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FOCUS ARTICLE

Diversity in ancient Maya water management strategies and landscapes at Caracol, Belize, and Tikal, Guatemala

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The Classic Period Maya cities of Caracol and Tikal possessed unique urban morphologies of water management. In part, the built environment at each city reflects adaptations to the hydrology of their landscapes. Caracol exists in a rugged, hilly, and karst environment; its residents invested their landesque capital in constructing agricultural terraces and residential reservoirs. These features created Caracol's anthropogenic garden-city landscape. This landscape was unified through a dendritic causeway system and the distributed nature of monumental nodes. The landscape of Tikal exhibits a lower slope, is generally smoother, and its residents invested in constructing a large and condensed site core along with their monumental reservoirs. Additionally, the people of Tikal invested in bajo margin agriculture. The differences in urban form and hydrology conditioned the resulting water management strategies employed by both cities; the resulting built environmental features are preserved in the archeological record. Because of its higher slopes, Caracol's landscape presents a greater hazard for soil erosion and faster rainfall runoff. Yet, the construction of distributed residential reservoirs and agricultural terraces acted to collect rainfall, increase soil saturation, and reduce this runoff. Tikal's landscape on the whole presents fewer hazards in terms of soil erosion but perhaps greater issues from torrential rainfall. Water management infrastructure at both cities reflects both their unique urban morphologies and environmental conditions.

This article is categorized under:
Engineering Water > Planning Water
Science of Water > Methods

KEYWORDS
Caracol, classic period Maya, geographic information system, Tikal, water management

1 | INTRODUCTION

Caracol, Belize, and Tikal, Guatemala (Figure 1) are two of the largest and best documented ancient cities in the Southern Maya lowlands. These cities flourished during the Classic Period (C.E. 550–900) and both were largely abandoned by the onset of the Postclassic Period (ca. C.E. 900–1550). Both cities exhibit distinctive developments and trajectories in terms of Maya urbanism. Tikal focused on constructing a well-defined, monumental site core (Haviland, 1970, figure 19) surrounded by higher settlement density and a partial earthworks barrier (Webster et al., 2007), while Caracol utilized a dendritic causeway system (A. F. Chase & D. Z. Chase, 2001, pp. 276–280) to interconnect distributed market nodes (A. F. Chase & D. Z. Chase, 2015; A. F. Chase, D. Z. Chase, Terry, Horlacher, & A. S. Z. Chase, 2015; D. Z. Chase & A. F. Chase, 2014a) amid

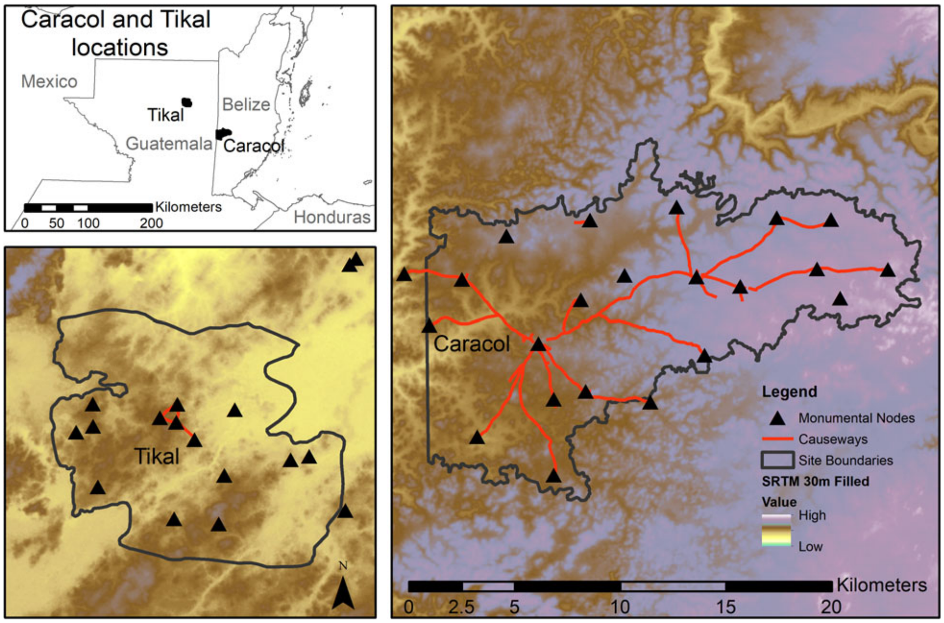

FIGURE 1 Map of Caracol, Belize, and Tikal, Guatemala, including modern national boundaries and the site boundaries utilized in this research in addition to the monumental nodes and causeway systems at both cities

its garden city landscape (A. F. Chase & D. Z. Chase, 1998, pp. 60–62; Graham, 1999, p. 191) of residential reservoirs (A. S. Z. Chase, 2016a), agricultural terraces (A. S. Z. Chase & Weishampel, 2016), and residential *plazuela* groups (A. F. Chase & D. Z. Chase, 2014, pp. 4–5, 9–13; A. S. Z. Chase, 2017, figure 2). In particular, and contrary to the similarities briefly mentioned by Ertsen and Wouters (2018), while only 76 km apart, both cities utilized unique systems of water management and exhibited distinctive urban morphologies of water use. While the underlying terrain has been modified by over a thousand years of human occupation (A. F. Chase & D. Z. Chase, 2016a), this same topography shows, at the macro scale, some important distinctions between the hydrology of both cities.

Both Caracol and Tikal exhibited a high degree of difference in their built environments (see A. F. Chase, D. F. Chase, & A. S. Z. Chase, in press; A. S. Z. Chase, 2019), and comparisons demonstrate the uniqueness of these cities compared to other contemporary Maya centers. As Wyatt (2014) has shown, the diversity of adaptations across Maya cities with regard to water use cannot be ignored; and, with regard to Maya water management strategies, Dahlin and A. F. Chase (2014) demonstrated both similarities and differences in the approaches used for water management by the ancient Maya of Caracol, Tikal, and Calakmul, Mexico. While neither Caracol nor Tikal utilized pressurized water, Palenque evidences a different system of pressurized water flow and a unique case of hydraulic water management by the Maya (French & Duffy, 2010, pp. 1029–1032; French, Duffy, & Bhatt, 2012, pp. 30–31). The present research focuses on the distinctions in water management between Caracol and Tikal. We acknowledge that other important distinctions between these cities existed in terms of politics, economics, and agriculture; however, the focus here is on water management as related to landscape. Two primary rationales for examining ancient Maya water use are the need for potable water for drinking and for water for agricultural subsistence. The water management systems of both Tikal and Caracol were influenced by their respective landscapes.

1.1 | Potable water

For Maya cities, potable drinking water was provided by monumental reservoirs, as at Tikal (Scarborough & Gallopin, 1991, p. 659), by constructed residential reservoirs, as at Caracol (A. S. Z. Chase, 2016a, figure 5), by constructed chultuns, as at Sayil (Dunning, 1994), and by natural, and sometimes modified, aguadas that occur throughout the Maya lowlands (Brewer, 2018). Each of these features provided a means for adapting water storage solutions to cope with the wet and dry seasonality of the Maya lowlands, sequestering water during the abundant wet season to provide for the multi-month dry season. The catchment and volume of these features requires detailed future analysis (sensu French & Duffy, 2014; French, Duffy, & Bhatt, 2013).

While chultuns—cavities constructed in underlying limestone bedrock—were used to both catch and store water in the Northern Maya lowlands, they were not similarly used in the Maya Southern lowlands. At Caracol, chultuns usually contain early burials and would not have been suitable for water storage (Hunter-Tate, 1994). Instead, Caracol possessed a few large reservoirs distributed among its monumental nodes—concentrations of monumental architecture including the presence of multiple large-scale features—(see A. S. Z. Chase, 2016b) along with thousands of constructed residential reservoirs managed at the household level (A. S. Z. Chase, 2016a). In contrast to Caracol, Tikal, relied almost exclusively on a centralized network of large reservoirs connected to the city center (Scarborough et al., 2012; Scarborough & Gallopin, 1991, p. 659) with existing research showing some evidence of limited residential reservoir construction (see Gallopin, 1990, p. 22; Weiss-Krejci & Sabbas, 2002). Future analysis of Light Detection And Ranging (LiDAR) survey data may provide more information on the water management at Tikal beyond the network of large reservoirs, potentially adding to our understanding of water management at the city (Canuto et al., 2018; Weaver, Carr, Dunning, Florea, & Scarborough, 2015).

The reservoir systems at both cities exhibit distinct differences in water management. Caracol distributed its potable water across the city with reservoir size heavily based on construction sequence (A. S. Z. Chase, 2016a, 2019). Large reservoirs co-occur with public architecture early in Caracol's history; however, over time the city water management strategy shifted to incorporate a multitude of smaller residential reservoirs distributed throughout the city's landscape (A. S. Z. Chase, 2016a). While Tikal did have some small residential reservoirs (Gallopin, 1990, p. 22), that city's focus appears to have been on a centralized system of reservoirs emanating from the urban core. The reservoir system at Tikal also grew over time by expanding the size and number of its large reservoirs (Scarborough, Dunning, et al., 2012). While the distributed versus centralized urban morphology of the two cities helps explain basic differences in the geographical layout of their hydrologic infrastructure, there are also crucial differences in the form and function water management infrastructure between both cities (D. Z. Chase & A. F. Chase, 2017; Dahlin & A. F. Chase, 2014; Lentz, Dunning, Scarborough, & Grazioso, 2018).

1.2 | Agricultural water

Agricultural water use showcases a variety of environmental adaptations. Labor to build agricultural terraces (A. F. Chase & D. Z. Chase, 1998; A. S. Z. Chase & Weishampel, 2016, pp. 358, 360) and construct raised fields (see Sluyter, 1994) showcases the investments that the Maya made in landesque capital (Håkansson & Widgren, 2014). Other major agricultural methods at Tikal include farming seasonal bajo margins (Dunning et al., 2018; Lentz et al., 2014; Lentz et al., 2018) and initially low-density swidden agricultural solutions (Lentz et al., 2018), which have a long and labored history in Maya research (see Harrison & Turner, 1978 vs. Reina, 1967). Milpa agricultural methods remained environmentally sustainable for smaller population densities, but higher population densities would have required either intensification in agriculture (sensu Boserup, 2008) or the importation of food (Dahlin & A. F. Chase, 2014, p. 144).

Caracol primarily utilized agricultural terraces (A. F. Chase & D. Z. Chase, 1998; A. S. Z. Chase & Weishampel, 2016; Murtha, 2002, 2009, 2015) and heavily modified its landscape (A. F. Chase & D. Z. Chase, 2016b) to provide for its subsistence needs (Dahlin & A. F. Chase, 2014, pp. 145–146, 146–147). Tikal instead focused on upland agriculture and bajo margin agriculture for its intensive agricultural needs (Lentz et al., 2018; Lentz et al., 2014, p. 18516). These landscape modifications have modern impacts, and affect the current flora that are present (Hightower, Butterfield, & Weishampel, 2014, pp. 10726–10727). While terraces are traditionally known to reduce soil erosion (Turner, 1974, p. 120) and Caracol's landscape benefits more from erosion control than Tikal's landscape would (see our Methods section below), these terraced fields were also constructed to manipulate the flow of water in a zigzagging pattern downslope to increase infiltration rates and the size of the root reservoir (A. S. Z. Chase & Weishampel, 2016, pp. 365–366). The end result of this terracing is that the inhabitants of Caracol could have provisioned most of their own food (Dahlin & A. F. Chase, 2014, pp. 145–146, 146–147; Murtha, 2002) because of a heavy labor investment in transforming their urban landscape (A. F. Chase & D. Z. Chase, 2016a, pp. 4–6; A. F. Chase & D. Z. Chase, 2016b, pp. 366–369).

Tikal, in contrast, would have required trade in foodstuffs to sustain its population (Dahlin & A. F. Chase, 2014, p. 146), assuming that its estimated population exceeded 45,000 people (see Culbert, Kosakowsky, Fry, & Haviland, 1990 vs. Lentz et al., 2014; Wong, Ribeiro, & Gomes, 2017). Trade and exchange in ancient foodstuffs is difficult to study (A. F. Chase et al., 2015, pp. 244–245; Jones, 2015, pp. 83–84); however, without trade among Maya cities it is almost impossible to adequately factor ancient calorie consumption (see Wong et al., 2017, for a detailed calorie consumption analysis that does not factor trade). Tikal utilized its location among the seasonal bajos and reservoirs to farm silted fields (Lentz et al., 2018; Lentz et al., 2014, p. 18517). The flatter landscape with these seasonal swamps prompted a different environmental response in Tikal than at Caracol, which covered its hillier landscape with agricultural terracing. In either case, both cities utilized distinct systems of agricultural intensification to provide for subsistence needs that respected the differences in the underlying landscapes.

1.3 | Maya water management

Theories of how the ancient Maya managed their water primarily originate from the dataset provided by survey and excavation at Tikal (Carr & Hazard, 1961). Fundamentally, the initial theory rests on Vernon Scarborough's foundational model of accretional development where Maya settlement shifted from concave to convex urban-watersheds (Scarborough, 1998, figure 2). This framework reinforces his concept of the Maya as a labor-tasking society, where applications of labor solved social problems and obviated the need for technological innovation (Scarborough, 2003). These theories provided the reasoning for Tikal's monumental reservoir construction over time and highlight the utility of these reservoirs and the ability of the elite to manage them to mitigate drought conditions (Gallopin, 1990; Scarborough & Gallopin, 1991). Lisa Lucero built upon this framework to create a complete theory of water management for the ancient Maya (Lucero, 2006a, 2006b). This theory of elite control focuses on the importance of elite management of monumental reservoirs. Such control naturally led elites to dominate water ritual and monopolize water iconography, resulting in water being conceptualized differently by the ancient Maya; rather than being a simple necessity, it became a resource associated with the rule and governance of elite families (Lucero, 2006b). Drought is often implicated in the Classic Period Maya collapse (Douglas, Demarest, Brenner, & Canuto, 2016; Douglas et al., 2015; Gill, Mayewski, Nyberg, Haug, & Peterson, 2007; Kennett et al., 2012, but also see Haldon et al., 2018), and Lucero's model suggests that the Maya collapse occurred as a result of a drought that demonstrated that elites did not in fact control rainfall (Lucero, 2002, 2006a). This led to a disintegration of the social contract between elite and nonelite and the fall of those elites as “scapegoats” (Iannone, 2016; Iannone, Houk, & Schwake, 2016). Alternatively, the collapse itself can be considered as transformative relocation (Nelson, A. S. Z. Chase, & Hegmon, 2014) or as an upward collapse (Erasmus, 1968). Based solely on the epicentral dataset from Tikal, no other currently available theory has explained the origin of elite power, the growth of the monumental center, and the eventual disintegration of Tikal (also see Lentz et al., 2018; Lucero, 2006a, 2006b).

While the elite control theory of water management relies on data from city centers and site cores, another trend in water management research focused on residential reservoirs (Johnston, 2004; Weiss-Krejci & Sabbas, 2002). These smaller reservoirs do not easily fit into the elite control model of water management because of the inherent difficulty in policing the use of these features. The further away from the monumental reservoirs and the concentrated nodes of elite monumental architecture, the more difficult it is for the elite to control water resources (Scarborough, 2003). Further research into residential water management went hand-in-hand with the advent of LiDAR survey in the Maya region. By providing large-scale, detailed settlement and landscape information, this technology has created a paradigm shift in Maya research (A. F. Chase et al., 2014; A. F. Chase, D. Z. Chase, Fisher, Leisz, & Weishampel, 2012). With LiDAR surveys, Mayanists are uncovering additional water management features, both natural and constructed, within Maya cities (Brewer, 2018; Brewer et al., 2017; A. S. Z. Chase, 2016a). These data do not support the elite control hypothesis. Instead, renewed interest in Maya water management theory has started to highlight the diversity of water management systems practiced by the ancient Maya (A. S. Z. Chase, 2019; French et al., 2013; Wyatt, 2014).

1.4 | Similar or distinct landscapes?

In a recent study, Ertsen and Wouters (2018) challenged the orthodox view of Maya water management at Tikal through the analysis of a simplified model of the hydrologic system at Tikal. While their primary findings concur with previous research about the ability of the monumental reservoirs to provision water in the dry season (Gallopin, 1990; Scarborough & Gallopin, 1991), the model suggests that (a) the hydrologic system at Tikal was regularly overburdened by massive water surpluses after large rainstorms and (b) the physical operation of the floodwater distribution system at Tikal could easily have been coordinated without centralized hydrologic management (Ertsen & Wouters, 2018). Taken together, Ertsen and Wouters take these results to suggest that, despite the known differences in form of their hydrologic systems, Tikal and Caracol may both have exhibited very similar water management strategies (Ertsen & Wouters, 2018). This conclusion leaves us with a paradox. If the hydrologic infrastructure of both Tikal and Caracol were similar decentralized systems designed to manage excess runoff, then why do we see clear distinctions in the built environment of water management features? This proposed similarity is asserted based solely on their model for Tikal without a separate model for Caracol. The centralized or decentralized nature of water management features is a contentious research topic, which will require future investigation. The research reported here focuses on testing the similarity of Caracol's and Tikal's agro-urban landscapes through landscape-level analysis of both ancient cities.

1.5 | Archeological evidence

Recent empirical analysis from both Tikal and Caracol supports the notion that the ancient Maya used reservoirs not only to manage water shortages, but also water surpluses and runoff. Analyses of Tikal's water management system have broadly concluded that the system of reservoirs, canals, and check dams functioned to control violent seasonal floods (Dunning et al., 2015; Scarborough & Sierra, 2015). Similarly, it has long been known that the system of agricultural terraces at Caracol acted to mitigate erosion and control runoff (A. F. Chase & D. Z. Chase, 1998; Healy, Lambert, Arnason, & Hebda, 1983; Murtha, 2002); however, further testing with LiDAR data also indicates that the terraces guided the flow of runoff from terrace to terrace in a zigzagging flow that would have further minimized runoff (A. S. Z. Chase & Weishampel, 2016). Caracol and Tikal both dealt not only with water shortages in the dry season, but also water surplus in the wet season.

At Tikal, archeological trends from the Late Preclassic through the Late Classic suggest the existence of an intensifying runoff problem. This trajectory charts the growth of population and land use, the expansion of hydrologic infrastructure, and increasing amounts of erosion and deposition followed by a reorganization to bajo margin agriculture and decreasing erosion (Lentz et al., 2018). Previous research has also suggested that historically the built environment helps manage a hydrologic runoff problem (Dunning et al., 2015; Ertsen & Wouters, 2018; Scarborough & Sierra, 2015). This hydrologic network at Tikal consisted of a chain of runoff-collection reservoirs connected by artificial canals and natural *arroyos*. The chain of reservoirs situated within this drainage network acted to mitigate the discharge rate by capturing runoff at intervals, greatly slowing its velocity before spillover further downstream. Likewise, additional channelized canals were constructed to ensure that the flow of violent flood events was directed toward the network of weirs, check dams, and reservoirs (Scarborough & Sierra, 2015).

The hydrologic infrastructure of Caracol likewise suggests the existence of a severe runoff problem. Research increasingly suggests that the terraces of Caracol functioned as an integrated hydrologic system. Unlike other terraced regions across the Maya Lowlands, about 80% of the land area at Caracol is covered in terraces. As a result, Caracol's drainage network is completely terraced (A. F. Chase, D. Z. Chase, & Weishampel, 2010, pp. 28–29; Hightower et al., 2014; Murtha, 2002). This includes terracing of the valleys, the hillslopes, and even the hilltops. Terraces also functioned to maximize infiltration, reduce discharge, and slow the flow of water through Caracol's drainage network (A. F. Chase & D. Z. Chase, 1998; A. S. Z. Chase & Weishampel, 2016; Healy et al., 1983; Murtha, 2002). This network of terraces controlled the downhill flow of water through the valleys that would otherwise have flowed through a natural network of seasonal torrents (A. S. Z. Chase & Weishampel, 2016; Murtha, 2002). The enormous number of these terraces suggests a potential for huge downstream transfers of sediment from hillslopes and upstream valleys. In addition, these terrace fields indicate excavation of existing soil and reconstruction of the soil down to bedrock from either human labor (Healy et al., 1983) or a unique geologic process (Coultas, Collins, & A. F. Chase, 1994); in sum, archeological evidence indicates that these terrace soils were not the result of infilling by erosion and deposition processes (Coultas et al., 1994; Healy et al., 1983). The hydrologic functions of terraces at Caracol might be seen as a crucial impetus to their construction—reducing runoff—in addition to expanding the cultivable area for a growing population. Taken together, this suggests that the potential magnitude of runoff and erosion at Caracol were also severe.

2 | METHODS

The following methods provide a set of metrics for testing the similarity between landscapes through Geographic Information System (GIS). While specific differences occur depending on the GIS platform of choice, these methods are applicable to both ArcGIS and Geographic Resources Analysis Support System (GRASS) GIS. We focus on the following methods: geomorphons, slope, and curvature. All of the data is based on the 30 m Shuttle Radar Topography Mission (SRTM) (Dorshow, 2012; Farr et al., 2007), and, as such, everything is derived from this primary elevation dataset. More complicated erosion and hydrology methods can be conducted, but the larger differences in those GIS methods are essentially captured within slope and curvature—the derivatives of elevation and of slope, respectively. No additional methods are required to test the fundamental question of landscape similarity or dissimilarity.

We conducted our analysis in GRASS version 7.4 and ArcGIS 10.5 with figures created in ArcGIS. To conduct the analysis with comparable data, we utilize the 30 m filled SRTM dataset freely available online (Farr et al., 2007; NASA JPL, 2013). The resolution of the dataset offsets any issues from the ancient built environment, that is, the terraces at Caracol, which would occur at a higher resolution. The area shapefiles for Caracol's extent were selected by the area of intensive terracing identified in the Belizean LiDAR (see A. F. Chase et al., 2011; A. S. Z. Chase, 2016b). Settlement and agricultural terracing continues beyond this boundary, but most terraces shift from full coverage to solely valley bottom terraces. The area shapefile for Tikal was selected from the boundary created by Puleston based on his settlement work at the city (Puleston, 1983).

2.1 | Geomorphons

Geomorphons have already proven their utility in LiDAR analysis at Caracol (A. S. Z. Chase, D. Z. Chase, & A. F. Chase, 2017); however, they are fundamentally an application of landscape openness (Yokoyama, Shirasawa, & Pike, 2002) reimagined by classification of the landscape into geologic forms (Stepinski & Jasiewicz, 2011). In essence, geomorphons use a moving window to select elevation change of positive, negative, or zero for raster cells along the eight cardinal and ordinal compass directions within a specified search distance (Jasiewicz & Stepinski, 2013).While the classification method itself is more complex than the following analyses, it is an improvement on the use of topographic position index, another useful landscape classification tool (Jenness, 2006). Geomorphon analysis was conducted with the r.geomorphon tool in GRASS using these variables: outer search radius = 8 cells (240 m), inner search radius = 3 (90 m), flatness threshold = 3°, and flatness distance = 4 (120 m).

The result of this analysis shows a landscape classification method of exploring the similarity of both Caracol and Tikal in Figure 2 and Table 1. These results show that Tikal has a generally flatter landscape than Caracol with more gradual changes in height. The uplands of Tikal are characterized by a series of broken ridges and hills that gradually slope downwards to seasonal bajos by means of an undulating series of footslopes, valleys, flats, and local depressions nestled among the hills. In contrast, Caracol's rugged topography is densely crowded with hills and ridges that slope steeply downwards into a winding network of long and narrow valleys; however, based on survey and ground truthing of LiDAR datasets actual water flow at

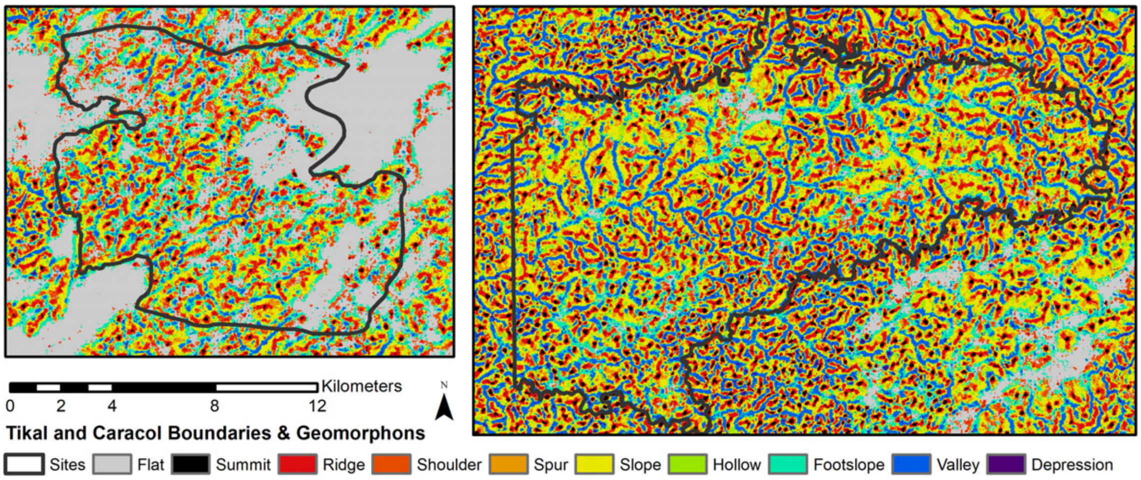

FIGURE 2 A comparison of geomorphons between Caracol and Tikal showing the distinct sets of landforms types present in each

TABLE 1 Comparative summary table of geomorphons, slope, topographic convergence index (TCI), and curvature for Caracol and Tikal. Values calculated in GRASS GIS

	Area (km^2)			Percent of area			
Geomorphon landform	**Tikal**	**Caracol**		**Tikal**		**Caracol**	
Summit	0.98	5.30		0.8%		2.7%	
Ridge	10.48	28.86		8.7%		14.8%	
Shoulder	18.34	10.42		15.3%		5.3%	
Spur	4.58	20.64		3.8%		10.6%	
Uplands total	*34.38*	*65.23*		*28.6%*		*33.4%*	
Valley	8.02	36.14		6.7%		18.5%	
Hollow	2.74	19.83		2.3%		10.2%	
Depression	0.23	1.15		0.2%		0.6%	
Lowlands total	*11.00*	*57.12*		*9.2%*		*29.2%*	
Slope	18.24	50.25		15.2%		25.7%	
Footslope	22.35	18.53		18.6%		9.5%	
Flat	34.04	4.24		28.4%		2.2%	
Metric	City	Mean	Median	*SD*	Range	Min	Max
Slope	Tikal	4.1	3.6	2.6	22.0	0.0	22.0
	Caracol	8.2	7.1	5.2	40.5	0.0	40.5
TCI	Tikal	7.8	6.4	4.0	25.1	2.9	28.0
	Caracol	7.1	6.0	3.5	26.8	2.3	29.1
Curvature	Tikal	−0.00005	−0.00001	0.00179	0.02548	−0.01068	0.01480
	Caracol	−0.00029	−0.00029	0.00272	0.03751	−0.01864	0.01886

Caracol is hampered by the existence of limestone sinks into which the water drains. This is not visible at the scale of the 30 m SRTM.

2.2 | Slope (and topographic convergence index)

Slope is the rate of elevation change and an important topographic variable in hydrological dynamics because it is proportional to the rates of runoff and erosion on hillslopes. GIS programs typically calculate slope as either a 3x3 or a 5x5 moving window, which stores the highest slope change, in degrees for our analysis, in that window within each raster cell (see Burrough & McDonnell, 1998). All basic GIS analytical tools for investigating hydrologic attributes of the landscape require slope. For instance, one applied metric, the topographic convergence index (TCI; Beven & Kirkby, 1979; A. S. Z. Chase & Weishampel, 2016) provides a topographic proxy for the propensity of each point on the landscape to be saturated from overland flow, based on local slope and flow accumulation. In GRASS, this method is provided by r.watershed and in either GRASS or ArcGIS this metric can be calculated with the following map algebra expression natural_log (*upstream_area*/by Tan [*radian_slope*]).[1]

In the case of slope, this metric highlights the smoother, less rugged nature of Tikal's landscape (Table 1). Tikal has a lower mean, median, standard deviation, and maximum slope than Caracol. Since slope is indicative of the velocity of flowing water and proportional to runoff and erosion rates, this higher and more variable slope at Caracol favored the construction of agricultural terraces and showcases the more rugged landscape of Caracol (Figure 3).

The TCI (Figure 4) indicates that Tikal has greater convergence of overland flow, and also reinforces the role played in the diffusion of overland flow by Caracol's terraces (A. S. Z. Chase & Weishampel, 2016). Tikal has slightly a higher TCI mean, median, and standard deviation; however, Caracol has a slightly larger range in TCI values (Table 1). In essence, Tikal

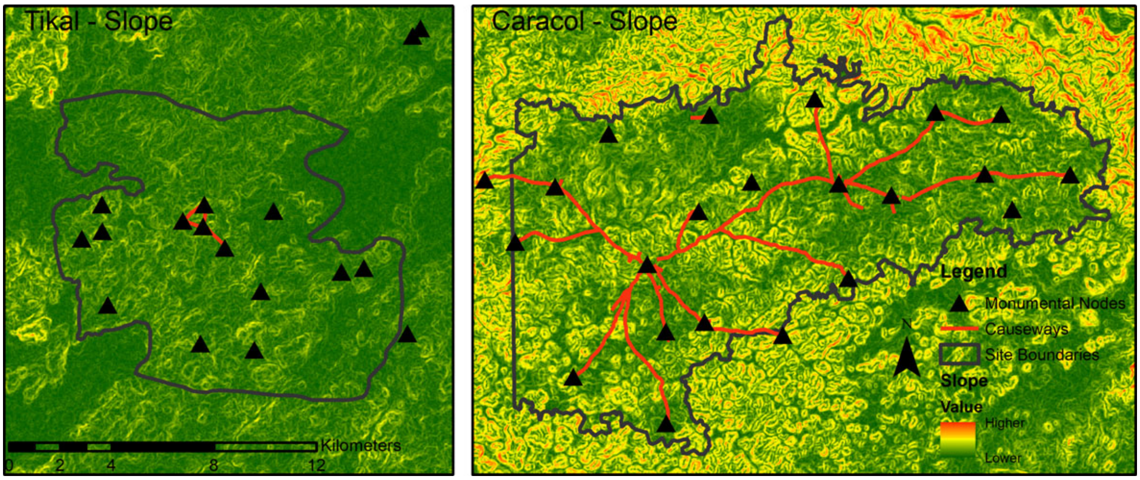

FIGURE 3 A map of slope at Caracol and Tikal. Higher slopes result in greater erosion

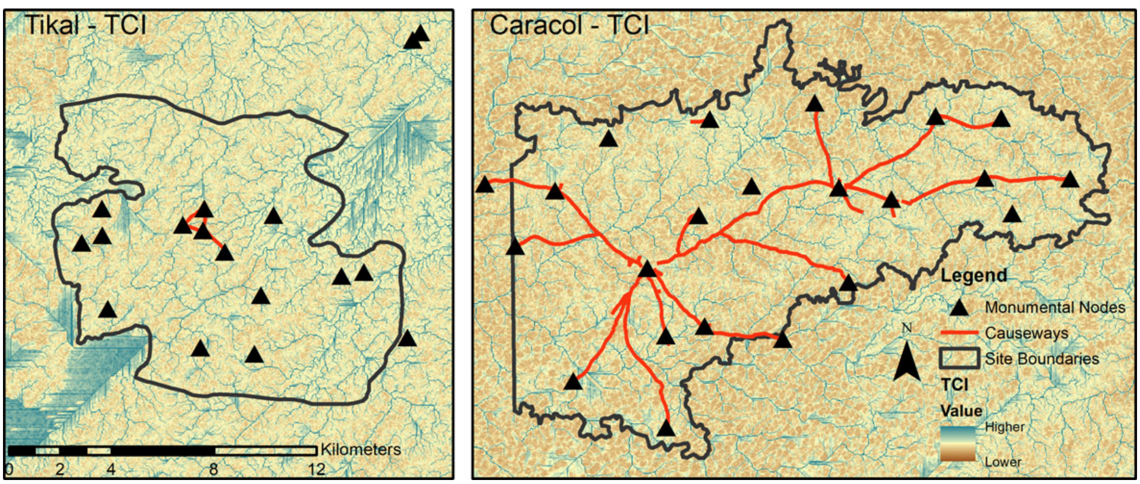

FIGURE 4 Topographic convergence index (TCI) also called the topographic wetness index (TWI) for Caracol and Tikal. This value indicates the expected saturation of water on a landscape

would be wetter on average than Caracol, while Caracol has more extremes because of the valleys and ridges identified as geomorphons above.

2.3 | Curvature

Curvature is the derivative of slope, measuring the rate of change of the slope. Higher curvature results in more erosion, and a more rugged landscape have a higher curvature. While there are a variety of potential curvatures, profile curvature parallel to slope provides a better indicator of landscape ruggedness and likely erosion. Curvature is calculated in a 3 × 3 window (see Moore, Grayson, & Ladson, 1991; Zevenbergen & Thorne, 1987). In GRASS, curvature is a byproduct that can be generated by *r.slope.aspect*, and in ArcGIS, the *Curvature* tool using profile curvature provides the same functionality but with different output value ranges than GRASS.

Caracol actually possesses a lower mean curvature than Tikal; however, curvature at Caracol has both a much higher standard deviation and range (Table 1). This mean that Tikal's landscape on average is more susceptible to erosion; however, Caracol's landscape has more drastic variation and uneven erosion potential. The high slopes and long narrow valleys seen in the geomorphon analysis impact the overall average, and in aggregate these features lower the average curvature present (see Figure 5).

3 | RESULTS

These fundamental topographic analyses demonstrate that the landscapes of both Caracol land Tikal were distinct (see Table 1). The geomorphon data shows that Caracol possesses far less relatively flat land than Tikal, with an abundance of ridges and valleys. Slopes at Tikal were lower, less variable, and smaller than slopes at Caracol; reinforcing the idea that Caracol possesses a more rugged landscape. TCI shows that convergence of overland flow is slightly higher at Tikal than at Caracol with more variability in TCI at Caracol. Finally, curvature shows that Tikal likely experienced more average erosion, while Caracol possessed a wider range of extremes in curvature. While future analysis can focus on more detailed hydrologic processes within these landscapes, these fundamental metrics suggest that these two cities had different landscapes with respect to the flow of water. These dissimilar landscapes echo the differences known archeologically in the built environments of Caracol and Tikal.

4 | DISCUSSION

The landscapes on which the cities of Tikal and Caracol (Figure 1) are *quantitatively* different, not just *qualitatively* different with respect to these simple topographic proxies for hydrology. While some water management features provided useful tools, not every ancient Maya environment permitted the same utility for those tools. While the environments did not dictate the water management systems utilized by these cities—as can be seen from Caracol's shift from monumental reservoirs toward residential reservoirs and agricultural terraces over time—the environment certainly conditioned the water management features that are present.

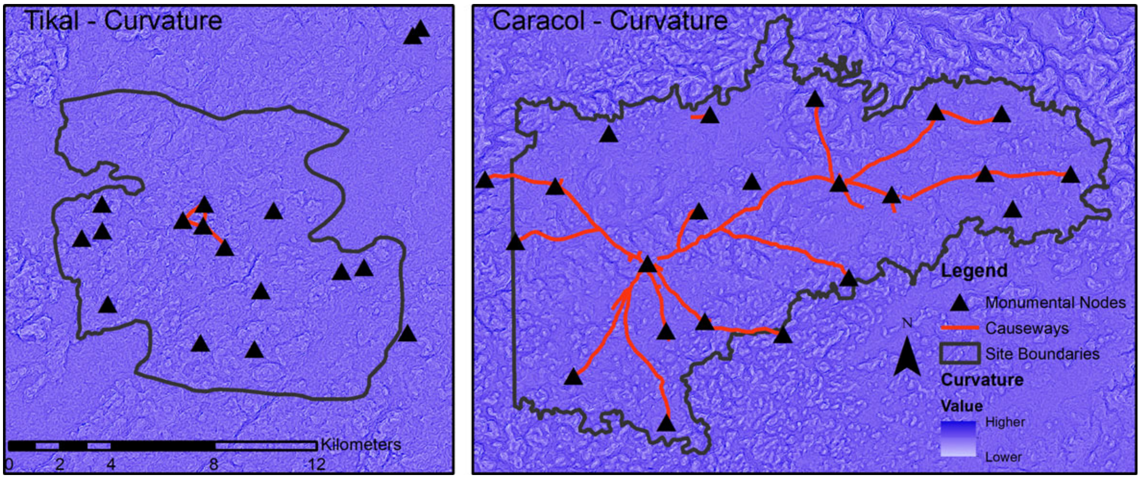

FIGURE 5 A comparative map of curvature, and the derivative of slope for Caracol and Tikal. Higher curvatures result in greater erosion

Two primary issues existed for the landscapes of Maya cities. The first issue was erosion from seasonal rainfall. This loss of soil probably provided some initial impetus for the construction of water management features in conjunction with a desire to harness rainfall when it was abundant, or to increase the soil saturation with water by reducing the speed of rainfall runoff. In this case, precipitation provided the necessary conditions for a city like Caracol with its rugged, karst environment in which it constructed its reservoirs and terraces. However, the second issue would have been the accumulation of too much water, as seen at Tikal (Ertsen & Wouters, 2018). Given the lower rate of erosion and higher rate of water saturation, in addition to the surrounding bajos, Tikal needed to drain and store water in a different capacity than Caracol. In addition, some of Tikal's reservoirs possessed floodgates and would have been utilized for irrigation of surrounding fields (Scarborough, Dunning, et al., 2012; Scarborough & Sierra, 2015).

Ancient Maya cities provided a diversity of water management features and systems (Wyatt, 2014). Solutions to water management issues could involve the use of labor over long periods of time and the investment in landesque capital, as at Caracol (A. F. Chase & D. Z. Chase, 2016b), or technological innovations that might have required water pressure, as at Palenque (French & Duffy, 2010). Tikal had its own bespoke system of reservoirs (Scarborough & Gallopin, 1991) and agriculture (Dunning et al., 2018; Lentz et al., 2018). In each case, the people living within ancient Maya cities engaged in an ongoing dialectic with their environment that could have resulted in path dependency or changes to management strategies (D. Z. Chase & A. F. Chase, 2014b; Scarborough, A. F. Chase, & D. Z. Chase, 2012). While focusing on the environment as the sole cause of change clearly ignores the roles of social, political, and economic issues in causing, maintaining, and perpetuating these water management features, the relationships between humans and their environments are clearly significant.

Even at the qualitative level of water theory, potable water storage features, and agricultural uses for water, Caracol and Tikal possessed distinctive systems of water management. The variation in built environment features indicate differences in both the underlying environment and the management systems employed by the ancient Maya. The landscapes reflect a hillier, more distributed system at Caracol and a convex, more centralized system at Tikal. However, the ancient Maya modified their landscapes over hundreds of years, creating a palimpsest of anthropogenic landscapes (A. F. Chase & D. Z. Chase, 2016a, pp. 9–11; A . F. Chase & D. Z. Chase, 2016b, pp. 366–369), and these changes affect the structure of the forest present today (Hightower et al., 2014, pp. 10726–10727). While westerners have considered these landscapes to be “natural” wilderness, these landscapes indisputably reflect the presence of people, as do most landscapes in the Americas (Denevan, 1992). These landscape modifications accreted over time and include the material remains that resulted from ancient decisions made about environmental factors, path dependencies, and management strategies spanning generations (D. Z. Chase & A. F. Chase, 2014b).

4.1 | Water and the tropical environment

Past considerations of the environment and the ancient Maya have focused on issues that may have hampered the development of civilization in the tropics (see Coe, 1957 versus Meggers, 1954). While not as deterministic as Meggers's suggestion that civilization could not flourish in the tropics (Meggers, 1954), this same debate is manifested in modern literature by a reliance on environmental factors for the collapse (French et al., 2012, p. 45). While the environment certainly plays a role, it does not single-handedly dictate how a civilization develops and flourishes. Social, economic, and political factors behind social change should not be neglected in discussions of collapse (see Haldon et al., 2018). For example, the environment and changes to it are insufficient to explain the collapse; as stated by Turner and Sabloff (2012), p. 13913), “… why did the Maya never reclaim the Classic Period heartland after its environmental recovery?” If the forest recovered in 100 years and the collapse of cities rested solely on environmental factors, then no environmental reason explains the lack of reoccupation of the region upon an environmental recovery (Turner, 2018). Modeling can showcase the power of simple economic interactions and their potential role in the collapse through cascading market failures (Heckbert, 2013, pp. 2.3, 2.13, 14.12; Heckbert et al., 2016). However, it is likely that the environment and its role in collapse has often been overplayed as a result of implicit bias against the potential of tropical environments (see Graham, 1999, pp. 189–190).

While environmental bias can cause issues, another issue might be the framing of the word “collapse.” As Erasmus (1968) asked 50 years ago, why could not this be an “upward collapse?” Maya civilization survives today. The Classic to Postclassic transition can be considered as a social reorganization or as transformative relocation (Nelson et al., 2014). Clearly this shift greatly altered Maya society, but it did not end Maya civilization. Instead, the Postclassic includes its own set of monumental cities and perhaps a systematic shift from overland to overwater trade routes (Gunn et al., 2017; Turner & Sabloff, 2012). Research has shown that investigations into Maya society often echo modern social and political issues (A. F. Chase & Scarborough, 2014; Middleton, 2017; Webster, 2007), and environmental change and social collapse provide a poignant narrative to our current political era.

While the ancient Maya possessed agency independent from simple environmental determinism, the environment did influence ancient practices (Gunn et al., 2017; Gunn, Matheny, & Folan, 2002; Lucero, Gunn, & Scarborough, 2011). In the case of water management, differences in landscapes highlight potential reasons behind the separate management systems utilized by Caracol and Tikal. This underlies the issue with simplifying complex issues such as Maya water management (Ertsen & Wouters, 2018) and ignoring the diversity present between and among Maya cities (A. F. Chase & D. Z. Chase, 2016a; Dahlin & A. F. Chase, 2014; Houk, 2015; Hutson, 2016). Models are not automatically useful in and of themselves, without consideration of how and why they are used and built (Till, Haverkamp, White, & Bhaduri, 2018). A one-size-fits-all attitude toward the ancient Maya will probably neither help shed light on the full range of processes that they experienced nor provide the useful modern comparisons that we desire (French & Duffy, 2014; Isendahl & Heckbert, 2017). In essence, understanding the diversity of responses and the variation in the environment helps us to underpin the water management strategies employed by the ancient Maya through their built environment. The implication of water in the collapse of the Classic period Maya cannot be separated from the structure of hydrologic management of this resource.

5 | CONCLUSION

Ancient Maya water management was complex and resulted from an interplay between management systems, urban morphology, and environmental hydrology. In the cases of Caracol and Tikal, both cities possessed unique infrastructures for their water management systems. Caracol adapted to its rugged and hilly karstic environment through a distributed system of agricultural terraces and residential reservoirs to manage rainfall runoff and increase the capacity of rainfall water storage in both the constructed reservoirs and the terrace root-zone reservoirs. The dendritic causeways interlinked this distributed system into a single city. Tikal adapted to its gentler slopes and smoother landscape through a centralized system of monumental reservoirs near the monumental architecture of the city center and bajo margin agriculture. These features facilitated the drainage of excess water, which would have been a more pressing issue for Tikal than the issue of erosion. In either case, both of these examples focus on the palimpsest of archeological landscape data present at the end of occupation. The fundamental differences in the landscape are shown quantitatively, not just qualitatively, through the utilization of SRTM 30 m data and geomorphons, slope, and curvature. The hydrology and environment clearly influenced the form of water management systems at both cities, but it did not dictate their responses. Initial settlement at Caracol focused on monumental reservoirs in a similar fashion to Tikal; however, as both cities evolved, they diversified their water management strategies in ways that complimented their distinct landscapes.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

ENDNOTE

[1]To avoid taking the natural log of zero in this analysis, the upstream area must include the drainage of each cell to itself. Radian slope can be calculated as follows: pi divided by 180 times slope in degrees within map algebra.

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