. Again, that in itself may be impressive, but it does not suggest that the assumed relations are those that actually explain the observations. Another comment would be that Kuil et al. suggest that all water immediately becomes available for agriculture, without taking into account potential differences in reservoir use or the flows that would be needed between the reservoirs and fields.

4 | TOWARD MODELING MAYA WATER

Despite the impressive progress in modeling Maya society, as expressed in these three model-based studies, the complexity of Maya communities with their agriculture, transport, and water systems still precludes full-scale model development for the Maya—and other ancient societies for that matter. Many model approaches—including the three presented above—set the simulation with a bird’s eye view on social and physical processes at a lumped scale, whereas our approach takes the many different perspectives of agents as the basis for modeling. We suggest that what is needed is a bottom-up approach, allowing drawing conclusions about the characteristics that result from the collective effect of individual decisions and the conditions that allowed these characteristics to emerge. Our suggestion is based on the three related pillars discussed so far:

1. Societies are realized by all agents, not just by elites, through daily activities and engagement with other agents.
2. Infrastructure is an expression of power, but not a guarantee. To realize power, continuous action is needed. For example, actual water flows matter.
3. Patterns that are observed should not be used to explain the process of patterning itself.

Developing a better understanding of these general observations within the large diversities in environment, ecology, and geology in the Maya area is challenging. It seems likely that these diversities have led to the presence of differences in organizational structure in the Southern Maya lowlands. However, the degree to which these organizational structures varied is still unclear. Has there really been a division in hierarchical and heterarchical water systems as is suggested by studies on Tikal and Caracol? Tikal, which has been studied extensively, is often linked to the model of a centrally oriented and controlled water system. The Tikal water system would have been designed to retain water and divide it over the larger Tikal area with the use of canals and drains to provide its entire population with water throughout the year (Scarborough & Gallop, 1991). Other studies suggest that similar centrally oriented organizational structures were present all over the Southern lowlands and that Maya rulers used the control they had over the water as a way to collect tribute from the inhabitants (Lucero, 2006). However, studies on the water system of Caracol (Chase & Chase, 1998; Crandall, 2006) suggest that the Caracol water system lacks evidence for a centrally oriented and controlled water system.

Water systems are shaped through complex interactions between *Hydrology*, *Hydraulics* and *Humans* (see Figure 2) (Ertsen, 2010). The 3H–Domain explicitly focuses on how the natural environment engages with human actions, provoking human responses (irrigation technology and management), affecting hydrological conditions, hydraulic patterns, and human actions anew. In order to learn more about the organizational structures of water systems in the Southern Maya lowlands during the Classic period (250–900 AD), we have studied to what extent similarities in the way water systems were controlled and organized could be explored by studying hydraulic properties and functioning of a Maya water system. We do not argue that modeling reveals the one and only management model for Maya systems, as system layout or size do not necessarily define management models (Hunt, 1988), but we will show that building models with the physical information available allows determining potential challenges for the Maya and as such their possible management options. Our emphasis is on the short-term changes and conditions in the Maya water systems, with a limited, but important outlook to their longer-term functioning.

In terms of short-term changes in conditions and circumstances Maya water systems had to deal with, the climate in the Southern Maya lowlands had a pronounced wet and dry season. In the wet season, up to 90% of the annual precipitation fell, leaving the 4-month dry season with the other 10%. This distribution of rainfall resulted in large amounts of water being available in the wet season, with only scarce rainfall during the dry season. The Southern lowlands consisted in large part of karst topography that could not retain water very well. The karstic conditions caused permanent natural water sources to be absent in most places. These conditions combined with the climate led to a risk of erosion in the wet season and a possible need for water for the dry season. The Maya of the Southern lowlands adapted their systems to handle these conditions. Well

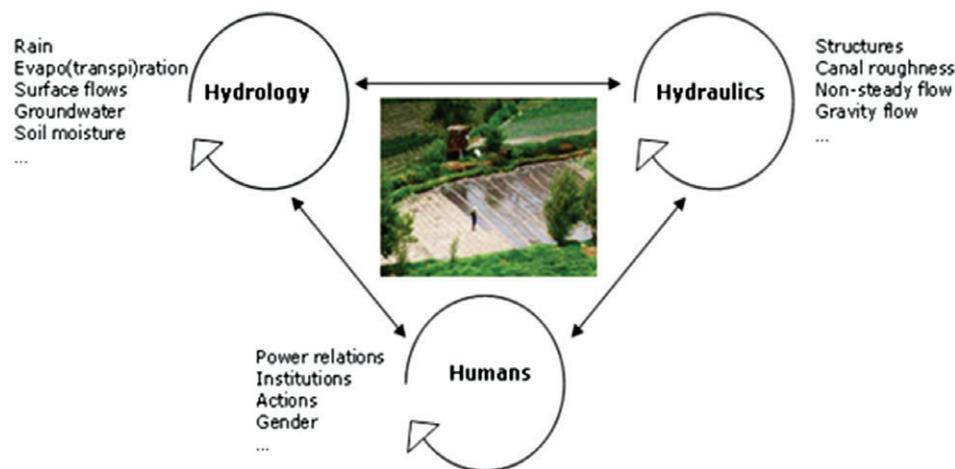


FIGURE 2 The 3-H domain (Woodson, 2016)

known is the shift from concave to convex micro-watersheds in the Classic period (Scarborough, 1998), when centrally located reservoirs were constructed to collect runoff water from the urbanized, paved hill-centers and could potentially distribute water from this center into the lower situated surrounding areas (Wyatt, 2014). These convex micro-watersheds have been found in the regional city centers, but also in smaller centers like La Milpa. The convex microwatershed created a top-down distribution of flows, both in terms of gravity and potential control. One of our aims is to assess to which extent such control was feasible, in order to develop more detailed ideas about how amounts of water present in downstream areas depended (partially) on water supplies from upstream areas.

Conditions in the Southern lowlands created a challenging living environment for the Maya. Weather variability and seasonal distribution of rainfall must have been important phenomena for the Maya. Most years, water availability in total would have been sufficient, but obviously this does not exclude certain periods of the year with water shortages. We are also interested in situations of water excess, when intense rain storms may have overloaded the water reservoirs and canals. How were potential flood damages distributed along the system? Did the Maya population anticipate the rains' seasonal distribution by adjusting the water system and organization throughout the year? Could such anticipation have been organized? The change of seasons has also been associated with seasonal changes in population in Maya city centers, as the dry season was more suited to travel and trade and water would have been available closer to the centers (Lucero, n.d.; Lucero, 2002). The ability of the concave water systems to deal with such additional stress could also be an indication for a need of specific organizational structures.

We include these different conditions and circumstances in our simple model to evaluate needs for any organizational structure, based on the hydraulic properties and functioning of the system in terms of efforts that may have been required to realize a certain outcome—in our case water distribution and flood prevention. In order to link water flows to efforts, the hydraulic modeling software SOBEK was used to compute both volume changes and flows in water systems. We included several agent-based elements, for example, the population using the water systems. We have created a SOBEK-scheme for the Tikal water system, as this system has been described most elaborately. Most dimensions of the system are known. Furthermore, Tikal was a large and influential city center in the Southern lowlands during the Classic Period. Model results for Tikal allow us to reconsider water systems of Calakmul and Caracol, two other urban centers in the Southern lowlands, in terms of similarities and differences with Tikal. In order to do so, we will discuss the similarities and differences between the water systems of our three urban centers first.

5 | THE REGIONAL CENTERS OF TIKAL, CALAKMUL, AND CARACOL

Lucero (2002)) presents a general set of characteristics for different Maya water systems (Table 1). She distinguishes three types of water systems: regional, secondary, and tertiary. The regional systems are those of the larger urban areas like Tikal, Calakmul, and Caracol. Their most important shared characteristic are the reservoirs situated in the central precinct of their centers. The water in these reservoirs is assumed to have been used for household purposes, water-related rituals and perhaps agricultural purposes in some centers. Another important use would have been religious activities of the Maya (Lucero, 1999, 2006). Rulers of the urban centers would have facilitated these spiritual rituals, to strengthen their position between deities and commoners. In order to feed the people in the regional centers, agriculture was present in the outskirts of the centers and nearby bajos (seasonally inundated wetlands). In some city centers, like Tikal, canals and drains have been found that could indicate that the water from the center itself could be released into these areas for irrigation (Scarborough &

TABLE 1 Overview of different Maya water-contexts (drafted with Lucero, 2002)

Type	Characteristics	Water infrastructure	Water use
Regional city center (e.g., Tikal, Calakmul and Caracol)	<ul style="list-style-type: none"> - Larger urban centers with high-density population - Many large architectural buildings in epicenter - Large residential area - Agriculture surrounds centers in nearby bajos - Ruler present that facilitated rituals and ceremonial events 	<ul style="list-style-type: none"> - Large scale - Large reservoirs that collect runoff from the many plazas and surroundings - Drains/ channels that distribute water to such reservoirs - Spiritual water places 	<ul style="list-style-type: none"> - Rituals - Domestic - Agriculture?
Secondary centers (e.g., La Milpa)	<ul style="list-style-type: none"> - Urban center with a lower population density - Rulers present, unclear whether they paid tribute to the regional ruler - Agriculture surrounds centers in nearby bajos 	<ul style="list-style-type: none"> - Relatively smaller scale compared to regional level - Reservoirs to collect water centrally 	<ul style="list-style-type: none"> - Domestic - Agriculture?
Tertiary settlements (e.g., agricultural settlements in the hinterlands)	<ul style="list-style-type: none"> - Small settlements of a few farmsteads or families - Local elites sponsor small-scale rituals 	<ul style="list-style-type: none"> - Very small or no shared water system - Cisterns, chultuns and aguadas 	<ul style="list-style-type: none"> - Domestic - Agriculture?

Gallopín, 1991). However, those same canals could have been used to relieve the center from its water in the wet season as well. Specifics of the three regional urban centers are discussed below, as these details are important for the modeling.

5.1 | Tikal

At its peak, Tikal would have counted 40,000–45,000 inhabitants (Lentz et al., 2015b), although estimates vary (Culbert, Kosakowsky, & Fry, 1990; Dahlin, 2014; University of Cincinnati, 2012). Reservoirs were fed with water from catchment areas ranging in size from 0.43 ha to 55 ha. All catchment areas ended in bajo-margin reservoirs or aguadas (natural depressions filled with water) in the outskirts of Tikal (Scarborough & Gallopín, 1991). Three reservoir types were present in Tikal; central precinct, residential, and bajo-margin. Central reservoirs were located in the epicenter of Tikal, in the neighborhood of large plazas and pyramids. It is argued that they stored water for the residential reservoirs and bajo-margin reservoirs as well (Scarborough, 1998). This means that water from those reservoirs was used for household purposes, ritual-based water usage and possibly to replenish the residential and bajo-margin reservoirs. Residential reservoirs were situated around the central precinct in the residential area. The reservoirs in this area were probably only used for household purposes. The bajo-margin reservoirs, located outside the urbanized area, received their runoff from the flanks of Tikal. Their size and position suggests that these reservoirs were used to irrigate agriculture at the borders of the bajos (Scarborough & Gallopín, 1991). Because these reservoirs were not positioned in residential areas, it is assumed that the water in the reservoirs would not have been used for household purposes. Besides the large central system, small household reservoirs called pozas have been found in Tikal as well (Gallopín, 1990). These pozas were often situated near larger residential structures. This would mean that the residential of Tikal would not have been solely dependent on the central system.

5.2 | Calakmul

Calakmul's settlement pattern is similar to Tikal, with a central precinct, a ring around it with residential areas and a series of agricultural areas outside the urban area. Calakmul relied during the dry season on 13 reservoirs of which the largest encompassed an area of 5 ha. The minimum retention capacity of these reservoirs together is estimated to be 200,000 m³. This would be enough to support up to 50,000–100,000 individuals (Braswell et al., 2004)—with numbers assumed for water use obviously influencing those estimates. Similar to Tikal, larger reservoirs were situated near pyramids and other important religious places (Flannery, 1982). The different reservoirs were linked to each other, allowing overflow from the highest reservoirs to lower ones. It is not clear whether this linked system was as extensive as the system found in Tikal. However, traces of canals between reservoirs have been found and Calakmul was surrounded by an extensive system of aguadas and canals. Both features could indicate the presence of a large linked system like in Tikal (Braswell et al., 2004; Geovannini Acuña, 2008; Sharer & Traxler, 2005). It remains unclear whether water was led to replenish bajo-margin reservoirs or to irrigate crops. Calakmul was situated next to a large bajo, which could have provided access to seasonal sources of water for agriculture (Folan et al., 1995; Gunn et al., 2014).

5.3 | Caracol

Caracol is sometimes called the garden city, because terraces with intensive agriculture were interwoven within a densely settled terrain. During its peak in the Classic period Caracol could have facilitated approximately 100,000 (Dahlin, 2014) to

150,000 people (Chase & Chase, 1998). The density of the terraces and residential areas was high, which could be the result of central planning—whether the highly irregular form of the terraces indicates that terrace and residential area construction is evidence against central planning falls outside our scope, but would require a similar analysis as we propose. Archeological evidence suggests that most terraces were developed alongside settlement increase and that the terraces grew in the same pace as the center itself (Chase & Chase, 1998). The water system in Caracol was different from Tikal and Calakmul. In the center of Caracol, large reservoirs can be found, but these do not seem to be linked to the residential and agricultural areas. These last areas do not show large reservoir. Instead, many smaller reservoirs and aguadas were located near terraces and residential areas (Crandall, 2006). The terraces would have been used to direct water into reservoirs below. Natural gullies led the water from the terraces into the smaller constructed reservoirs. In the residential areas small reservoirs were found as well, with enough potential to supply water all year round for small groups of people. This would mean that Caracol inhabitants relied less on a central water system compared to Tikal and Calakmul—which could be evidence for a nonhierarchical organization (Crandall, 2006).

6 | MODELING TIKAL'S WATER CONTROL

As already mentioned, Tikal's water system has been studied most elaborately and many of the elements in this water system have been described extensively. A Tikal water system has been created in SOBEK, which computes both reservoir water volumes over time and water flows between reservoirs. In the model, some of these flows represent hydrological processes like rain, evaporation and seepage. In addition, some flows represent human actions. Actions like using water or changing reservoir settings are translated into flows. Therefore, our model can compute the influence of human actions in combination with hydrological processes and reservoir volumes. These interactions within the water system will create feedback, for example, by changes in water levels which could result in floods. Our model is based on Tikal water system characteristics as described in Gallopín (1990) and the maps of Tikal from the University of Pennsylvania. A schematization of the entire water system on a map of Tikal with all the reservoirs (including names), their position and the links between them can be found in Figure 3.

Flows into reservoirs result from rain on the catchment area of the reservoir and the reservoir itself. Outflows are evaporation from reservoir surfaces, seepage on the catchment area, and water demands by users of reservoirs. These flows bring or remove certain amounts of water per time step. We have modeled these flows in hydraulic terms as pumps, with maximum flows as pumping capacity, and switch-on/switch-off behavior based on water levels in the reservoirs. A consequence of this modeling choice is that all inflows and outflows—with the exception of spill-overs—happen instantaneously for all the reservoirs. In reality, one would expect a certain delay time for downstream flows. However, in such a steep and partly paved system, these delay times would have been very small.

6.1 | Rain and runoff

In the Southern lowlands, the dry season lasts from January until the start of May, with a large variation in daily rainfall even within a dry season. Not including such variation would mean losing much valuable information about the functioning of the water system. Therefore, daily rainfall data were used instead of average monthly or even yearly data—with actual data coming from present weather data (in line with Scarborough & Gallopín, 1991) from 2014 in Belize—the weather station nearest to Tikal with daily rainfall data. For simplicity sake, the reservoirs are modeled as squares with vertical sides, so the surface of the reservoir does not change when the water height fluctuates. Inflows are modeled all year round and are independent from water levels in the reservoir. Runoff from the catchment areas and the rain on the reservoirs would have flowed into the reservoirs at all times, whether the reservoirs still could store this water or not. Both inflows are combined in a single pump with the capacity to add all rainfall without stopping pumping of water into the reservoirs.

6.2 | Evaporation and seepage

Evaporation values are computed on monthly basis as many of the climate data required to make this computation are not available in daily values. It is assumed that the daily values are equal to the monthly values divided by the number of days in the month, so each day in the same month has the same evaporation rate. As evaporation fluctuates much less than rain, this is a reasonable assumption. Total outflow caused by evaporation is computed by multiplying evaporation rate with reservoir surface value. Assuming that runoff from the catchment area is a rapid process, evaporation of incoming water from the catchment is set to be zero. Gallopín (1990) defines both maximum and minimum rates of seepage for all catchment areas. We have used average seepage rates. Catchments produce runoff when rainfall is higher than seepage rate.

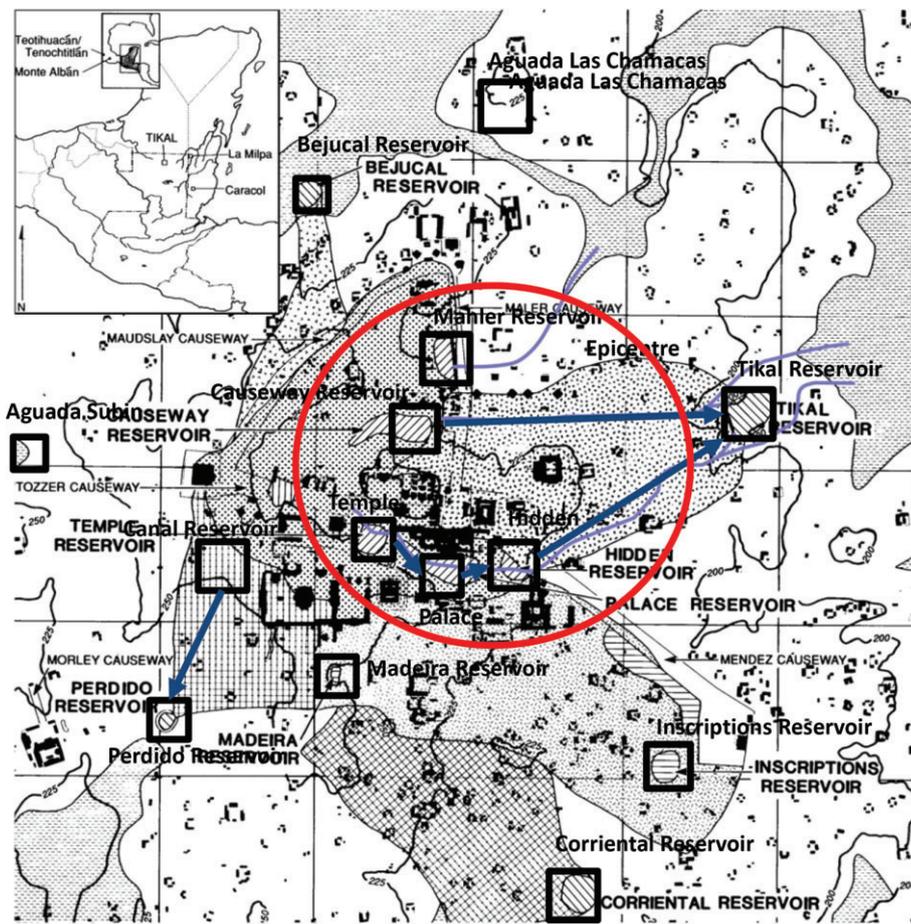


FIGURE 3 The schematization of the central water system of Tikal (base map taken from Scarborough & Gallopin, 1991)

6.3 | Water use

Tikal's inhabitants use those model reservoirs that are assumed to have provided for household purposes. Every user in Tikal's periphery withdraws 11.1 L/day in the wet season and 22.2 L/day in the dry season (Gallopin, 1990). People living closer to and within the epicenter may have had higher water demands. We set water demands in the central part of Tikal twice as high and in the epicenter four times higher (Gallopin, 1990). However, in our model, everyone uses the central water supply system—the large reservoirs—for their 11.1 L/day in the wet season and 22.2 L/day in the dry season. Additional water demands would have been supplied for by the pozas. These pozas are not included in our model, as their dimensions and numbers are still unclear. Nevertheless, it is not unreasonable to assume that pozas provided additional water supplies above the base supplies that the large reservoirs could provide for a first estimation of flows related to use(r)s. Thus, the outflow caused by the water demands equals the number of users times the water demand for each reservoir. In the dry season the water demand is twice as high. To compute the total water demand, the number of users each reservoir provides for needs to be known. As pozas are not included in the model, the distribution of users defined in (Gallopin, 1990) could not be used. It is assumed that users are distributed proportionally to the volume of the reservoirs. We have divided the volume of each reservoir by the total volume of all the reservoirs used for household purposes and used this ratio against the total number of inhabitants of Tikal.

6.4 | Outflows

These different outflows are modeled using two separate pumps. The first pump represents the outflows due to evaporation and seepage. As these flows are always potentially present, but depend on water in the reservoir, the pumps shut down only when the water level in the reservoir reaches zero. The water demands by the users are modeled with a pump whose capacity equals the demand. This pump shuts down when reservoir water levels drop below 5 cm. Subtracting water from an almost empty reservoir would be very challenging and likely not even possible. As such, when our model results show a reservoir water level of 5 cm or lower, we can assume that the reservoir was under stress. With new water coming in regularly, most of the times water keeps flowing in or out during the whole modeling sequence. Therefore, dropping reservoir water levels are the clearest sign for water stress within our modeling framework.

levels during events in order to prevent the water overflowing the reservoirs. In a second setup, we made crest levels changeable in height. In the dry season, crest levels are set at maximum reservoir water level in order to retain the maximum amount of water. During the wet season, crest levels at the start are lower than surface level to prevent overflowing. In the deeper reservoirs, weirs are 1 m below surface level, whereas in the other reservoirs crest heights are half the reservoir depth. At the end of the wet season, crest levels are slightly higher to start retaining maximum amounts of water for the dry season. At the start of the dry season crest levels are at maximum level (which is surface level) again. This variability of crest levels would require some kind of human activity to move crests and respond to circumstances.

7.2 | Dry season nucleation

Lucero (2002, n.d.) (see also Gallopin, 1990) suggest that during the dry season people from hinterland settlements gathered in regional centers to use the more extensive water systems in the dry season. We have modeled both a stable number of inhabitants all year round and an increase of 30% of the population in the center during the dry season. We assume that an increase of 30% in the center would still keep people in the outside settlements to perform all kind of tasks of maintenance, resource collection, or agriculture. These people would have had access to water through small-scale water systems and/or springs.

7.3 | Agriculture

The maps of Tikal by the Pennsylvania University suggest some links or drainages between reservoirs. However, there is no clear evidence that the water in the bajo-margin reservoirs was linked to the agricultural areas in the margins of the bajos. Furthermore, was irrigation the main purpose of the canals or were the links present to relief the central part of Tikal during the wet season from excess water? We have studied the impact of including patches of raised fields for each bajo-margin reservoir on water levels and flows to check to what extent reservoirs could have sustained agriculture on a scale that may have been required for a large city as Tikal.

7.4 | Changing weather conditions

As average conditions do not exist, we need to study how any systems would have coped with fluctuations and extremes. In Maya discussions, particularly drought is suggested as driver of Maya collapse. To test how resilient Tikal's water system was to drought, we have included different materializations of drought in the model. We have studied the effect of an elongated dry season (or delayed wet season), a "dry" wet season (without larger rainfall events), and a drought at the end of the rainy season. These scenarios allow us to see whether the central precinct could have acted as a feeder system for other reservoirs. In a final modeling scenario, we have included local pozas to see whether these water volumes would make a difference.

8 | RESULTS

In our basic scenario with fixed weirs, average rain and stable number of inhabitants, the Tikal water system could easily sustain all the inhabitants of Tikal, without shortages of water. The system returns to a fully replenished state before the start of the next dry season. The fact that all the reservoirs are fully replenished at the end of the year shows that the system could have sustained Tikal year after year, if all years would be average. However, as mentioned, the average does not exist.

8.1 | Weather anticipation

For weather events and possible overflowing of the reservoirs, our model results for scenarios 1–4 suggest that the Maya may have had difficulty to anticipate on the changing weather of the seasons by modifying spills. The option to change weir settings has little effect on the overall behavior of the reservoir. Water levels fluctuate at most a couple of decimeters around selected weir levels and values for maximum daily overflow and total annual overflow volume are pretty similar to values for the basic scenario. These results suggest that the Maya may not have implemented much management actions in their water systems, as it would take much effort and would not result in a large advantage for the people of Tikal. It would have been most likely that system dimensions and properties were fixed—obviously requiring maintenance, but not necessarily daily actions.

8.2 | Dry season nucleation

A 30% increase in population in the dry season in our model has a negligible effect on water levels and discharges of Tikal's reservoirs. This small difference can be explained by looking at the ratio between total outflow and water use for each reservoir. Water use is only a small part of the total outflow. After this initial result, we wanted to test how large demands could become before any substantial stress on the system. We checked effects of 100 and 400% increases of water demands. Doubling water demands has a relatively small effect; in the dry season the water levels drop a couple of centimeters to at most a decimeter below levels in the original case. As such, there is a difference, but the drop in water levels is so small that it would not have caused any severe problems. An increase of 400% in water demand has a much larger effect: large dips occur in water levels of most reservoirs during the dry season, with the largest dips in the three reservoirs in the central precinct (Temple, Palace, and Hidden). This suggests that other reservoirs were better able to cope with the increase in demand—but not all, as at the end of the dry season, the Las Chamacas reservoir actually reaches our critical 5 cm level, although only for a few days which would make the effect far from catastrophic. Still, the resilience of Tikal's water system certainly has a limit. An important result with possible longer-term effects is that reservoirs may no longer be fully replenished after a year, resulting in lower water levels in the next year. Growing population plus a series of dry years would have created serious problems for Tikal's water supply.

8.3 | Agriculture

Those reservoirs that would not have been used for household purposes could have sustained about 35 ha of raised fields with maize. With data from the Food and Agricultural Organization suggesting that 1 ha could yield from 6 to 15 tons of maize per harvest (White & Schwarcz, 1989) and allowing for lower potential yields for maize of the Maya (selecting the lower limit of 6 tons), 35 ha would have supported some 1,600 people per year. This number assumes that up to 50% of the diet of the Maya consisted of maize (Ertsen, 2014) and that modern diets consisting of 50% maize require a daily maize consumption per person of about 359 g of maize. Thousand six hundred people per reservoir would only be a small part of the total number of inhabitants of Tikal. It is less likely that the reservoirs could have sustained irrigation for all the crops needed to provide food for Tikal's people.

8.4 | Changing weather conditions

The water system in Tikal was the only permanent water source available to the Maya of Tikal. A delay in the arrival of the wet season, modeled by removing all large rainfall events for May and/or June maintains results very close to the baseline. Water levels drop slightly during May with the 1 month delay and during May and June with the 2 months delay. Similar to the results on doubling the water demands, even the smaller rainfall events proved to be sufficient to keep reservoir water levels similar to the levels in the original case. In a next step, we decreased all larger rainfall events to thresholds of maximally 30 mm/day and 10 mm/day, respectively, to simulate a year without large rainfall events, storms, or hurricanes. The first threshold of 30 mm/day does not have any effect. The 30 mm/day seem to be enough to replenish the reservoirs regularly. The lower 10 mm/day threshold has some effect, with some water levels slightly lower during the dry season. However, even these relatively small rainfall events are sufficient to sustain Tikal's system. Only when we move to an extreme scenario with two additional dry months at the end of the dry season (March and April) we encounter many reservoirs with rapidly decreasing water levels. It is again Las Chamacas that falls below the critical water level for the last few days of the dry season. Even now, the wet season still appears to be able to replenish all reservoirs. Tikal's system is quite resilient to droughts within a single year.

8.5 | Pozas

As explained above, we assumed that pozas sustained additional water demands of wealthy inhabitants of Tikal and those inhabitants situated closer to water. Using the descriptions of three groups of pozas (Gallopín, 1990), we tested the effect of pozas on a daily water balance, outside the hydraulic model, for both normal and extreme weather conditions. Our results suggest that the pozas could have maintained additional demands during an average year, but during large droughts—like our 2-month drought in March and April—some pozas would fail during the last couple of days of the dry season. This “failure” of pozas was included in a final model scenario by increasing water use from reservoirs—either halfway or at the start of April. Our results show that reservoir water levels drop substantially with such an increase in water demands in an already stressed situation. All reservoirs are able to cope with the added stress, except Las Chamacas and Canal. Las Chamacas falls dry soon after the start of the drought, Canal falls dry the very last days of the drought. The Hidden reservoir in the epicenter

has dwindling water levels. At the lowest point, only 15 cm of its water is left, suggesting some vulnerability. Nevertheless, with the arrival of a regular wet season all reservoirs are replenished.

9 | THE TIKAL WATER SYSTEM MODEL

Obviously, our Tikal model is basic, despite the many characteristics that are already included. The performance of the water system in Tikal is determined by many different elements, structures, agents, feedback loops, and all sorts of influences from outside the system. Only a few of these elements are included in the model. To build the model we have used data sets from secondary literature that already include ideas on how the system could have functioned and as such may have stressed certain characteristics. Both these problems have a straightforward solution: an interdisciplinary research project that combines archeological findings with hydraulics and modeling, possibly extending our agency-part further as well, without using those data based on calculations of studies that support too different ideas about the organizational structures. Obviously, a modeling program like SOBEK has its limits. Our model setup with pumps for most flows would not have had huge effects on model results, but more realistic hydrologic behavior could be included with other models. Finally, we have included Maya agents through their demands and translation into flows. Obviously, more human agency than demands alone were important in Maya water systems. It is recommended to include more agency in future modeling efforts.

Despite all these limitations, some results deserve to be highlighted. Tikal's water system seems to be capable handling drought conditions. There would have been no need to convey water from the central reservoirs toward the lower reservoirs; all reservoirs can easily handle their local demands. Tikal may have had more problems with surpluses of water compared to shortages of water. After large rainstorms there are large spill-over events. Not dealing with these flows could lead to erosion and flooding of certain lower areas. Our 30 mm/day threshold suggests that such a maximum was more than sufficient to replenish the reservoirs and would have already caused spill-over events. Thus, rainfall events larger than this 30 mm/day would certainly have caused large spill-overs. Keeping in mind that some of the rainfall events can be larger than 100 mm/day, much water needs to be drained from central Tikal into lower lying areas during and after such events. Maya studies may need to focus as much on wet events as they do on dry ones.

Besides the large variability, rainfall in the Southern lowlands is also unpredictable. At the start of the wet season large gaps can occur between larger rainfall events. Even at the end of the wet season, when rainfall events occur more frequently, there is no way of predicting when and if such large rainfall events will occur. The Maya of Tikal may not have been able to predict weather conditions accurately, which made lowering water levels in reservoirs to prevent spill-overs after a large rainfall event unlikely. It seems more likely that the drains and links between the reservoirs in the epicenter and the reservoirs in lower situated areas had to keep the epicenter of Tikal dry. This could even go as far that central reservoirs were not there to replenish those lower situated reservoirs. This would still be a top-down distribution, but one distributing floods and not beneficial use. Flood drainage would have required less regulated and coordinated management as well, once systems were in place.

In situations of extreme drought, it could have been possible that the links between reservoirs were also used to replenish reservoirs downstream, but most of our scenarios do not give much reason to use such a centrally controlled feeder system as was suggested by (Lucero & Fash, 2006; Scarborough, 1998). Even our increase of 400% relative to the population distribution assumed in the baseline study, would not necessarily induce a need for water flows from the epicenter toward lower situated reservoirs. The system is also fairly resilient to the influences of human agency, like sudden increases of water demands, caused by an increase in population or an increase in water use. For most reservoirs the amount of rainwater flowing into the reservoirs is much higher than evaporation and water use for household purposes. Our modeling suggests that it may not have been easy to produce water-related problems in Tikal on the short term (compare with Scarborough et al., 2012). If those problems that may have occurred could have been easily remediated in a next season in most cases, one could speculate that the Maya did not have that much reason to anticipate longer-term drought. It is not easy to see long-term changes in short-term signals either. This observation does not suggest at all that the Maya did not have a longer-term perspective as such—the famous Maya calendar is clear proof of such perspective. Nevertheless, our modeling results suggest that any direct link between climatic changes and water system operation are far from straightforward.

Concerning agriculture around Tikal, our results suggest that the reservoirs assigned to agricultural may not have been able to irrigate enough land to sustain the Tikal population. However, if the water was used to bridge droughts for rain-fed crops instead of continuous irrigation, it could have provided benefits for larger areas. With much agriculture being practiced in the hinterland areas, not all the food had to be produced directly around Tikal anyway. These results do not rule out the option that reservoirs were used as a buffer to prevent flooding of valuable agricultural areas after large rainfall events. As such, it is still unclear what the functions of the bajo-margin reservoirs and the links to the bajos would have been: support agriculture, protect agriculture, or both?

Most lower reservoirs seem to have required less or no support from the central reservoirs in terms of water supply. This could mean that supplying water from the central precinct to reservoirs below could not have been used to express power. Furthermore, many people could have relied on the pozas for much of their water demand on household level—like the many small reservoirs found in Caracol. The release of flood water was not likely to be centrally controlled either. Spillovers would have been uncontrollable in timing and quantity, which again could indicate that the water system of Tikal was not as hierarchically organized as suggested. Gravity builds a hierarchy for sure, but not necessarily a top-down management—although moving flood water to downstream areas could be seen as evidence of hierarchy.

10 | CONCLUDING REMARKS: TIKAL, CALAKMUL AND CARACOL

Our model results of Tikal show that the links in between the reservoirs could have been used to drain the area. Rather than replenish lower reservoirs to meet water demand, such a system could have reduced risks of erosion. If this concept is applicable more generally, the water system of Tikal could have had more similarities with the water system of Calakmul and Caracol than was anticipated in previous studies. In Calakmul, links and canals have also been found between reservoirs and toward aguadas situated near a bajo. The similar layout of the system led some scholars to conclude that Calakmul had to have a centrally organized water system like in Tikal. However, it is possible that the canals in Calakmul were also used to drain the center rather than to replenish lower reservoirs. This would mean that in all three regional centers the supply of water in residential areas was not controlled by the reservoirs in the epicenters.

The water system of Caracol deviates from the other two in the sense that large reservoirs seem to have been absent in its residential and agricultural areas. Caracol's water supply was only on household or field level with the use of small reservoirs. In Tikal and Calakmul, the larger reservoirs present in the residential and agricultural areas do suggest that people relied at least partially on the central water system. With our hydraulics suggesting a much less hierarchical functioning for Tikal, however, Caracol may have been less different from Tikal and Calakmul in terms of centrality of management, despite the different shape and layout of the system. It is clear that further research into the organizational structures of the Maya water systems is required, as such research into the hydraulics of the systems would shed a different light on the water systems of Tikal, Calakmul, and Caracol. We have suggested that the hydraulics of the Maya water systems may show smaller dissimilarities in terms of possible organizational structures in the Southern Maya lowlands, but much more remains to be done.

We could produce this conclusion because in contrast to much Maya work that focused on the larger regional entities and has perceived much in terms of elites controlling the water features, we focused on everyday things—in terms of water use, rainfall, and actions. In much archeological research, attention for daily activities is typically translated into attention for nonelites. There is, however, no reason to assume, or actually there is a need to consider, that elite control is also an everyday thing. Realizing power is hard work. Related to perspectives of social complexity and hierarchical changes, it is also reasonable to suggest that infrastructure is a key for power relations. Infrastructure is a power relation.

Our hydraulic modeling may have been basic, but suggests that we may need to ask ourselves how Maya water management would have been made central, or not, and to what extent. How much work was actually required? It is clear that building the systems would have required some coordinated effort, but perhaps using the system may not have needed much central control. We have discussed the basics of some first efforts for Maya systems. All our water sketches were of the “central” type, as these offer good data sets for the type of models we present. There is no reason to assume, however, that similar modeling efforts cannot be made for other situations in the Maya area and elsewhere.

11 | BEYOND THE MAYA—TOWARD MODELING SOCIETIES

In this paper, we do not go as far yet to discuss fuller models of growing complexity. Obviously, more than water is needed for that. The Maya case is an excellent test for what emerging social complexity means in tropical conditions, with other water resource and control issues and different rhythms of nonhuman agents—including vegetation and crop growth, soils, and properties of organic processes. Outlines for such models have been sketched elsewhere (Ertsen, 2014, 2016b). We argue, however, that our short-term model we discuss here should be part and parcel of—if not basis for—any more sustained effort to model and analyze (Maya) societal complexity as an everyday phenomenon. We are not arguing that central or local systems are the same, nor that one is better than the other. We do argue that all water systems and situations should be understood on the same theoretical mode.

The theoretical and methodological underpinning of our modeling efforts is that “development” or “increasing social complexity” (or rather “complicatedness”) is local and constructed within and through networks of actors. Micro and macro

are irrelevant concepts, as the micro shapes the macro while being created. Similarly, there is no “inside” or “outside,” or “local,” or “context,” as these concepts are continuously (re)created. Studying networks with any prior explanatory division in terms of hierarchical levels, contexts or power relations needs to be avoided as much as possible. We do not argue that hierarchies, arenas, and institutions do not exist, but that they are constructed and confirmed—or not. The constructions themselves, however, can never be used as explanatory forces. We may observe strong hierarchies, but that does not mean that those hierarchies should be taken for granted. Instead, we should force ourselves to study how these hierarchies could (not) be maintained.

A methodological consequence has to be that a multitude of local agencies need to be taken into account—as we did in our modeling with reservoirs, rain, weirs, management actions, etc. In order to achieve such a more detailed analysis, however, one obviously needs the data sets to do so. As our paper suggests, existing Maya scholarship does indeed allow a rather detailed level of analysis—although we do envision another use of the rich data sets than many modeling studies offer. The many studies that are based on correlations between observations, including the Maya modeling efforts we have discussed (Gunn et al., 2017; Heckbert, 2013; Heckbert et al., 2010, 2016; Kuil et al., 2016), have difficulty to transform results into explanations or causations between different agents that actually produced the reality that comes to us through our observations. We argue that these larger-scale and longer-term correlations—as for example, between drought and elite disappearance—need to be explained in terms of causalities between short-term agencies.

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FURTHER READING

Beach, T., Luzzadder-Beach, S., Dunning, N., Jones, J., Lohse, J., Guderjan, T., ... Bhattacharya, T. (2009). A review of human and natural changes in Maya lowland wetlands over the Holocene. *Quaternary Science Reviews*, 28, 1710–1724.

REFERENCES

- Abbott, D. (Ed.). (2003). *Centuries of decline during the Hohokam classic period at pueblo Grande*. Tucson: University of Arizona Press.
- Algazi, G. (2010). Bringing kinship (back) in: On David Warren Sabean, Simon Teuscher, Jon Mathieu (eds.), *Kinship in Europe, 1300–1900* (New York: Berghahn, 2007). *Mediterranean Historical Review*, 25, 83–92.
- Altaweel, M. (2008). *The imperial landscape of Ashur: Settlement and land use in the Assyrian heartland*. Heidelberg, Germany: Heidelberger Orientverlag.
- Barton, C. M. (2014). Complexity, social complexity, and modeling. *Journal of Archaeological Method and Theory*, 21, 306–324.
- Berry, K. A. (2014). Actor-network theory and traditional cultural properties: Exploring irrigation as a hybrid network in 19th century Hawai'i. *Human Geography*, 7, 73–87.
- Braswell, G. E., Gunn, J. D., del Rosario Dominguez Carrasco, M., Folan, W. J., Fletcher, L. A., Morales Lopez, A., et al. (2004, 2004). Defining the terminal classic at Calakmul, Campeche. In A. A. Demarest, P. M. Rice, & D. S. Rice (Eds.), *The terminal classic in the Maya lowlands: Collapse, transition, and transformation* (pp. 162–194). Louisville, KY: University Press of Colorado.
- Chase, A. F., & Chase, D. Z. (1998). Scale and intensity in classic period Maya agriculture: Terracing and settlement at the “garden city” of Caracol, Belize. *Culture and Agriculture*, 20, 60–77.
- Conteras, D. A. (Ed.). (2017). *The archaeology of human-environment interactions. Strategies for investigating anthropogenic landscapes, dynamic environment, and climate change in the human past*. London, England: Routledge.
- Crandall, J. (2006). *Water and the mountains: Maya water management at Caracol, Belize*. (Unpublished MSc thesis). University of Central Florida, Orlando.
- Culbert, T. P., Kosakowsky, L. J., Fry, R. E., & Haviland, W. A. (1990, 1990). The population of Tikal, Guatemala. In T. P. Culbert & D. S. Rice (Eds.), *Pre-Columbian population history in the Maya lowlands* (pp. 103–121). Albuquerque: University of New Mexico Press.
- Dahlin, B. H., & Chase, A. F. (2014). A tale of three cities: Effects of the AD 536 event in the lowland Maya heartland. In G. Iannone (Ed.), *The great Maya droughts in cultural context: Case studies in resilience and vulnerability* (pp. 127–155). Boulder: University Press of Colorado.
- Davies, M. I. J. (2009). Wittfogel's dilemma: Heterarchy and ethnographic approaches to irrigation management in eastern Africa and Mesopotamia. *World Archaeology*, 41, 16–35.
- Dobres, M.-A., & Robb, J. (Eds.). (2000). *Agency in Archaeology*. London, England: Routledge.
- Doolittle, W. E. (2010). Learning to see the impacts of individuals. *The Geographical Review*, 91, 423–429.
- Erickson, C. L. (1988). Putting ancient agriculture back to work. *Expedition*, 30, 8–16.
- Ertsen, M. W. (2010). Structuring properties of irrigation systems. Understanding relations between humans and hydraulics through modeling. *Water History*, 2, 165–183.
- Ertsen, M. W. (2012, 2012). Modelling human agency in ancient irrigation. In F. Bertonecello & F. Braemer (Eds.), *Variabilités environnementales, mutations sociales: Nature, Intensités, Échelles et Temporalités des changements* (pp. 199–209). Éditions APDCA: Antibes, France.
- Ertsen, M. W. (2014). Step after step the ladder is ascended. Human agency in irrigated (anti) landscapes. In D. Nye & S. Elkind (Eds.), *The anti-landscape* (pp. 45–60). Amsterdam, The Netherlands: Rodopi.
- Ertsen, M. W. (2016a). A matter of relationships: Actor-networks of colonial rule in the Gezira irrigation system, Sudan. *Water Alternatives*, 9, 203–221.
- Ertsen, M. W. (2016b). Friendship is a slow ripening fruit. An agency perspective on water, values, and infrastructure. *World Archaeology*, 48, 500–516.
- Ertsen, M. W. (2016c). *Improvising planned development on the Gezira plain, Sudan, 1900–1980*. New York, NY: Palgrave MacMillan.

- Ertsen, M.W., & Wilkinson T.J. (2014). *Understanding long-term trends in ancient water systems*. In: 9th International Congress on the Archaeology of the Ancient Near East, Basel.
- FAO. (2015). Crop water information: Maize. FAO water. Retrieved from: http://www.fao.org/nr/water/cropinfo_maize.html
- Flannery, K., & Marcus, J. (2012). *The creation of inequality. How our prehistoric ancestors set the stage for monarchy, slavery, and empire*. Cambridge, MA: Harvard University Press.
- Flannery, K. F. (1982). *Maya subsistence: Studies in memory of Dennis E. Puleston*. London, England: Academic Press.
- Folan, W. J., Marcus, J., Pincemin, S., del Rosario Dominguez Carrasco, M., Fletcher, L., & Morales Lopez, A. (1995). Calakmul: New data from an ancient Maya capital in Campeche, Mexico. *Latin American Antiquity*, 6, 310–334.
- French, K. D., & Duffy, C. J. (2014). Understanding ancient Maya water resources and the implications for a more sustainable future. *WIRES Water*, 1, 30–313.
- French, K. D., Duffy, C. J., & Bhatt, G. (2013). The urban hydrology and hydraulic engineering at the classic Maya site of Palenque. *Water History*, 5, 43–69.
- Gallopin, G. G. (1990). *Water storage technology at Tikal, Guatemala* (Unpublished MSc thesis). University of Cincinnati, Cincinnati.
- Gardner, A. (Ed.). (2007). *Archaeological perspectives on social agency, power and being human*. London, England: University College London Institute of Archaeology Publications.
- Geovannini Acuña, H. (2008). *Rain harvesting in the rainforest: The ancient Maya agricultural landscape of Calakmul, Campeche, Mexico*. Oxford, England: Archaeo Press.
- Gill, R. B. (2000). *Great Maya droughts: Water, life, and death*. Albuquerque: University of New Mexico Press.
- Gunn, J. D., Folan, W. J., Isendahl, C., Carrasco, D., Del Rosario, M., Faust, B. B., & Volta, B. (2014). Calakmul: Agent risk and sustainability in the western Maya lowlands. In A. F. Chase & V. L. Scarborough (Eds.), *The resilience and vulnerability of ancient landscapes: Transforming Maya archaeology through IHOPE* (pp. 101–123). Toronto, Canada: American Anthropological Association.
- Gunn, J. D., Scarborough, V. L., Folan, W. J., Isendahl, C., Chase, A. F., Sabloff, J. A., & Volta, B. (2017). A distribution analysis of the central Maya lowlands ecoinformation network: Its rises, falls, and changes. *Ecology and Society*, 22, 20.
- Harrower, M. J. (2009). Is the hydraulic hypothesis dead yet? Irrigation and social change in ancient Yemen. *World Archaeology*, 41, 58–72.
- Heckbert, S. (2013). MayaSim: An agent-based model of the ancient Maya social-ecological system. *Journal of Artificial Societies and Social Simulation*, 16, 11.
- Heckbert, S., Baynes, T., & Reeson, A. (2010). Agent-based modeling in ecological economics. *Annals of the New York Academy of Sciences*, 1185, 39–53.
- Heckbert, S., Isendahl, C., Gunn, J., Brewer, S., Scarborough, V. L., Chase, A. F., ... Sinclair, P. (2016). Growing the ancient Maya social-ecological system from the bottom up. In C. Isendahl & D. Stump (Eds.), *Applied archaeology, historical ecology and the usable past*. Oxford, England: Oxford University Press.
- Hodder, I. (2012). *Entangled: An archaeology of the relationships between humans and things*. Hoboken, NJ: Wiley-Blackwell.
- Hunt, R. C. (1988). Size and the structure of authority in canal irrigation systems. *Anthropological Research*, 44, 335–355.
- Iannone, G. (Ed.). (2014). *The great Maya droughts in cultural context: Case studies in resilience and vulnerability*. Boulder: University Press of Colorado.
- Knappett, C. (2011). *An archaeology of interaction. Network perspectives on material culture and society*. Oxford, England: Oxford University Press.
- Kuil, L., Carr, G., Viglione, A., Prskawetz, A., & Bloesch, G. (2016). Conceptualizing socio-hydrological drought processes: The case of the Maya collapse. *Water Resources Research*, 52, 6222–6242.
- Latour, B. (2000). When things strike back: A possible contribution of ‘science studies’ to the social sciences. *British Journal of Sociology*, 51, 107–123.
- Latour, B. (2005). *Reassembling the social: An introduction to actor network theory*. Oxford, England: Oxford University Press.
- Latour, B., & Strum, S. C. (1986). Human social origins: Oh please, tell us another story. *Journal of Social and Biological Structures*, 9, 169–187.
- Lentz, D. L., Dunning, N. P., & Scarborough, V. L. (2015a). Defining the constructed niche of Tikal. In D. L. Lentz, N. P. Dunning, & V. L. Scarborough (Eds.), *Tikal: Paleoecology of an Ancient Maya City (280–296)*. New York, NY: Cambridge University Press.
- Lentz, D. L., Dunning, N. P., & Scarborough, V. L. (2015b). *Tikal: Paleoecology of an ancient Maya City*. Cambridge, England: Cambridge University Press.
- Lombardo, U. (2015). Raised fields of Northwestern Bolivia: A GIS based analysis. Academia. Retrieved from: http://www.academia.edu/6519977/Raised_Fields_of_Northwestern_Bolivia_a_GIS_based_analysis
- Lucero, L. J. (1999). Water control and Maya politics in the southern Maya lowlands. *American Anthropologist*, 9, 35–49.
- Lucero, L. J. (2002). The collapse of the classic Maya: A case for the role of water control. *American Anthropologist*, 104, 814–826.
- Lucero, L. J. (2006, 2006). The politics and sacred power of water in classic Maya society. In L. J. Lucero & B. W. Fash (Eds.), *Precolumbian water management: Ideology, ritual and power Classic water systems* (pp. 116–128). Tucson: University of Arizona Press.
- Lucero, L. J. (n.d.). Water Management in Lowland Mesoamerica. In *Water and Humanity: Historical Overview*; Scarborough, V.L., Ed.; UNESCO: Paris, France, in press; 2011.
- Lucero, L. J., & Fash, B. W. (Eds.). (2006). *Precolumbian water management: Ideology, ritual, and power*. Tucson: University of Arizona Press.
- Maisels, C. (2012). *The archaeology of politics and power. Where, when and why the first states formed*. Oxford, England: Oxbow Books.
- Marcus, G. E. (1989). The problem of the unseen world of wealth for the rich. Toward an ethnography of complex connections. *Ethos*, 17, 114–123.
- Marcus, J., & Stanish, C. (Eds.). (2005). *Agricultural strategies*. Los Angeles, CA: Cotsen Institute of Archaeology.
- Martin, A. M. (2005). Agents in inter-action: Bruno Latour and agency. *Journal of Archaeological Method and Theory*, 12, 283–311.
- McAnany, P. A., & Yoffee, N. (2010). *Questioning collapse. Human resilience, ecological vulnerability, and the aftermath of empire*. Cambridge, England: Cambridge University Press.
- Mithen, S. (2012). *Thirst: Water and power in the ancient world*. London, England: Weidenfeld and Nicolson.
- Robin, C. (2013). *Everyday life matters. Maya farmers at Chan*. Gainesville: University Press of Florida.
- Rost, S. (2015). *Watercourse management and political centralization in third-millennium B.C. southern Mesopotamia: A case study of the Umma Province of the Ur III period (2112–2004 B.C.)*. (Unpublished dissertation). Stony Brook University, New York.
- Scarborough, V. L. (1998). Ecology and ritual: Water management and the Maya. *Latin American Antiquity*, 9, 135–159.
- Scarborough, V. L. (2000, 2000). Resilience, resource use, and socioeconomic organization. A Mesoamerican pathway. In G. Bawden & R. M. Reyecraft (Eds.), *Environmental disaster and the archeology of human response*. Maxwell Museum of Anthropology Anthropological Papers No. 7. Albuquerque: University of New Mexico Press.
- Scarborough, V. L. (2003). *The flow of power. Ancient water systems and landscape*. Santa Fe, NM: SAR Press.
- Scarborough, V. L. (2005, 2005). The rise and fall of the ancient Maya: A case study in political ecology. In R. Costanza, L. J. Graumlich, & W. Steffen (Eds.), *Sustainability or collapse? An integrated history and future of people on earth* (pp. 51–60). Cambridge: MIT Press.
- Scarborough, V. L. (2006, 2006). An overview of Mesoamerican water systems. In L. J. Lucero & B. W. Fash (Eds.), *Precolumbian water management: Ideology, ritual and power Synthesis and conclusion* (pp. 223–235). Tucson: University of Arizona press.
- Scarborough, V. L., & Gallopin, G. G. (1991). A water storage adaptation in the Maya lowlands. *Science*, 251, 658–662.
- Scarborough, V. L., & Lucero, L. (2010). The non-hierarchical development of complexity in the Semitropics: Water and cooperation. *Water History*, 2, 185–205.
- Scarborough, V. L., Dunning, N. P., Tankersley, K. B., Carr, C., Weaver, E., Grazioso, L., ... Lentz, D. L. (2012). Water and sustainable land use at the ancient tropical city of Tikal: Guatemala. *Proceeding of National Academy of Sciences*, 109, 12408–12413.

- Schouten, P. (2013). The materiality of state failure: Social contract theory, infrastructure and governmental power in Congo. *Millennium - Journal of International Studies*, 41, 553–574.
- Schwartz, G. M., & Nichols, J. J. (2006). *After collapse. The regeneration of complex societies*. Tucson: University of Arizona Press.
- Sharer, R. J., & Traxler, L. P. (2005). *Ancient Maya*. Redwood City, CA: Stanford University Press.
- Smith, M. L. (2010). *A prehistory of ordinary people*. Tucson: University of Arizona Press.
- Strum, S. S., & Latour, B. (1987). Redefining the social link: From baboons to humans. *Social Science Information*, 26, 783–802.
- University of Cincinnati. (2012). Largest ancient dam built by Maya in Central America. ScienceDaily. Retrieved from: http://www.sciencedaily.com/releases/2012/07/120716191443.htm?utm_source=feedburner&utm_medium=feed&utm_campaign=Feed%3A+sciencedaily+%28ScienceDaily%3A+Latest+Science+News%29
- Ur, J. A. (2005). Sennacherib's northern Assyrian canals: New insights from satellite imagery and aerial photography. *Iraq*, 67, 317–345.
- Ur, J. A. (2010). Cycles of civilization in northern Mesopotamia, 4400–2000 BC. *Journal of Archaeological Research*, 18, 387–431.
- Van de Poel, I., & Verbeek, P. (2006). Ethics and engineering design. *Science, Technology & Human Values*, 31, 223–236.
- Verbeek, P. (2006). Materializing morality. Design ethics and technological mediation. *Science, Technology & Human Values*, 31, 361–380.
- White, D. C., & Schwarcz, P. H. (1989). Ancient Maya diet: As inferred from isotopic and elemental analysis of human bone. *Journal of Archaeological Science*, 16, 451–474.
- Wilkinson, T. J., & Rayne, L. (2010). Hydraulic landscapes and imperial power in the near east. *Water History*, 2, 115–144.
- Wilkinson, T. J., Rayne, L., & Jotheri, J. (2015). Hydraulic landscapes in Mesopotamia: The role of human niche construction. *Water History*, 7, 397–418.
- Wilkinson, T. J., Wilkinson, E., Ur, J. A., & Altaweel, M. (2005). Landscape and settlement in the neo-Assyrian empire. *Bulletin of the American Schools of Oriental Research*, 340, 23–56.
- Wittfogel, K. (1957). *Oriental despotism. A comparative study of total power*. New Haven, CT: Yale University Press.
- Woodson, M. K. (2016). *The social organization of Hohokam irrigation in the Middle Gila river valley, Arizona*. Gila River Indian Community Anthropological Research Papers 7. Tucson: The University of Arizona Press.
- Wyatt, A. R. (2014). The scale and organization of ancient Maya water management. *WIREs Water*, 1, 449–467.

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