Using Lidar and GIS to Investigate Water and Soil Management in the Agricultural Terracing at Caracol, Belize

Adrian S.Z. Chase and John Weishampel

Archaeological lidar (Light Detection And Ranging) is effectively used to enhance the discovery and full coverage survey of sites. Initial lidar application in the Maya Lowlands of Belize in Central America highlighted its ability to "see" beneath the rainforest canopy and reveal the presence of ancient settlement (Chase et al. 2010; Chase et al. 2011). Only a few studies in Hawai'i and the American Southwest have used lidar to investigate agricultural terracing (Dorshow 2012; Ladefoged et al. 2011; McCoy et al. 2011; Wienhold 2013). However, comparable large-scale lidar survey coverage with the ability to consider agricultural practices exists for sites between Caracol and the Belize Valley (Chase et al. 2014; Chase et al. 2011) as well as the city of Angkor Wat in Cambodia

ABSTRACT

In April 2009, a lidar survey flown by the National Center for Airborne Laser Mapping recorded 200 square kilometers of terrain that comprised the Classic Period Maya city of Caracol, Belize. The data revealed a highly manipulated landscape of dense settlement, agricultural terraces, and residential reservoirs. Literature on Maya agriculture has discussed the benefits of terraces in controlling soil erosion, retaining water, and managing the gravitational flow of water; however, until now these benefits have not been quantified or demonstrated on the ground at scale. This research utilizes these lidar data and data derivatives in order to test the degree to which the ancient Maya manipulated their environment and were able to support large-scale populations through their landscape management practices. As such, the research provides evidence supporting the significance of agricultural terraces and their impact on limiting soil erosion, increasing water retention, and permitting flow control over rainfall runoff. This research also highlights the conscious effort by the ancient Maya to manage the hydrology of their terraced landscape.

En Abril de 2009 Centro Nacional para Mapas Láser en Vuelo (NCALM) realizo un levantamiento aéreo utilizando lidar con el que se mapeo la topografía de 200 kilómetros cuadrados que incluyen ciudad Maya de Caracol en Belice que corresponde al periodo clásico. Los datos revelaron una topografía altamente modificada con asentimientos densos, terrazas agrícolas y represas hídricas residenciales. La literatura sobre agricultura Maya ha discutido las ventajas de las terrazas agrícolas para controlar la erosión de los suelos, retener y manejar el flujo gravitacional del agua; sin embargo, hasta ahora estas ventajas no han podido ser cuantificadas o demostrados en el campo a gran escala. Este estudio utiliza los datos de lidar y datos derivados para determinar el grado en que los antiguos Mayas manipularon su medio ambiente para poder sostener grandes poblaciones a través de sus prácticas de manejo y modificación del terreno. Como tal, la investigación proporciona evidencia para soporta la importancia de las terrazas agrícolas y su impacto en la reducción de la erosión de los suelos, aumentar la retención de agua, y el controlar de el flujo de las aguas lluvias. Además, este estudio destaca el esfuerzo intencional de los antiguos Mayas para manejar la hidrología de su terracería agrícola.

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(Evans et al. 2013). At Caracol in particular, lidar has highlighted the staggering degree of agricultural terracing with over 80 percent of the initial 200-km lidar study area systematically covered in terraces (Hightower et al. 2014). This study area does not include the boundaries of the site, and future research should shed light on additional terracing beyond this sample area.

A series of important archaeological investigations and analyses of food production and terracing among the ancient Maya took place in the 1970s and 1980s (Flannery 1982; Harrison and Turner II 1978; Turner 1974, 1983; Turner II and Harrison 1983). The addition of lidar-derived data to this body of research provides support for many of the initial theories and assumptions about the significance of agricultural terracing in the Maya area. Using lidar from Caracol, Belize, this paper quantifies potential effects of agricultural terracing, testing these historical assumptions about Maya agriculture and shows how the ancient Maya consciously manipulated their landscape.

The ancient city of Caracol, located on the Vaca plateau in Belize (Figure 1), was continuously occupied for over 1,500 years from roughly 600 B.C. until after A.D. 900 and contained over 100,000 people in A.D. 650, Caracol's apogee (Chase and Chase 1994). Caracol was founded in a location with plentiful rainfall, but lacked natural standing bodies of water (Chase and Chase 1987). The ancient people of Caracol modified their environment to harness rainfall for two purposes. They created reservoirs, excavated rectilinear features lined with stone and sealed with clay or lime-plaster, to sequester rainfall and provide potable drinking water; and they used agricultural terraces, features cut into steep and shallow slopes, to provide rain-fed agricultural fields retaining heavily manipulated soils behind outer and inner stone retaining walls. These terraces covered both valleys and hillsides with artificially lowered slopes and stone embankments that served to manipulate rainfall runoff to retain both water and soil in support of crop growth. The entire landscape has been modified to suit these purposes (Chase et al. 2011).

As noted above, theories related to ancient Maya agriculture have moved beyond early views of the Maya as solely milpa or swidden agriculturalists and now include many other techniques of agricultural production (Harrison and Turner II 1978; Turner II 1983). There is recognition that the ancient Maya practiced intensified agriculture through terracing, raised and drained fields, and other methods (Flannery 1982; Harrison and Turner II 1978; Turner II and Harrison 1983). Agricultural intensification helps explain the high population densities of the ancient Maya that could not be supported by slash-and-burn agriculture alone (Chase et al. 2011; Harrison and Turner II 1978). Caracol showcases a highly intensified agricultural landscape that also contrasts with initial theories of ancient Maya agriculture that viewed the Maya people as solely milpa or swidden agriculturalists (Dumond 1961); the site confirms the work of Flannery, Harrison and Turner II, and others (Flannery 1982; Harrison and Turner II 1978; Turner II and Harrison 1983; Turner II 1974, 1983) in providing a clear alternative view to early suggestions that the southern Maya Lowland environment could not sustain a complex society (Meggers 1954). However, a comparison of the costs and benefits of swidden and intensive agricultural terracing merits discussion.

As Conklin (1961:28) notes, Mayanists predominantly focus on the interrelated factors of production and population. In terms of agricultural methods, swidden requires the least amount of labor from the farmer while providing the highest return of food per hour worked (Boserup 1965:29). While intensified methods of agriculture lead to higher levels of food production overall, they exhibit reduced efficiency in terms of food per hour worked for the same amount of land. The complex relationship between farmers and intensification of agriculture involves the interplay between individual, institutional, and social subsistence requirements (Scott 1976; Wolf 1966), along with the availability of land and labor for different farming methods (Brookfield 1972:31–35). Additionally, the possibility of agricultural "involution" exists, whereby apparently saturated agricultural production supports additional labor and incremental production sufficient to feed the additional individuals contributing that additional labor (Geertz 1963:80–81). Thus, intensifying agriculture requires a greater investment in land and labor, while at each stage producing smaller marginal utilities of food production, but with increasing food production per area of cultivated land (sensu Boserup 1965).

Agricultural terraces likewise required labor to produce and maintain, but provided a larger quantity of food per unit area as compared to swidden agriculture. Research on agricultural terracing identifies several key improvements that terraced fields provide compared to similar non-terraced terrain, although not all aspects may be present within a single field or field system: (1) reducing the amount of soil erosion, (2) reducing run-off, (3) enhancing the infiltration of water into fields, (4) increasing the soil's water reservoir, (5) increasing overall arable land, or (6) increasing the depth of soil (Donkin 1979; Spencer and Hale 1961; Thomas et al. 1980; Treacy and Denevan 1997). The dependence on rainwater for agriculture at Caracol may have been a factor in the extensive terracing present at the city. Even today, the agricultural terraces at Caracol appear to retain nutrient rich soil, conserve water, alter erosion, and affect modern forest growth (Chase and Chase 1998; Coultas et al. 1984; Coultas et al. 1993; Healy et al. 1983; Hightower et al. 2014). Two additional clarifying points should also be mentioned here. Firstly, the soil of the Caracol terraces differ from the bedrock beneath them completely lacking a C soil horizon, and secondly all stones larger than 1 mm are located in the terrace wall rather than the terrace's soil (Healy et al. 1983:406 and Figure 4). These facts partially indicate the substantial labor that went into constructing these features; these terraces were not constructed by building a course of stones and letting the soil form behind them.

While agricultural terraces provided materials and food, reservoirs provided drinking water. The people of this ancient city engineered the collection and storage of rainfall in reservoirs, and this water would have helped ensure a potable source of water during the dry season. The nearest non-ephemeral body of water is the Macal River, located over 15 km away from the epicenter by air over hilly and mountainous terrain (Chase and Chase 1987). The causeways, the white plastered roads of the ancient Maya, connected the monumental architecture within

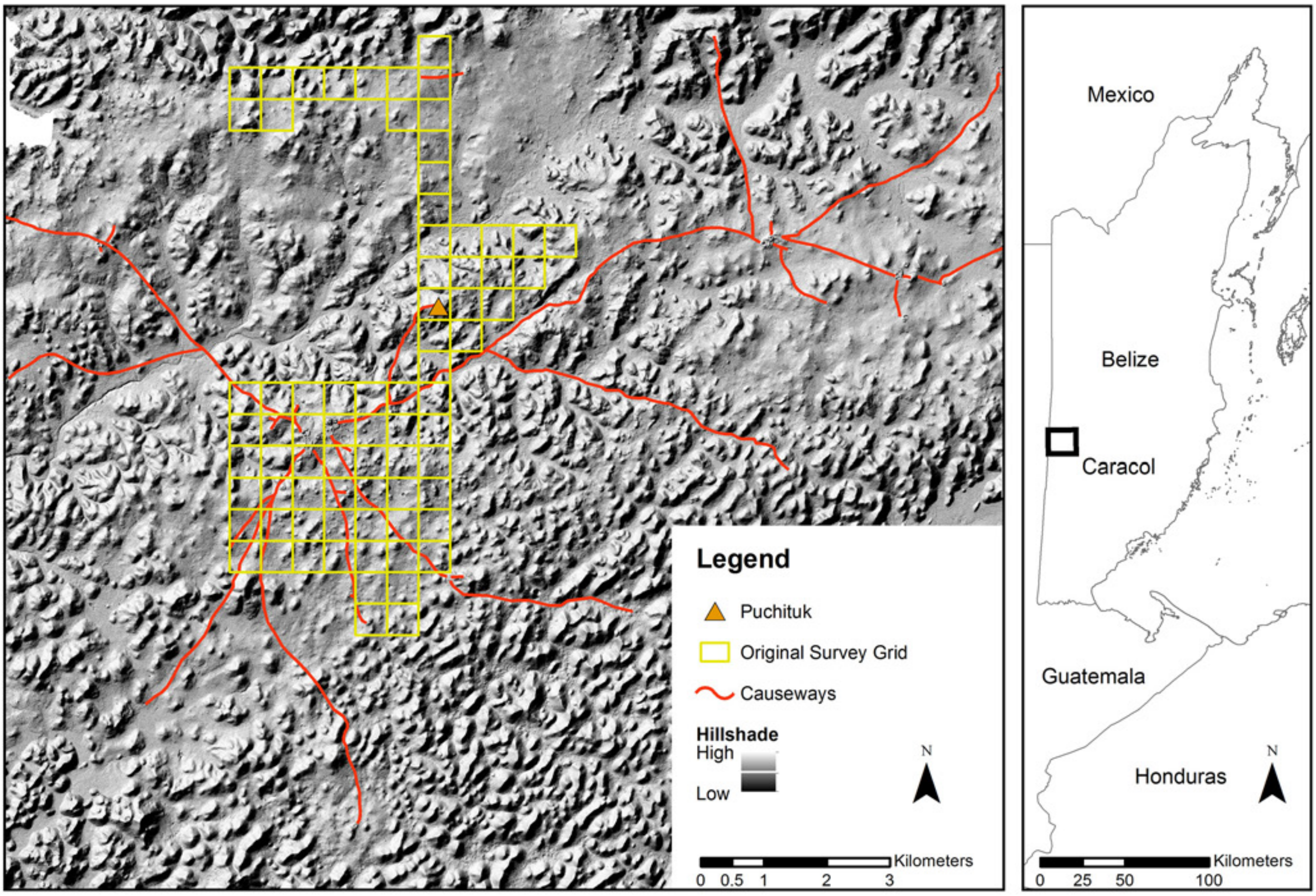

FIGURE 1. The location of Caracol, Belize, represented by the 2009 lidar coverage extent. The lidar-derived DEM as a hillshaded terrain model with the old survey grid (the ground survey extent prior to lidar) and causeways.

the city but do not extend all the way to the river, getting within 4 km of the riverbank at the closest point, with hilly terrain blocking the rest of the way. With these facts in mind, the existence of any large human settlement here showcases the hydrologic acumen of the ancient Maya. The people of Caracol built a city where no modern settlement now exists and the entirety of the city's water came from rainfall.

MATERIALS AND METHODS

2009 Lidar Survey

In April 2009, a lidar survey flown by the National Center for Airborne Laser Mapping (NCALM)[1] recorded 200 km^2 of terrain that comprised Caracol (Chase et al. 2011). The acquired data revealed a densely settled city spread throughout this area with residential groups situated within an extremely manipulated landscape. The lidar data helped demonstrate the full extent of the widespread Maya urban settlement that existed in this portion of the Vaca Plateau. Settlement was interspersed with agricultural terraces and residential reservoirs. Agricultural terraces hypothetically provided the ability both to grow food and to direct the gravitational flow of water over the terrain. Residential reservoirs caught and sequestered runoff rainwater from plazas, terraces, and plains. Thus, through the use of these constructed terraces, the ancient people of Caracol probably controlled hydrology and soil erosion and, through the use of residential reservoirs, they could weather the dry season. The focus within this paper is on documenting the functionality of the terraces themselves using the lidar data collected from Caracol.

The ground returns from the classified point cloud data, derived from lidar flights, were used to generate a Digital Elevation Model (DEM), a grid of cells along latitude and longitude with the elevation represented and stored within them (see Fernandez-Diaz et al. 2014). The resulting DEM represents the ground resolution at 1 m^2 per cell for all of the 200 km^2 of the original 2009 dataset. There were, on average, 1.35 classified ground returns per square meter (Chase et al. 2011:391). Using the DEM generated from the lidar dataset (Figure 1), additional and complementary datasets[2] and indexes[3] were calculated to measure the effects of terracing on the landscape. For example, GIS algorithms can allow for the measurement and reporting of the degree of water control and erosion prevention.

While our primary research goal relies on obtaining measurements for water retention, water flow, and erosion for the terraced fields, we also compare these values against unmodified landscapes as a control. How did the terraces affect their edaphic[4] conditions in different landscape typologies? Do terraces on slopes, valleys, or plains have the same impact? Are the impacts of terraces on these landscape measurements significant? By looking at these questions, we can attempt to understand why the residents of Caracol created hundreds of square kilometers of terraces.

The lidar analysis makes evident that the people of Caracol invested an immense amount of labor into terracing. While the monumental architecture, central palaces, and elite residential compounds may receive more attention from archaeologists (in part because their size makes them easier to find), there are many, many more household-level features on the landscape than monumental features. Caracol's "downtown" and its outlying termini are connected by causeways, and these nodes are characterized by monumental architecture such as formal plazas, ballcourts, and E-Groups (Chase and Chase 1987:10–54). While these nodal causeway termini structures required large amounts of labor to construct, these labor investments occur in just .2 km^2 of this ancient city. In contrast, there are more than 160 km^2 of terraces, 80 percent of the sample area, at Caracol (Chase et al. 2010:28–29; Hightower et al. 2014) and more than 1,400 residential reservoirs (Chase 2012:48–49) within the 200-km^2 survey area. Even with three-dimensional energetics, the labor investments in monumental architecture pale in comparison to the investments made in constructing terraces and reservoirs, which were often excavated to bedrock, built, and maintained throughout the entire landscape of this city. The household plazuela groups existed in this landscape of residential-use reservoirs and agricultural terraces, and the integration of these features gives Caracol the characterization of a "garden city," where harnessed rainwater provided drinking water and permitted agriculture within the urban cityscape (Chase and Chase 1998).

The Caracol Maya constructed two general types of reservoirs. Large monumental reservoirs exist near monumental architectural centers (Lucero 2006a, b; Scarborough and Gallopin 1991; Scarborough 1998) and smaller residential reservoirs exist near households (Chase 2012; Weiss-Krejci and Sabbas 2002). Both reservoir types are identifiable in the lidar dataset. The monumental reservoirs at Caracol have surface areas between roughly 1,000 and 7,000 m^2, while the far more numerous residential reservoirs have surface areas clustering around 25 m^2 with sizes ranging from 5 to 77 m^2. Outlier sized intermediate reservoirs also appear in residential contexts. While visual inspection and survey easily identifies the large reservoirs, the smaller reservoirs require more detailed reconnaissance. Nevertheless, even these features can be discovered by inspection of the DEM and classified point cloud (or even the raw point cloud) data using visual inspection of local relief models (Chase 2012; Hesse 2010), sky-view factor (Kokalj et al. 2011; Zakšek et al. 2011), and other visualization techniques such as openness and geomorphons (Doneus 2013; Stepinski and Jasiewicz 2011).

The thousands of residential reservoirs at Caracol very likely provided drinking water to households throughout the year, especially during the dry season (Chase 2012). Many of these reservoirs were architecturally integrated adjacent to, or on one side of, the plastered plazas of these plazuela groups. Plazas often incorporated channels, slopes, or drains to funnel rainfall into adjacent reservoirs. The plastered surface of these plazas inhibited the permeation of rainfall and increased runoff into the reservoirs. In contrast, some reservoirs existed amid the terraced fields, suggesting that they may have held water for agricultural purposes.

The terraced fields themselves occupied valley bottoms, valley slopes, and occasionally hilltops. They occurred ubiquitously throughout the landscape. Though dependent on rainfall, these terraces provided the agricultural needs of Caracol's population (Murtha 2002). While terracing has been analyzed and studied through traditional means (Treacy 1987; Valdivia 2002), the lidar data for Caracol allow for a more detailed analysis of terraces (Chase et al. 2010). This dataset permits the possibility of measuring the slopes of terraces and simulating the flow of water across them. This allows for an analysis of erosion and water flow patterns of terraces and helps us gain insight into the water and soil management practices of the ancient people of this Maya cityscape.

Terrain Modeling

To provide a visual reference for the following analyses, a large-scale hillshaded terrain model draped over a slope model of the sample region is provided (Figure 2). For these analyses we used ArcGIS[5] and conducted analysis off of the DEM instead of the raw lidar data for a more streamlined algorithmic approach to analysis. We found it easier to reason about algorithmic analysis on 200 km^2 at a 1-m resolution in x and y directions in a raster instead of analyzing a raw xyz point cloud of approximately 4.28 billion measurements. Available computational resources factored into this decision as well, especially the availability and ease of use of map algebra. Finally, it should also be noted that many of the steps below can be replicated through ArcGIS algorithms, map algebra, and algorithms in other GIS packages such as GRASS GIS.

As a preparatory step before running any of the following flow algorithms, a filling algorithm was run over the dataset. The filling algorithm generates a new DEM by iteratively searching through the original DEM identifying and raising the elevation of any sinks to ensure that water flows continuously over the entire surface of the raster and off the edges of the study area. The filling algorithm step removes small errors in the data. For example, centimeter-sized cell depressions caused by random error from the collection and interpolation of the lidar-derived DEM are filled. It also removes small depressions, which may exist, but can cause issues with the heuristics of the flow algorithm including reservoirs. This filling algorithm is required because the default flow algorithm assumes that if water has entered a cell with no adjacent cells of lower elevation, then the water will remain in that cell.

Three primary datasets require calculation from the DEM before additional analysis can be undertaken. First, the flow direction[6] raster provides a representation of the direction in which water would flow off of every cell. Second, the flow accumulation[7] raster provides the accumulated flow of water into each cell based on the flow direction raster. For our purposes, we want to ensure that each cell counts itself for flow; as such, within ArcGIS, the ultimate raster of upstream flow consists of map algebra to add one to every cell in the flow accumulation raster. Third, the slope[8] is also necessary (Figure 2). Many slope algorithms calculate slope in degrees or percent rise; however, for our purposes,

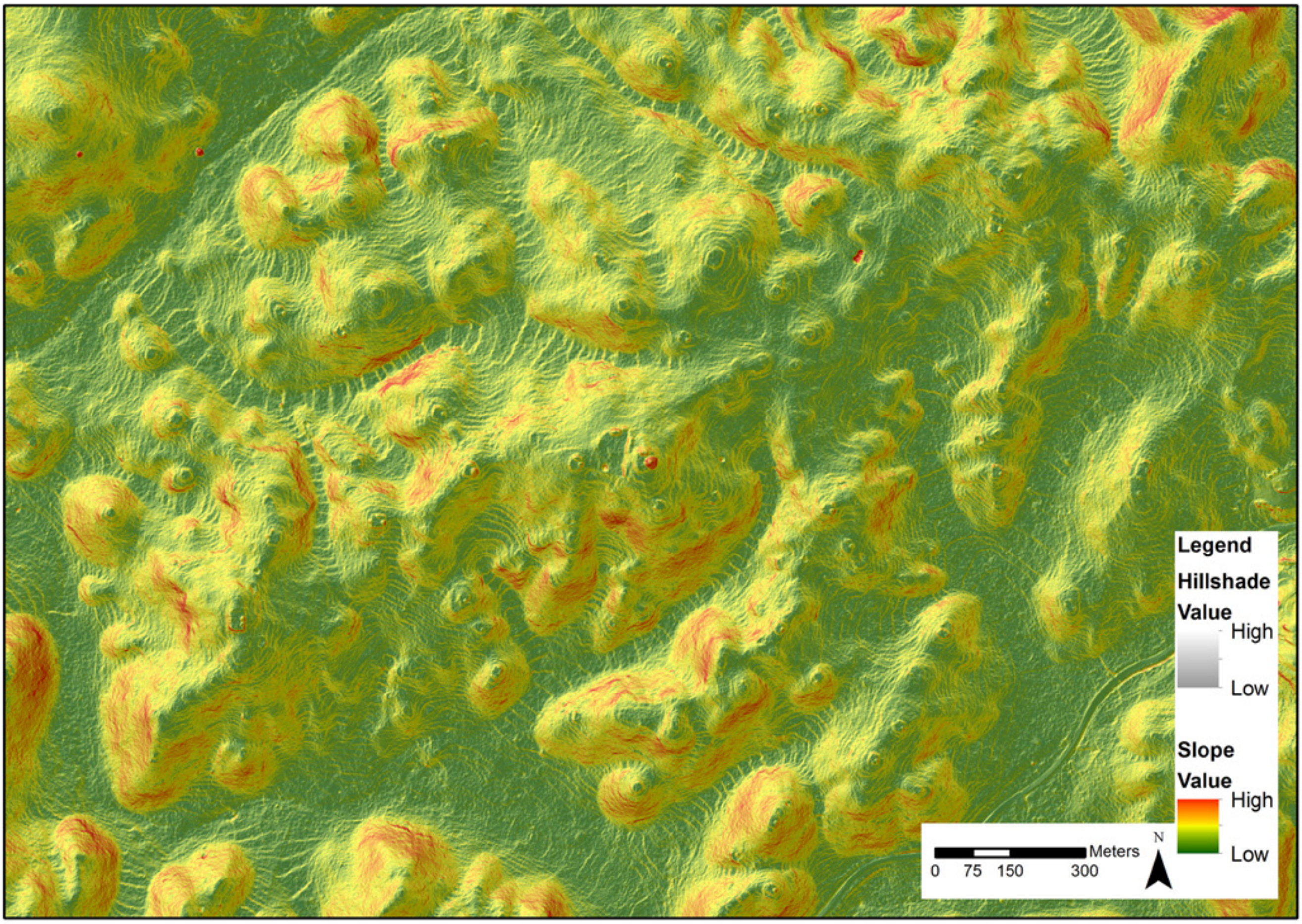

FIGURE 2. A slope colored hillshaded terrain model visualization of the Puchituk terminus.

degree slope must be converted into radian slope using map algebra to multiply degree slope by the pi-over-180 conversion ratio. Radians provide a unit of measure based on the arc-length of a circle and, as such, are required in trigonometric calculations where physical distance is desired, rather than degrees.

From these primary (e.g., flow direction, slope, catchment area) topographic measures, analytically derived, secondary (e.g., radiation load, topographic wetness, stream flow) topographic indices have been developed though terrain analysis of DEMs (Florinsky 1998; Florinsky et al. 2002; Moore, Gessler, et al. 1993; Moore, Turner, et al. 1993; Wilson and Gallant 2000). Following the general approach that has been applied to archaeological landscapes in arid environments (Ackermann et al. 2008; Wienhold 2013), we used the high-resolution DEM to serve as the template to model water-retention and erosion-mitigation effects of ancient Maya agricultural engineering in this humid tropical system.

Erosion and Hydrology Indices

Three secondary indices—(1) Topographic Wetness Index (TWI), also called the Topographic Convergence Index, (2) Stream Power Index (SPI), and (3) Sediment Transport Index (STI)—were calculated across the 200-km^2 DEM (e.g., Figure 3a) using both the Map Algebra and the Hydrology, Surface, and Topography toolboxes developed for ArcGIS. These hydro-geomorphic metrics are readily calculated from digital terrain maps and have been used for a variety of landscape studies that focus on surface water flow and soil erosion. However, these generic indices represent static models that assume equilibrium conditions based on topographic gradients and do not account for real cause and effect or heterogeneity in soil, vegetation, and weather conditions. Thus, dynamic weather events or variations in ecophysiology associated with differences in land cover are not included. More mechanistic models, such as the Soil and Water Assessment Tool (SWAT) or hydro-archaeological approaches, would require more detailed site-specific soil and precipitation parameterization but could be applied to assess the effects of terracing (e.g., French et al. 2013; Yang et al. 2009) under changing climate and ecosystem conditions. These could be historic climate (Medina-Elizalde and Rohling 2012) or current deforestation (Weishampel et al. 2012) patterns. The application of these more reductionist models is beyond the scope of this article.

The Topographic Convergence Index (TCI) (Beven and Kirkby 1979) provides an estimate of soil saturation based on flow convergence (Equation 1 and Figure 3). The TCI value will be higher in valleys and lower on ridges and slopes. It represents the amount of water retained in the soil. Cells of similar values

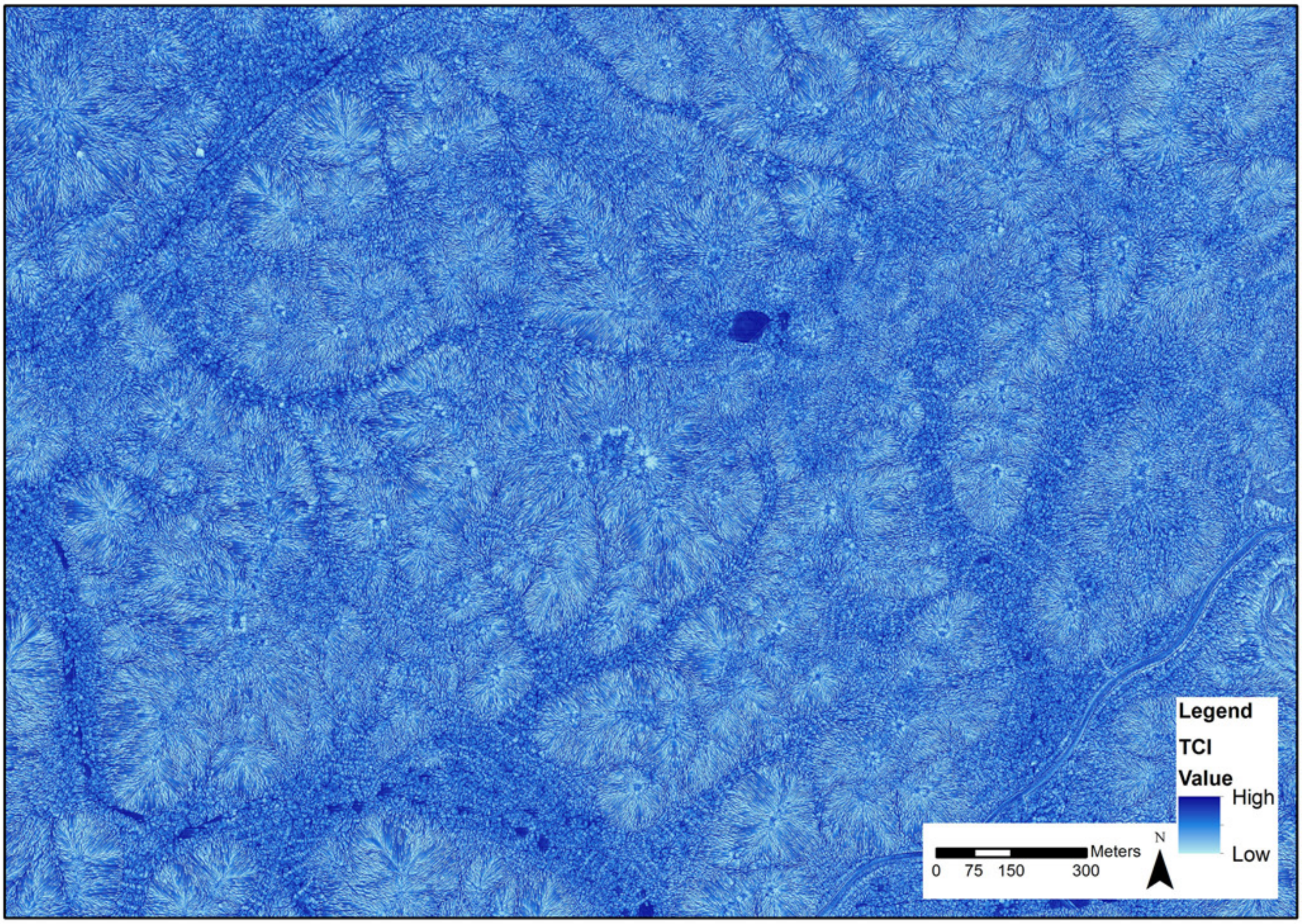

FIGURE 3. TCI (Topographic Convergence Index) visualization of the Puchituk terminus.

will become saturated around the same time and cells with higher values will become saturated before cells of lower values. As such, in places where water pools or flows slowly, TCI will be higher. Ideally, to be effective, terracing should help retain water and will thus have a higher TCI value than the unmodified landscape.

$$\text{TCI} = \ln \frac{\text{Upstream area}}{\tan(\text{Slope})} \quad (1)$$

The Stream Power Index (SPI) (Moore, Turner, et al. 1993), almost a converse of the TCI, provides a measurement of the erosive power of overland flow (Equation 2 and Figure 4). It assumes that water discharges proportionally to catchment size. The SPI dataset shows the most likely locations of water flow and the amount of water that will flow over the landscape. In order to reduce erosion and increase water saturation, the SPI should be lower on terraces than on unmodified landscapes. The SPI value is lower if water meanders along a greater surface area than if it runs straight across the landscape. Ideally, water would flow across the greatest amount of agricultural soil, so the resulting path of the water's flow should appear to zig and zag over the terraces.

$$\text{SPI} = \text{Upstream Area} \times \tan(\text{Slope}) \quad (2)$$

The Sediment Transport Index (STI) (Burrough 1998) provides a measurement of soil erosion and deposition (Equation 3 and Figure 5). It is related to the Universal Soil Loss Equation (Dunning and Beach 1994; Wilson and Gallant 2000) and is thought to be appropriate for areas with complex three-dimensional topography (Moore, Gessler, et al. 1993). The index is based on the speed and amount of flowing water. Soil preservation is often hypothesized to be the reason for terrace construction. Consequently, the STI value should be lower for terraced than non-terraced landscapes. Given that these terrace features have persisted for 1,000 years without maintenance, this should be the case.

$$\text{STI} = \left(\frac{\text{Upstream Area}}{22.13}\right)^{0.6} \times \left(\frac{\sin(\text{Slope})}{0.0896}\right)^{1.3} \quad (3)$$

Basic assumptions of these three topographic models include steady-state conditions and soil (e.g., transmissivity) and climate (e.g., precipitation, evapotranspiration) homogeneity across the landscape (Beven 1997; Wilson and Gallant 2000). After comput-

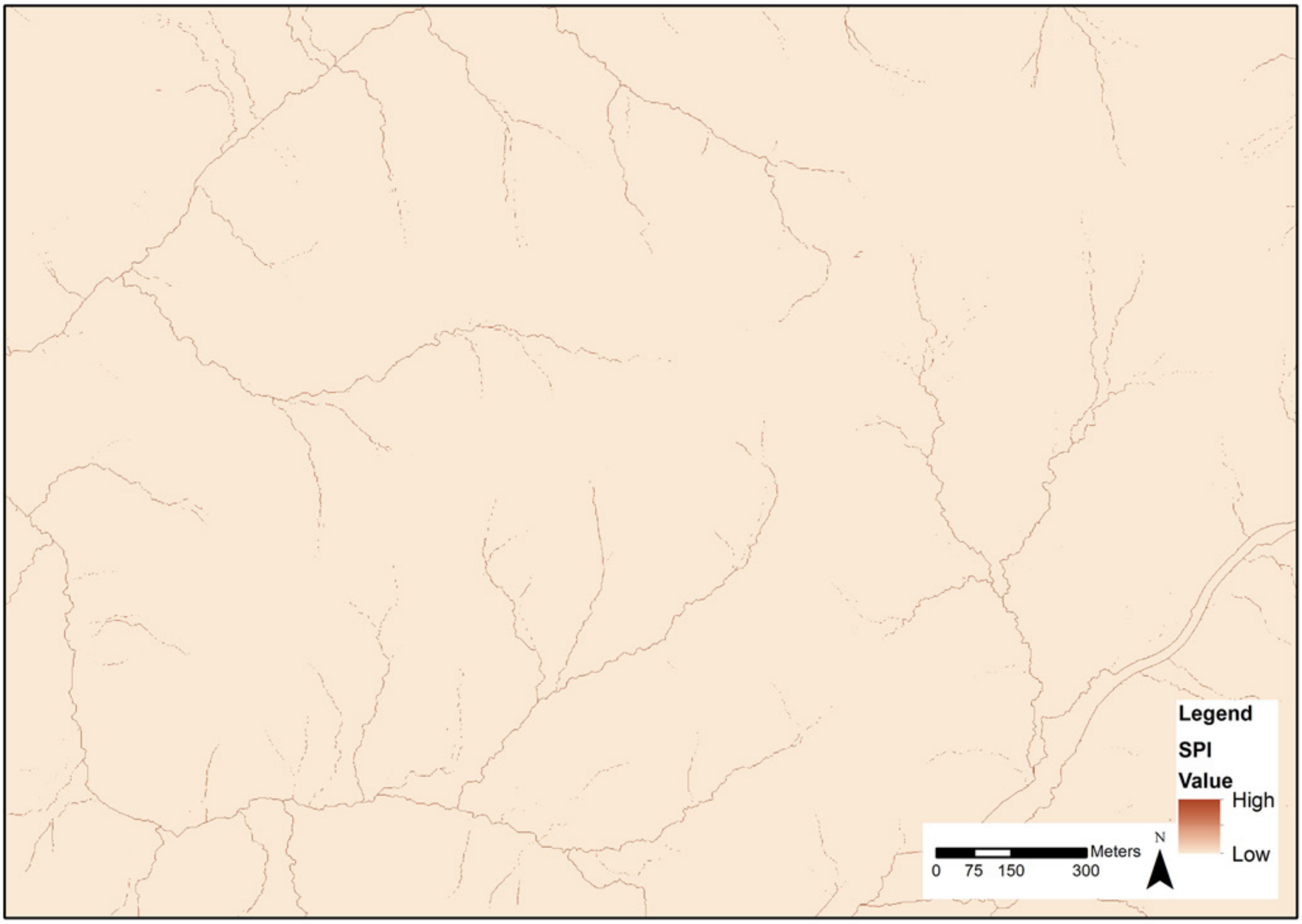

FIGURE 4. SPI (Stream Power Index) visualization of the Puchituk terminus.

ing these separate datasets of hydrology and erosion, the next step requires the comparison of these values for each landscape type. The Topographic Position Index (TPI), calculated using the cited algorithm (Jenness 2006), allows for the partitioning of the landscape into a typology—in this case, sorting features into what the algorithm calls "land cover classes" consisting of "hilltops," "slopes," "U-shaped valleys," and "plains" (Figure 6). At the most simplistic level, TPI landform analysis provides the difference between a cell's own elevation and the average elevation of surrounding cells at multiple scales (in this case 4 m and 40 m) and can include information about slope (in this case, above or below 6 degrees). These scales preserved the "staircase" pattern of terraces where the fields were treated as plains and the walls as slopes. The resulting values from this elevation difference incorporate the slope of the cell to assign it a topographic type, thus differentiating TPI from local relief models (additional information can be found in Jenness 2006). Using the datasets calculated above, and the typology created from TPI, we can study the effects of terracing by looking at terraced and non-terraced locations, as per Hightower et al. (2014:Figure 2), and their values in different landscape types.

We randomly placed 900 100-m^2 circular plots in a stratified systematic sampling fashion across the landscape. This resulted in 150 samples for each of the following land cover classes: terraced slopes, non-terraced slopes, terraced valleys, non-terraced valleys, terraced plains, and non-terraced plains. Each sample from the land cover classes stated above had their TCI, SPI, STI, and slope values averaged together by class. We tested the statistical significance of terraced and non-terraced land cover class values using one-way analysis of variance (ANOVA) tests. ANOVA was chosen because it allows for a t-test style comparison of more than two groups and reduces the occurrence of type I errors[9].

Water Flow over the Terraces

In order to evaluate the effects of water flow on terraces, additional analysis was required. From the above indices and the hydrology analysis of stream flow, it appears that water zigzags over the terraces at least in local circumstances. What follows is an analysis to showcase this zigzagging flow over a large area. In order to conduct this analysis, 10 km^2 of valley (and only valley) terraces were digitized primarily through classified slope (zero° to five°, above five° to seven°, and above seven°) and geomorphons (Stepinski and Jasiewicz 2011) visualizations representing 1,455 terraced fields (shown in Figure 7). These visualizations facilitated valley terrace identification, but did not aid in the identification of hillside or hilltop terraces; it is likely that future tweaks and analysis will help pull out these features, which tend to be narrower fields on more rugged terrain.

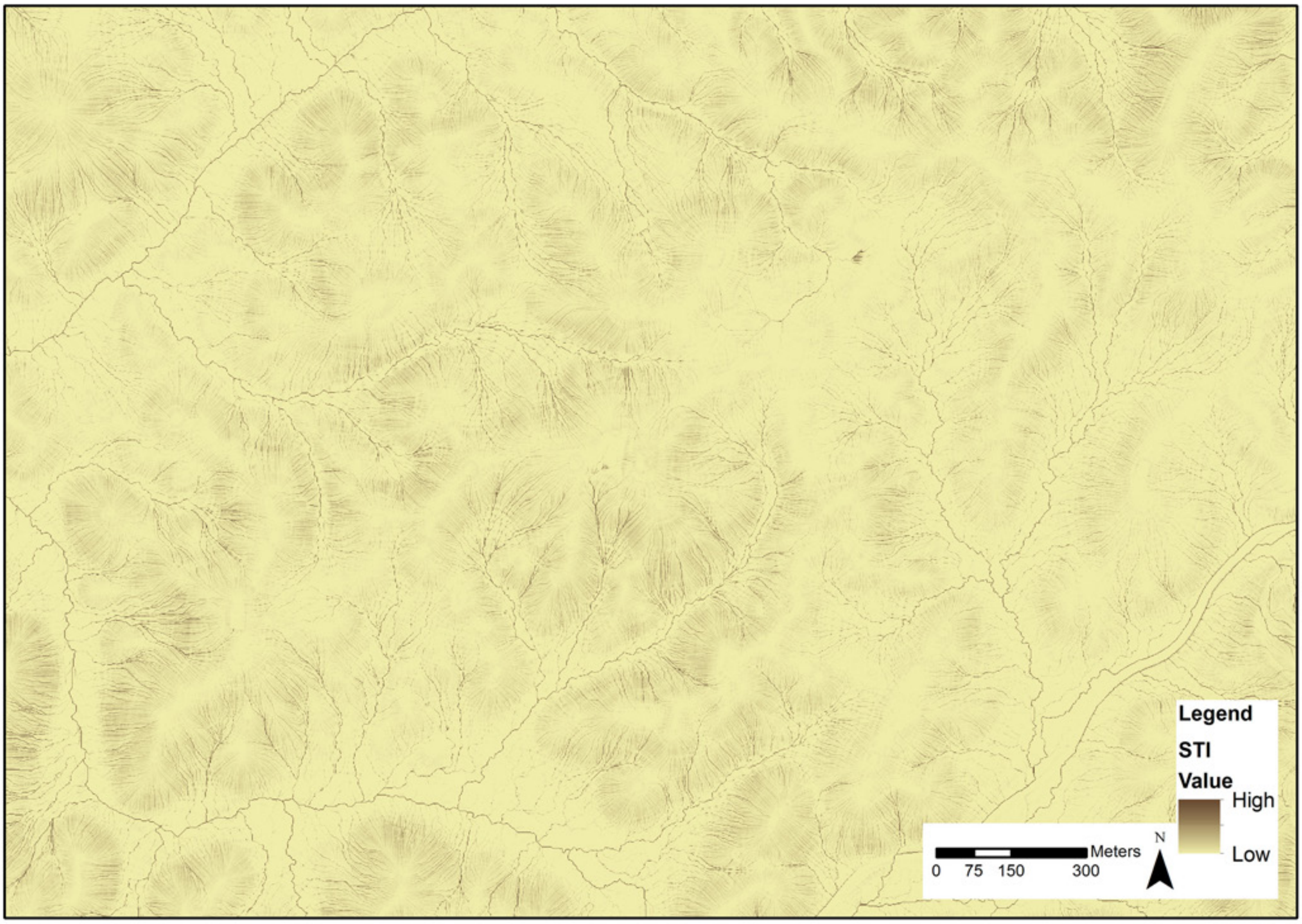

FIGURE 5. STI (Sediment Transport Index) visualization of the Puchituk terminus.

This analysis makes use of the aspect[10] raster of compass directional drainage. For our purposes, compass degree aspect was insufficient and aspect in radians[11] was required. We also utilized the flow accumulation map from earlier (prior to the addition of 1 to every cell), but converted it into a binary classification of Boolean values based on whether the raster cells had at least 1 ha of flow. Those with 1 ha of flow or more were coded as 1 and those without were coded as 0. This facilitates map algebra multiplication, as the binary classification can act as a raster mask (i.e., 1 multiplied by a value is itself and 0 multiplied by a value is 0).

With the above datasets, we used the digitized terrace polygons as boundaries to take the mean aspect under the terraces as a whole and the mean aspects under the portions of the terrace that had received at least 1 ha of flow. In essence, this gives us an average drainage direction of the whole terrace and the average drainage direction of the DEM reconstructed water flow. Since these measurements are in radians, the method of taking the mean is the non-trivial Equation 4 shown below. The final step was to subtract the terrace aspect mean of likely flow from the terrace aspect mean for the whole terrace. This number, after conversion back to a degree value between negative and positive 90, represents the flow of water over the terrace against the natural terrace orientation. The resulting map of terraces coded by flow can be seen in Figure 7.

$$Mean(list_x)_{rad} = a\tan 2 \sum_{x}^{list_x} \cos(x_{rad}), \sum_{x}^{list_x} \sin(x_{rad}) \qquad (4)$$

If water flows directly over the terrace in the fastest and most direct manner, then the value after subtraction will be near 0, indicating that the water flows almost directly downhill. However, only 173 out of the 1,455 terraces (12 percent) have values between 1 degree and negative 1 degree, only 334 (23 percent) have values between 2 degrees and negative 2 degrees, and only 734 (50 percent) have values between 5 degrees and negative 5 degrees. If we took the null hypothesis that terraces did not affect the direction of water flow over their surface and all values are near 0, then the chi-squared statistic of the above numbers are 1129.6, 863.7, and 357.3 respectively. All of these are well in excess of $p = .001$ significance; thus we can soundly reject the null hypothesis for each case, indicating that terraces do affect the flow of water. Moving on, the hypothesis of zigzagging water would be supported if water flows in a pattern of negative, positive, negative or positive, negative, positive over sets of three terraces. While this occurs quite frequently,

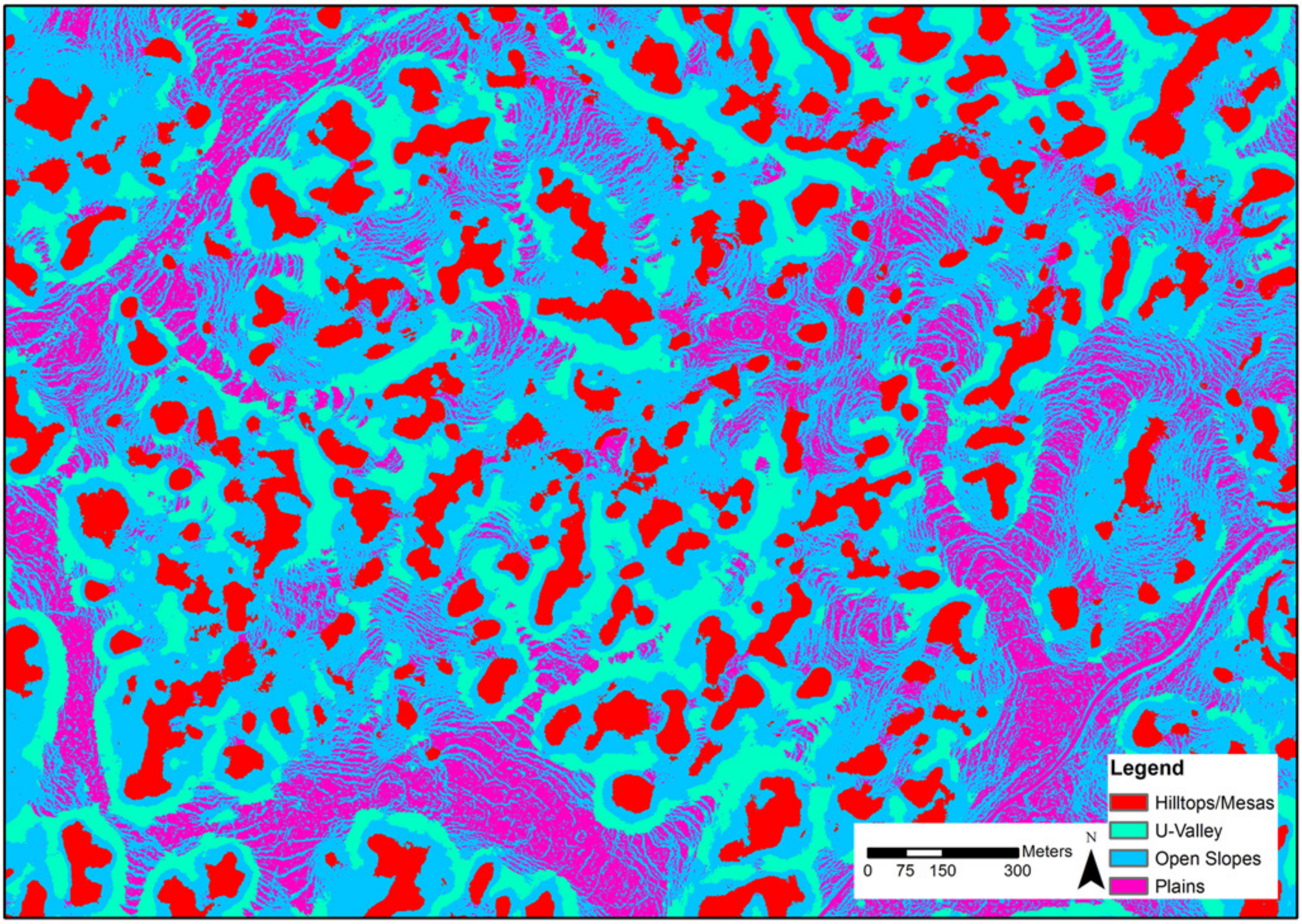

FIGURE 6. TPI (Topographic Position Index) visualization of Puchituk terminus

it does not occur on every terrace field (Figure 7). As such, this rudimentary analysis indicates that valley terraces do indeed affect the flow of water and that the ancient Maya altered the hydrology of their landscape in complex ways; however, it does not specifically demonstrate that water zigzagged over every single terrace.

DISCUSSION

The resulting graphs (Figure 8) show that terraces increased soil wetness on slopes, reduced the power of flowing water on slopes and plains, inhibited soil erosion on slopes and plains, and significantly reduced the average slopes of hillsides, which is certainly a trivial and definitional aspect of terraces. In general, terraces provided the greatest benefits on hillsides, but they also proved beneficial on open plains, especially as shown in the water flow analysis. The reduction in water power resulted from the meandering behavior terraces encouraged as water flowed across them. The terraces actually slowed the flow of water, and this reduction in erosion and increase in soil wetness arose directly from this reduction in stream flow power. Based on the prevalence of terraces in U-shaped valleys, there must have been different, tangible benefits that the people of Caracol recognized in constructing these terraces other than soil erosion prevention and water retention, at least based on the indices and statistical analysis from this research. Possibilities include: the prevention of soil erosion during large tropic storms, the construction of valley terraces preceding the construction of hillside terraces with the hillside terraces previously providing those benefits (Arlen Chase, personal communication 2014; Macrae and Iannone 2011), and other intersecting historical, social, or cultural dimensions beyond the scope of this analysis.

While the indices indicate that the terraces successfully affected the flow of water and edaphic conditions of the soil, it is not entirely clear what the ancient Maya knew about these properties when initiating construction of the field system. Terraces affect the edaphic conditions of the soil by leveling out the soil surface and reducing runoff. The direction of flow over the terraces—downhill but in a pattern that ensured water flowed over the entire fields—increased the infiltration of water into the soil and increased the water reservoir in the soil. Recent research has shown that terraces affect the growth of modern trees; they have an increased canopy height when compared to vegetation in non-terraced fields (Hightower et al. 2014:10724–10726). The change in slope and increase in soil wetness should have been visibly apparent to the ancient Maya, and while they may have perceived a decrease in erosion from major downpours, the variation in erosion between terrace fields on the hill-slopes and

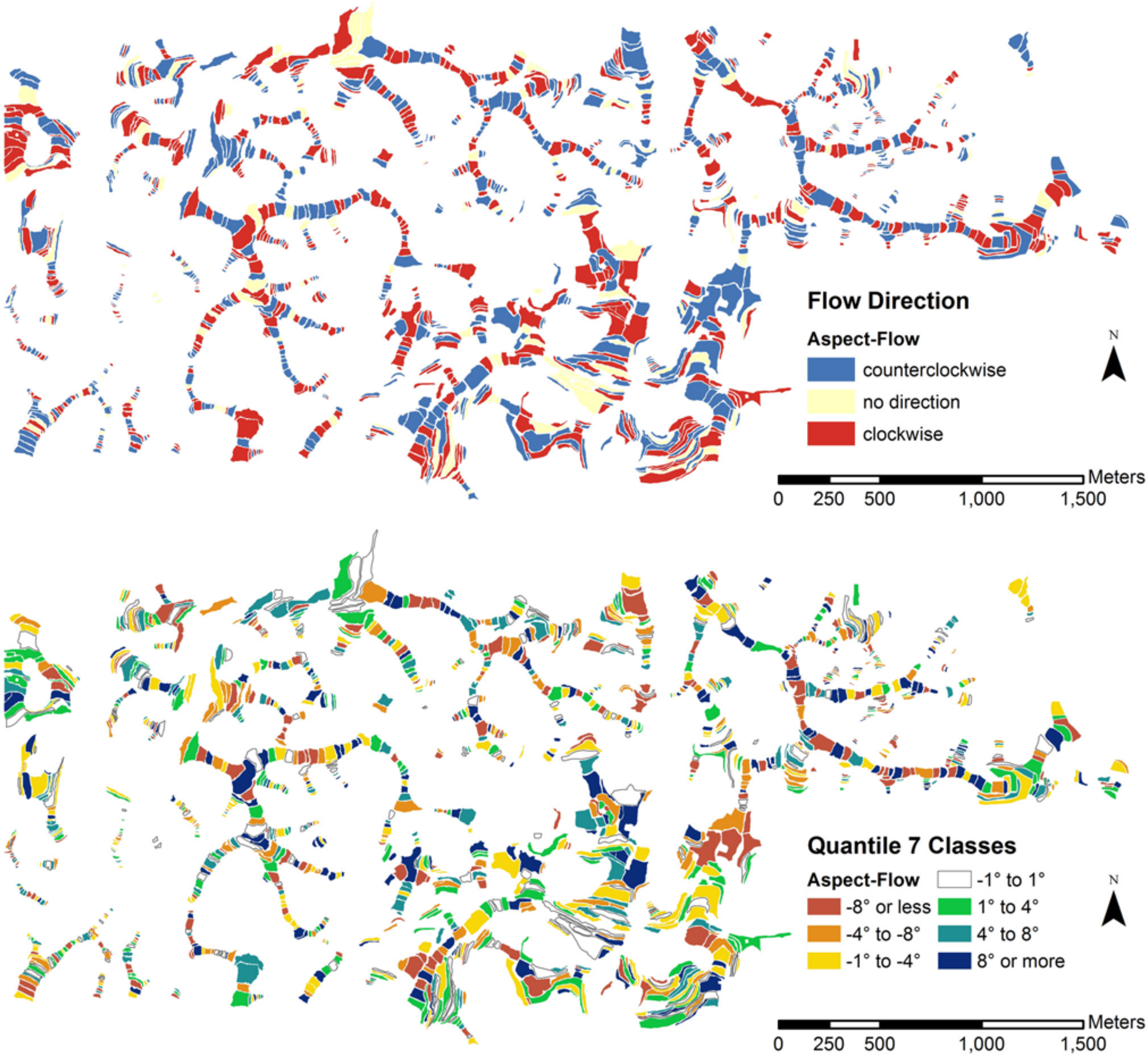

FIGURE 7. This figure shows the valley terrace orientations according to the terrace flow analysis outlined in this paper. The terraces have been classified into clockwise and counterclockwise flow (top) and 7 classes (bottom) to indicate the degree of difference in flow direction.

in the plains of the valley floors may have been less immediately visible. Due to the reliance on rainfall to provide irrigation to the terraced fields, it is quite likely that the increase in soil wetness and water infiltration, rather than erosion reduction, provided the two primary factors encouraging the construction of terraces at Caracol, especially given the presence of these terraces 1,000 years later without intermittent maintenance. The labor investment in building the terrace walls and in moving soil provided the tangible benefit of increased agricultural yields.

The ancient residents of Caracol engineered their terraces to increase agricultural productivity. The lack of rainwater during the dry season was offset by increasing the water retention of soil through the construction of terraced fields. The retention of water in the terraces themselves provided the major accomplishments of this terraced system of agriculture. Needless to say, the terraces represented a monumental investment in labor for landscape modification. This effort allowed for full exploitation of rainfall and kept this ancient city alive. The integrated system of households, reservoirs, and terraces formed the economic base for this ancient city, and the lidar data and subsequent analyses provide us with the tools to comprehend the full extent of the landscape modifications undertaken by the ancient people of Caracol.

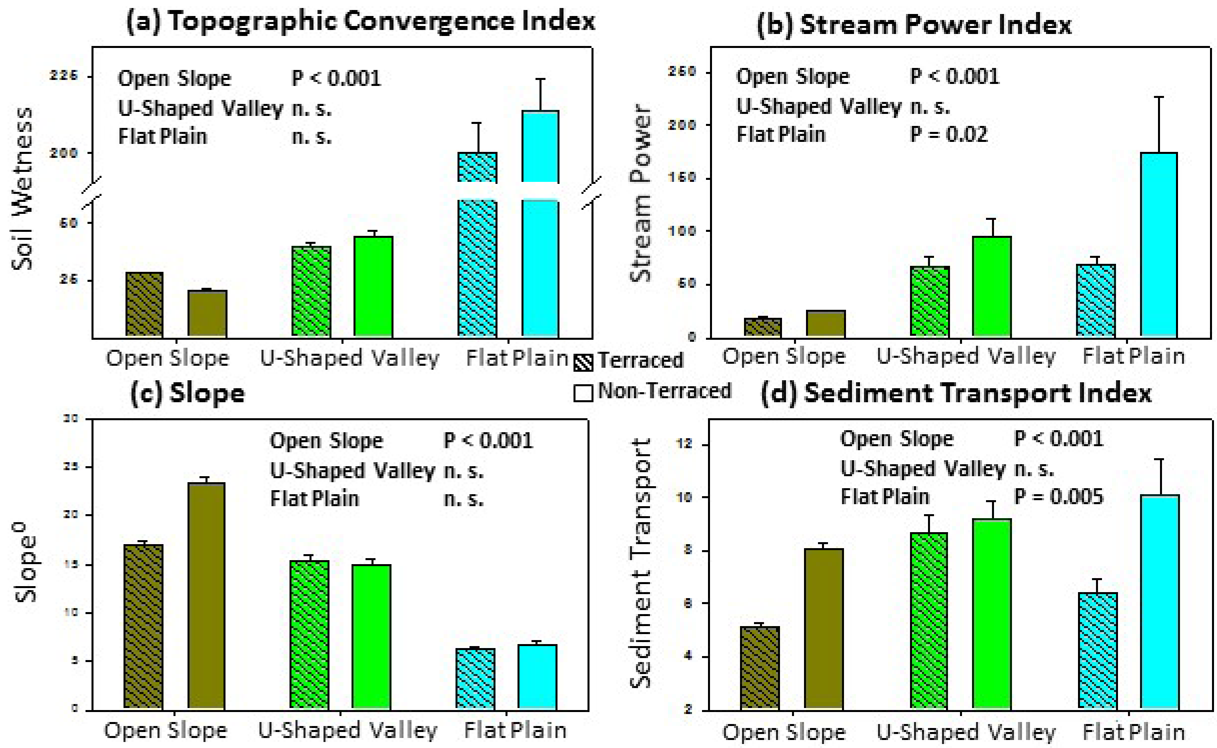

FIGURE 8. Comparisons of indices for (a) soil wetness, (b) stream power, (c) slope, and (d) sediment transport for terraced and non-terraced areas found in open slope, U-shaped valley, and flat plain landforms. Extensions above the bars represent standard error for the 150 samples from each landform and land use category. Significant differences between terraced and non-terraced areas are denoted with p-values, with n.s. meaning "not significant" in a statistical sense.

CONCLUSION

This analysis of terrace hydrology demonstrates two of the potential underlying principles motivating the construction of agricultural terraces by the people at Caracol. First, terraces reduced soil erosion, and second, they increased the water retention of the soil. This remains true even when analyzing the terraces over 1,000 years since their last maintenance. While previous investigation of terraces at Caracol has found that they improve the growth of modern vegetation (Hightower et al. 2014), this quantitative analysis sheds light on possible explanations for those findings. While these two factors may provide all of the necessary information to explain the importance of agricultural terraces to this ancient city, historical and social processes may share responsibility. They may explain the presence of terraces in U-shaped valleys where these indices show negligible increases in soil wetness and erosion reduction. For example, terraces may have initially been constructed in valleys and then subsequently been expanded to the slopes as indicated by (Arlen Chase, personal communication 2014; Macrae and Iannone 2011). In addition, the methods utilized for this analysis are not specific to this dataset and can be employed with any digital elevation model data.

In any case, this research highlights the complexity of the ancient Maya at Caracol. These agricultural terraces represent a high degree of agricultural intensification and a sophisticated construction effort to provide subsistence agriculture from rainfall on this hilly and mountainous terrain. The large area covered by these terraces and the extraordinary labor required to build them may even indicate agricultural "involution" (sensu Geertz 1963) at this ancient city. This type of quantitative analysis highlights the great potential in using lidar, GIS, and remote-sensing technologies to answer archaeological questions, and, just like the research before it, it raises as many questions as it potentially answers. Future research could investigate the construction sequence of terraces, provide information on the potential resilience terraces provided against extreme weather conditions such as torrential rain or hurricanes, create more detailed simulations of actual water flow and crop growth in these agricultural terraces, or aid in reconstruction of the landscape topography through computational methods to add eroded soil back to the landscape. Beyond this list of future topics, ideally this research provides the first small step toward establishing the agricultural productivity of ancient Maya cities.

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Data Availability Statement

In accord with the wishes of the Institute of Archaeology in the country of Belize, the lidar data reported in this paper are not available to the general public in order to protect the country's archaeological resources from further looting. However, the LAS digital files are on file with the Institute of Archaeology in Belize and may be provided to qualified professional researchers for valid teaching and learning purposes on a limited basis. The person to contact in Belize with regard to these files is: Dr. John Morris, Director, Institute of Archaeology, Archaeology Museum and Research Centre, Culvert Road, Belmopan City, Belize; phone: 501-822-2227; email: research@nichbelize.org. The archaeological data collected by the Caracol Archaeological Project (formerly University of Central Florida; now University of Nevada, Las Vegas) are collected under a yearly permit issued by the Institute of Archaeology since 1985; the most recent permit number is IA/H/2/1/16(03); the last 20 years of annual archaeological excavation data may be found in the season reports at www.caracol.org. The collection of the lidar data for Caracol in 2009 was carried out under the yearly Caracol Archaeological Project permit. The collection of the lidar data for Western Belize in 2013 was a collaborative effort by the archaeologists working in Western Belize with the Institute of Archaeology and was not issued a formal permit; the funding for the 2013 lidar was channeled through the University of Central Florida.

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NOTES

1. See organization website for further details: ncalm.cive.uh.edu
2. Datasets: flow direction, flow accumulation, and slope
3. Indexes: topographic convergence index, stream power index, sediment transport index, and topographic position index
4. Edaphic: of or relating to the inherent qualities and conditions of the soil itself, as opposed to external conditions provided by factors such as climate, flora, or fauna.
5. The analysis presented here can be replicated in any GIS platform with map algebra equations or native algorithms. ArcGIS was chosen because of the software's map-making capabilities for the figures in this article.
6. Algorithmically, the neighbor with the lowest elevation (out of the eight adjacent cells—four for the cardinal directions and four for the ordinal directions) is selected and that direction is stored within the cell.
7. Using the flow direction dataset, the flow accumulation traces the movement of water from cell to cell. It keeps track of and updates the number of cells that drain into other cells.
8. Slope is the degree value of change across each cell. Slope for this analysis was calculated from the degree change in a 3-x-3 cell window over each cell in the DEM using the ArcGIS slope algorithm. After calculating degree slope, we multiply each cell in map algebra by $\pi/180$ to obtain radian slope values.
9. Type I errors are statistical errors where the null hypothesis is accidentally rejected when it is actually true.
10. Aspect is the compass direction in which water would flow out of any raster cell based on its eight neighbors (cardinal and ordinal). It utilizes the rate of change in the horizontal and vertical directions and trigonometry before it is converted into compass degrees (where north is zero).
11. Radian to degree conversion is as follows:

$$x\_in\_radians=(\pi)/(180°)\times y\_in\_degrees$$

AUTHOR INFORMATION

Adrian S.Z. Chase ■ Arizona Sate University, PO Box 872402, Tempe, AZ 85287-2402 (adrianszchase@gmail.com)

John Weishampel ■ University of Central Florida, P.O. Box 160112, Orlando, FL 32816-0112