Focus Article

Beyond elite control: residential reservoirs at Caracol, Belize

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The Classic Period Maya (300 CE to 900 CE) built many of their cities away from standing, flowing, or subterranean water resources. Because of this, scholars have suggested that one key manifestation of ancient Maya ritual and political authority was the control and management of water housed in large central-site reservoirs, rectilinear excavated features that were lined with stone and coated with plaster or clay to catch and store rainfall runoff. This research assesses those arguments by using remote sensing data to map residential reservoirs—smaller versions of the monumental reservoirs in city centers—from the intensively investigated city of Caracol, Belize. The Caracol Maya were entirely dependent on rainfall and built monumental and residential reservoirs throughout their city. Using a 200-square kilometer Digital Elevation Model created from LiDAR (Light Detection and Ranging) data, research uncovered the extent of ancient water capture at Caracol. Analysis of the LiDAR data reveals a conservative count of 1590 reservoirs at Caracol; this is more than 25 times the number of reservoirs identified by traditional ground survey methods. These data demonstrate how the people of Caracol were able to successfully harness the water available in their environment. In addition, the decentralized nature of Caracol's reservoirs suggests that elite power, at least in this ancient city, was not based on control of water resources due to the ubiquity of residential reservoirs throughout the site.

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INTRODUCTION

Human society depends upon water for numerous aspects of day-to-day life, sustenance, and livelihood. Different historic and environmental conditions have resulted in various water management systems over time. For contemporary society, the availability of water and the impact of climatic change and human activities on water supplies have generated special urgency.[1,2] The ancient Maya of Central America (Figure 1), while located within a sub-tropical environment, also faced problems of water management. Analysis of ancient Maya water management is of significance not only for discussion of the rise and fall of ancient Maya society, but this data can also potentially be used to elucidate human adaptations and inspire future water planning efforts. Especially since a 20-person field research project can still run out of water in a city which once had over a hundred thousand residents.[3]

In the Classic Period (roughly from CE 300 to 900) the Maya established many of their cities at a distance from natural surface or ground water. As a result, the ancient Maya built specialized features (i.e., reservoirs, *chultunes*, and agricultural terraces) or altered natural features (i.e., *aguadas* and *cenotes*) to harness the abundant rainfall of their environment. This focus on rainfall-based subsistence also implicates water as a critical factor during the Classic Maya collapse where drought may have resulted in

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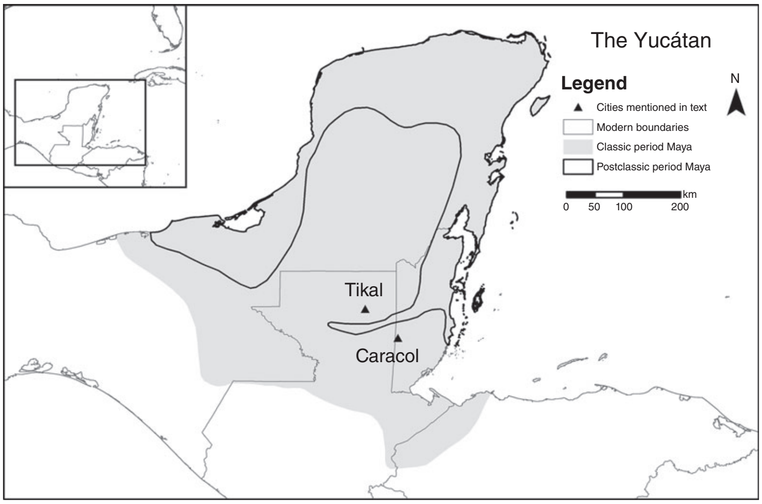

FIGURE 1 | Map of the Maya Area.

social and ecological instability.[4] Advocates propose that insufficient water availability resulted either from a series of great droughts[5] or from general inconsistency in rainfall.[6] Lucero[7] has suggested that the collapse may have resulted when the non-elite abandoned the elite due to the failure of the elite water rituals to bring rainfall during an extended drought period.

Investigations of Classic Maya cities in the southern Maya lowlands[8,9] evince very large centrally constructed reservoirs, large humanly constructed and rectilinear water catchment features constructed with limestone and sealed with clay or lime plaster, adjacent to the monumental architecture in city centers (Figure 2). The ubiquity of monumental reservoirs at these urban centers have led to a theoretical focus on the emergence of the elite through top-down control over intertwined systems of water ritual and water management.[7,8,10] This bears a passing similarity to Wittfogel's[11,12] hydraulic hypothesis which argued for irrigation systems which required managerial positions that morphed into the despotic elite of society. Wittfogel has often been used as a strawman for cases of both irrigation systems following political centralization and irrigation systems arising from collective action, but his theory still provides academic contention in analyses of irrigation and power.[13,14] However, all the reservoirs in this analysis served for sustenance rather than for irrigation, in fact the only potential irrigation method might have been pot irrigation of crops—although archaeological evidence for this has not been identified at Caracol.

Research on ancient Maya water management systems[15] has focused on a variety of features such as chultuns, 'bottle-shaped limestone cysts,'[16] raised field agricultural systems,[17] and constructed landscapes.[10,18] Much information about water storage derives from site centers[10,19,20] where reservoirs exist in proximity to palaces and temples. However, smaller reservoirs are also known from both Caracol[21] (Figure 3) and other Maya sites.[22] In addition, the most recent Maya water research has focused on the variety of water features,[23] and the complex hydraulic processes of specific water features.[24,25]

The city of Caracol was occupied from around 650 BCE until 900 CE. By its apogee in 650 CE, the city was occupied by over 100,000 people.[3] The city also exists along an east–west trade route that bypasses the Maya Mountains.[26] The city center was located 15 km away across hills and mountains from the nearest river. As such, the residents constructed many monumental and residential reservoirs along with over 160 square kilometers of terraced agriculture fields.[27,28] The monumental architecture at Caracol is concentrated in nodes attached by a dendritic causeway system; the rest of the city is filled in with *plazuela* residential groups, small reservoirs for residential use, and agricultural terraced fields of heavily manipulated, fertile soils whose primary purpose was the capture of rainfall in the terrace's soil reservoir.[29–32] As such, this was a city of gardens,[33,34] but not by any means a garden city.[35,36]

Identification of non-epicentral reservoirs remains difficult due to both their smaller size and depth. In addition, the rainforest canopy obscures these features during tropical survey projects and remote sensing through satellite imagery or aerial photography. However, LiDAR (Light detection and

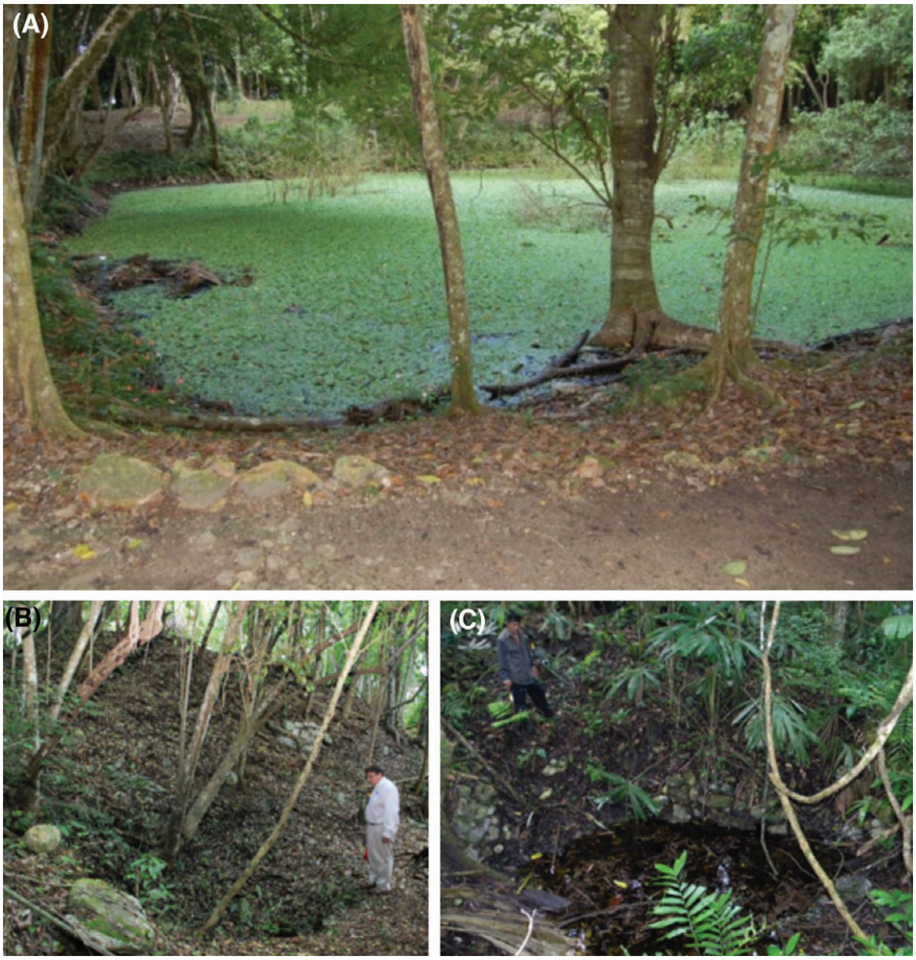

FIGURE 2 | Ground-truthing of reservoirs at Caracol. (A) the largest Caracol reservoir in the epicenter and still holds water today. (B and C) smaller household reservoirs which also still retain water.

ranging) conducted at Caracol, Belize[27,37,38] (Figure 3) permits us to survey the rainforest floor remotely through the jungle canopy, enabling the study of water management systems within larger settlement survey areas. LiDAR provides a window through the jungle canopy into past landscape modification, providing for the creation of digital elevation models (DEM) showing detailed topography of the ground surface, sometimes called a digital terrain models. While time consuming, visual inspection of LiDAR-derived imagery is substantially faster than on-the-ground survey.

While automated extraction would be the ultimate goal of LiDAR survey, automated algorithms still need to be created for many feature types. The natural processes of soil erosion and silting that have taken place since ancient Maya times have partially filled the reservoirs and made their edges less angular and more irregular making them very difficult for automated detection algorithms to accurately identify. The rugged karstic landscape adds to the difficulty of automation procedures better suited to flatter terrain. Unfortunately, current automated identification systems have not been successfully employed to detect Maya archaeological features independent of human visual inspection; however, a data set for future automated testing would be invaluable.

Using ArcGIS on the LiDAR DEM already acquired from the Caracol Archaeological Project,[27,37,38] I located reservoirs and studied their distributions across the landscape. Reservoirs were identified through visual inspection using different visualization schemes from Hillshaded Relief Models[39,40] to Sky-view Factor[41,42] and also local relief models.[43,44] The initial set of 58 mapped reservoirs formed the initial training set, Then 270 additional reservoirs were remotely identified with 47 additional

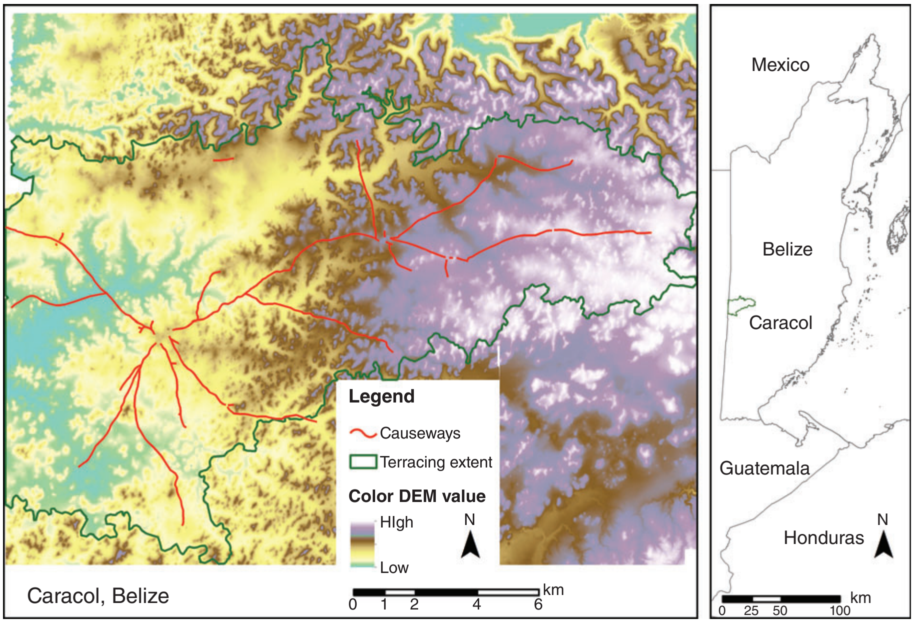

FIGURE 3 | This map shows where Caracol is located in Belize, and extent of intensive terracing at the site. However, terracing and settlement continue beyond this boundary.

reservoirs ground-truthed. All 47 were positively identified as reservoirs; however, other potential depressions were marked for investigation. These turned out to be an open tomb, a tomb entrance with a collapsed capstone, and two chultuns. Once positively identified and cross-checked, reservoir features were recorded as ArcGIS vector data. Following this, the visualizations were recalibrated and tested to facilitate additional investigation. As a result, the total number of confidently identified reservoirs at Caracol has increased to 1590. This number forms a conservative estimate of the total number of reservoirs at the site. Both silting and the small size of residential reservoirs makes their remote identification more difficult than the larger more central reservoirs.

Spatial analysis of reservoirs helped determine whether they were concentrated in 'epicentral areas'—locations with monumental architecture in the center of the site—and thus elite controlled, or in a decentralized distribution among residential groups in a fashion indicative of non-elite use and control. This research provides concrete data on the widespread distribution of water resources at Caracol, and does not support the theory of restrictive, centralized elite control of water resources by the ancient Maya at this city. This coupled system of centralized monumental reservoirs and decentralized residential reservoirs further contributes to considerations of the resilience and rigidity of the Classic Period Maya and their use for modern sustainability scholars.[45–48]

THEORY

Water and Collapse

Water is often central to theories of the Classic Maya collapse. As noted above, many Maya cities were founded in locations lacking rivers, lakes, or other natural year-round water resources.[9] In the case of Caracol, there is no flowing water for at least 15 km from the site center,[21] and the dendritic causeway system does not extend to that river but rather ends 4 km from that river—over hills and rugged terrain—at its closest point. Contemporary scholars generally argue that there was no single cause for the abandonment of Classic Maya cities,[49] as such a drought or lack of water is generally perceived as an insufficient mono-causal explanation for the Classic Maya collapse. In addition, the collapse occurred throughout the Maya lowlands, but did not take place uniformly at all sites.[50,51] Some sites even prospered during the collapse.[49] Further, it is well established that the Classic Maya collapse occurred over a very large time span, at least 200 years from about CE 750 to 950.[52] Radiocarbon dating calibration curves suffer from three flat zones which obfuscate the absolute timing of the collapse.[50] These flat zones correspond with the date ranges from CE 680 to 760, 790 to 880, and 900 to 950. As such, any two-sigma (95% probability) radiocarbon dates near these ranges cover large swaths of time.

Regardless of the actual causes or processes of the collapse, a lack of natural freshwater (standing, flowing, or subterranean) resources at most, if not all, Classic Maya cities certainly provided no bulwark against environmental change and drought. For example, while the monumental reservoirs of Tikal would have been able to supply the city beyond the 4-month dry season[19] for 6 months of drought, the inclusion of the residential reservoirs would have allowed the total emergency water supply to last up to 18 months,[53] a longer drought would have depleted both water supplies.[10] Another consideration of collapse revolves around water, rituals, and the supernatural. Following Lucero[7,15] the Classic Maya elite gained their power and prestige by constructing monumental reservoirs and providing the water therein to others. The elite then specialized in sacred rituals and placated the supernatural forces that provided water. Ergo, a drought shows that the elite no longer have the ritual power to guarantee water and the non-elite abandoned them entangling drought and political processess.[7] However, if residential reservoirs were spread throughout the landscape in sufficient number to accommodate the entire population of a given city over the course of a lengthy drought period, then these residential reservoirs could reduce both the need for monumental reservoirs and the ability of the elite to manage site-wide water resources.

Maya Water Management

Perhaps the best case for elite control over water resources has been advanced with evidence from the ancient city of Tikal in modern Guatemala. Based on the grandeur of the central reservoirs and the detailed civic planning exemplified by the construction of those reservoirs and their drainages in association with the major plazas, Scarborough and Gallopin[19] argue that the elite built and managed access to these water sources. The control over these reservoirs enabled elite authority over the populace of downtown Tikal[10]; however, Scarborough[18] also notes that in peripheral areas—given the decentralized nature of Maya settlement and the ease of reservoir construction in karstic limestone bedrock—complete elite control over reservoirs could not have occurred.

Together, the work of Scarborough[10,18] and Lucero[7,8] provide the primary contemporary theory on Classic Period Maya water management practices. Both emphasize elite control over water, at least near urban centers.[8,18] Scarborough views the reservoirs in the epicenter of Tikal as important ritual and political statements about the power of the elite which, given their prodigious size and water storage capacity, would be difficult to dispute, especially since the civic architecture turned the monumental portion of Tikal into a large catchment for its six great reservoirs.[54] Lucero[7,8] expands upon Scarborough's initial ideas by focusing on the ties between Maya views of a watery underworld and reservoirs. She suggests that the elite gained and maintained their power through control over these centralized reservoirs.[7] She proposed that certain members of Maya society built large reservoirs and received disproportional gain from them, eventually forming the societal elite.[7] Once this elite had gained power, they constructed elaborate water rituals to maintain good ties with the supernatural forces in order to assure future water resources and perpetuate their elite status.

Other scholars such as Weiss-Krejci and Sabbas[22] have argued that research into Maya water management has been conducted with too great an emphasis on the reservoirs near the monumental architecture of the city centers. They sampled 16 small depressions in northern Belize as potential reservoirs and found evidence that four of them had in fact been used for water storage. They also mention that at Tikal there are over 65 depressions similar to the ones they had researched. Based on their investigation, even the shallowest and smallest depression could have provided year-round drinking water for 94 people, assuming 2.8 liters of drinking water per person per day.[22] This implies that small reservoirs should be considered when scrutinizing water management. Even so, in order for an effective argument that household reservoirs significantly impacted water management, these reservoirs would need to be ubiquitous across the landscape.

More recent investigations into water management have been less directly focused on hydraulics and hydrology. Research has shown that the Maya were capable of complex manipulation of water through both the creation of water pressure[24,25] and the construction technique employed in agricultural terraces.[29] In addition, the diversity of water features indicates not only that the ancient Maya adapted their water needs to their environmental conditions but also that the question of centralized control needs to be reanalyzed within each of those feature types.[23] The question of who controlled water management systems still remains a relevant question Mayanists.

METHOD

Models of Control

The site of Caracol made extensive use of reservoirs for water storage. The spatial contexts of these reservoirs can be used to examine the extent of centralization in the control of water resources. In this article two opposing, but not interdependent, models test the degree of elite control over reservoirs at Caracol.

Model I, Elite Control of Water Resources: The elite controlled access to water resources and derived their political and ritual power from this control.[7] This hypothesis would be supported if reservoirs are located predominantly or exclusively in association with site epicenters, monumental architecture, or elite residential units which can be easily monitored. The ability to monitor and manage the distribution of water underlies this view of top-down water management of water resources.

Model II, Distributed, Non-Elite Control of Water Resources: Given the focus on shared resources and identity at Caracol,[55] water resources may have been managed by individual residential groups, extended family units, or neighborhoods. This hypothesis would be supported by the widespread distribution of reservoirs among residential groups. This decentralized distribution would have made top-down management and monitoring by the elite difficult if not impossible.[56]

Earlier fieldwork at Caracol had recorded reservoirs in all mapped areas of the site at a density of five reservoirs per square kilometer[33,57] with a total of 58 reservoirs mapped during survey. Previous research had also outlined the capacity of the epicentral reservoirs.[20] However, the overall mapping was incomplete as residential reservoirs are often small, irregular, and obscured by overgrowth—and frequently located off the sides of the residential units that were the focus of the mapping effort. Excavated reservoirs have also contained as much as one meter of silt infilling. An attempt to determine whether reservoirs were elite or non-elite controlled required detailed study and identification of reservoirs at the site.

Light Detection and Ranging

Mayanists pursuing remote sensing have successfully used satellite imaging to identify the locations of Maya sites and structures and augmenting traditional aerial photography.[58] However, due to the dense sub-tropical canopy these remote sensing techniques do not effectively show detailed aspects of ancient landscape modification. LiDAR rectifies this situation by penetrating the jungle canopy.

LiDAR is a remote sensing technology utilized to measure distance. The process works as follows. A LiDAR emitter sends out laser pulses. As part of that pulse travels and reflects off of a surface such as a leaf on a tree or the ground surface, it bounces returning some of that pulse's energy back to the emitter, allowing for multiple returns per pulse. The distance from the emitter to the reflective surface is then calculated based on the travel time of the laser pulse.[59] When measurements are combined with a GPS reading and an altimeter, the pulses can be recorded as points with latitude, longitude, and elevation or as spatial relationships of x, y, and z values.

The Caracol dataset consists of over 4.28 billion LiDAR points with an average point density of 1.35 ground returns per square meter,[37] later augmented by additional LiDAR to define the eastern extent of the site.[38] The end result of this LiDAR data collection was a survey dataset of which only 13% of the ground surface had been previously mapped.[27] However, these data in their raw point-cloud form do not facilitate all analyses. In this analysis, the raw LiDAR data was formatted into a DEM of ground returns.[60] By utilizing LiDAR data it became possible for the first time to document the extent of the ancient landscape modification throughout the roughly 200 square kilometer survey area of both large and small structures, raised platforms, terraced fields, causeways, and reservoirs. Identification and classification of features within the LiDAR dataset requires a separate set of skills as the interpretation of remote sensing images entails a bird's eye view of the landscape. In addition, LiDAR-derived archaeological datasets require a new set of analytical procedures that connect ground-based archaeology to views of the entire palimpsest of the landscape being studied in conjunction with ground truthing.

Visualization Methods

Based on the survey maps with 58 reservoirs, the initial inspection of 270 reservoirs utilized multiple hill-shaded terrain models, a terrain relief model which simulates a raking light source onto the underlying DEM.[39,40] However, this visualization method became outmoded by two other visualization algorithms. The first, sky-view-factor[41,42] asks, what proportion of the whole sky is visible from a given location on the landscape. This method essentially illuminates the whole landscape at once, reduces the need to use multiple simulated raking light images of the same feature. The second, a new visualization method created independently for this research,[44] is closely related to local relief models.[43] In this method, the elevation of the current cell was subtracted from the mean elevation of the cells in an annulus (donut) with an outer radius and an inner radius. One and five and three and eight were the two inner and outer radius pairs that proved to be most efficient for these analyses. The resulting value was stored in a new raster dataset with the original cell's row and column value. This produced an image showing where the landscape was both higher and lower than 'expected,' highlighting local topographic variation (Figure 4).

Initially this method utilized a histogram equalization color stretch. However, further investigation of reservoirs after the initial set of 47 ground-truthed reservoirs in the 2012 and 2013 field seasons indicated that the majority of reservoirs could be identified with a custom histogram coloring: negative 5 m to negative 1 m, then negative 1 m to negative 60 cm, and lastly negative 60 cm to negative 20 cm. Identification of the majority of reservoirs in this research entailed switching between this custom coloring, the histogram equalization coloring, and the sky-view-factor image of the Caracol dataset to identify reservoirs with a high level of confidence. As a final check, each reservoir was investigated on the raw DEM with its color histogram stretched to the values of the cells in that reservoir. The use of this medley of visualization techniques and double and triple checking helps ensure with a high level of confidence that all features identified remotely are indeed reservoirs.

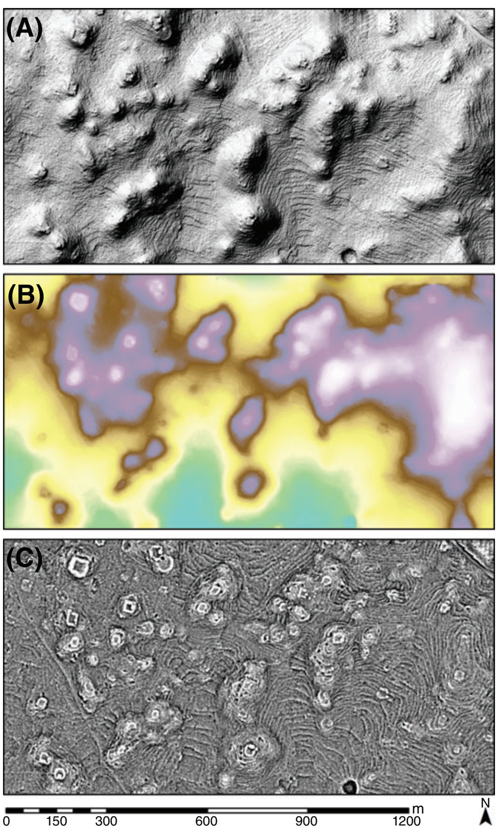

FIGURE 4 | Multiple visualizations methods showing the same landscape. (A–C) hillshaded relief model, colored DEM, and the custom local relief model.

Remote Detection of Features

The research project described in this article contained three basic steps: locate a sample of known reservoirs within the LiDAR DEM to determine the basic signature of those features; visually identify other possible reservoir features with the same signature throughout the 200 square kilometer area; and, confirm the identifications through previous mapping and on-site ground-truthing of 103 reservoirs.

The first step in reservoir identification relied on matching up sections of the hand-drawn site maps from survey projects from the 1980s through the 1990s. Reservoirs were noted on survey maps and then located in the DEM. This initial stage of reviewing existing maps and comparing them to the various visualizations was useful in determining key reservoir characteristics. In addition, the resulting sample of roughly 270 reservoirs was used to fine tune the visualizations used for reanalysis of the whole region.

Many features were noted using the procedures outlined above. Some of these features, while similar to reservoirs, had distinctive qualities to them allowing them to be removed from the sample. The ancient Maya also constructed chambers in the bedrock that were entered through circular holes—and some of these are open today. Called chultuns these bottle-shaped limestone cysts tend to have small sides and entrances but a greater depth than reservoirs. There is a general consensus that chultuns were used for water storage in the northern Lowlands based on the initial reports of Stephens[61] as well as on subsequent research.[62] Thompson[63] studied 60 chultuns at Labná and determined that they were most likely utilized for water storage; however, some of these water storage features had been converted into burial chambers in antiquity. It has also been theorized that some chultuns may have been used to store food. Through experimental archaeology Puleston[64] discovered that chultuns in the Southern lowlands around Tikal had the perfect conditions for the storage of ramon fruits and he suggested that they were used for this purpose. Another suggested use for chultuns was for brewing maize beer.[65] In contrast, the residents of Caracol appear to have used chultuns as early burial places.[66] As these burials are from earlier occupation and are usually undisturbed—and as there is no indication that surfaces were sealed for water retention—it is clear that the people of Caracol did not use chultuns for water storage. Thus they were removed from the sample of potential water storage features.

Other features such as caves or sinkholes can initially also look like reservoirs, but they can be distinguished because they are too large, too deep, or lack the semi-rectangular nature of the reservoirs.[67] Looters' pits can look like reservoirs at initial review; however, these features can usually be distinguished by their indistinct outlines and disturbed, bumpy surface. Furthermore, they are generally found in locations, such as in the middle of a structure, which are inconsistent with reservoir placement. Finally, other features such as open tombs can be difficult to distinguish from reservoirs as both features are rectangular and have about the same depth. The difference between them is that reservoirs possess slanted sides while open tombs have steep 90° sides. Thus, very detailed inspection of the LiDAR data is necessary, and in at many cases it may be impossible to accurately identify this feature type without ground-truthing.

With these false positive situations in mind, I conducted a systematic search through the entire dataset by establishing a grid of one-kilometer squares over the entire dataset. Each of these squares had an associated binary number value. Each number was initialized to zero. Zero signified that square had not yet been searched. After searching that square, the value was changed to one, signifying that it had been searched. Clearly marking previously inspected locations in the grid permitted a systematic search over the entire dataset. In order to avoid false positives, the elevations along the interiors and exteriors of these features were double-checked. In addition, no features less than 20 cm in depth were included, nor were small diameter (less than 1 or 2 m in width) reservoirs searched for to avoid small depressions such as tree falls or other small pits, even though some reservoirs of this size had been located during ground survey. In a DEM with 1-m resolution, features of this size are difficult if not impossible to identify securely because the cells are nearly the same size as the features.

As a result of the systematic search, use of multiple visualizations and colorings, and determination, 1590 reservoirs have been identified through remote sensing at Caracol (Figure 5). The initial survey mapping of 58 reservoirs provided the first training dataset. This allowed for the identification of 270 reservoirs through various hill-shaded relief models. Then, a subsample was retested with other visualization methods and led to a prediction that there were about 1400 reservoirs at Caracol.[44] In the end, 1400 was an underestimate and 1590 is almost certainly an underestimate as well; however it is an order of magnitude more reservoirs than had been identified at the site initially.

DISCUSSION

Households at Caracol either constructed their own reservoirs or had access to reservoirs in the immediate surrounding area. The distance between a household plazuela unit and the reservoirs never exceeds 120 m. Thus, each of Caracol's residential groups had access to a reservoir in their own group or in a neighboring group or terraced field in close proximity. Absolute elite control over these distributed water resources would have been difficult or impossible to maintain given the spatial extend and distribution of the identified reservoirs as suggested by Scarborough.[18] While the monumental, downtown reservoirs could easily have been monitored and retained by the elite, the system of centralized elite water control identified at Tikal by Scarborough[10] and described by Lucero[7,8] does not appear to be the one employed at Caracol. The distribution of the reservoirs across Caracol, along with the variety of shapes and sizes, would also imply a lack of standardized elite control over the reservoirs dispersed throughout the terraced landscape.

Three classes of reservoirs can be seen in the dataset of reservoir surface areas (Figure 6). The first class encompasses 95% of the 1590 reservoir sample and comprises the residential reservoirs under 77 meters-squared. The second class includes 4.6 percent of the 1590 reservoir sample and are the nearby outliers from the box and whisker plot. This class includes all reservoirs above 77 meters-squared but less than 400 meters-squared in surface area. The final class is composed of the monumental reservoirs with over 1000 meters-squared. They make up only 0.4% of the 1590 reservoir sample at Caracol. While all the largest reservoirs are found near the epicenter and termini groups, all the smallest reservoirs are found near residential groups and their terraced agricultural fields.

These reservoirs possess no standardization of size or shape. If they did, then the box and whisker plot in Figure 6 show a very narrow box instead of the four large quartiles of reservoir sizes covering a range from 5 meters-squared to 77 meters-squared in nearly equal parts. Instead the people of Caracol likely constructed them based on factors that varied among groups such as catchment size, labor availability, and social requirements or family size. Some reservoirs are also not excavated into the ground. Instead they are built-up and integrated into or next to the large plazas in these spaces. While the smaller reservoirs have a general similarity in length and width, they still exhibit a great deal of variability. This suggests that there was no centralized reservoir contractor or other controlling factor to standardize their size.

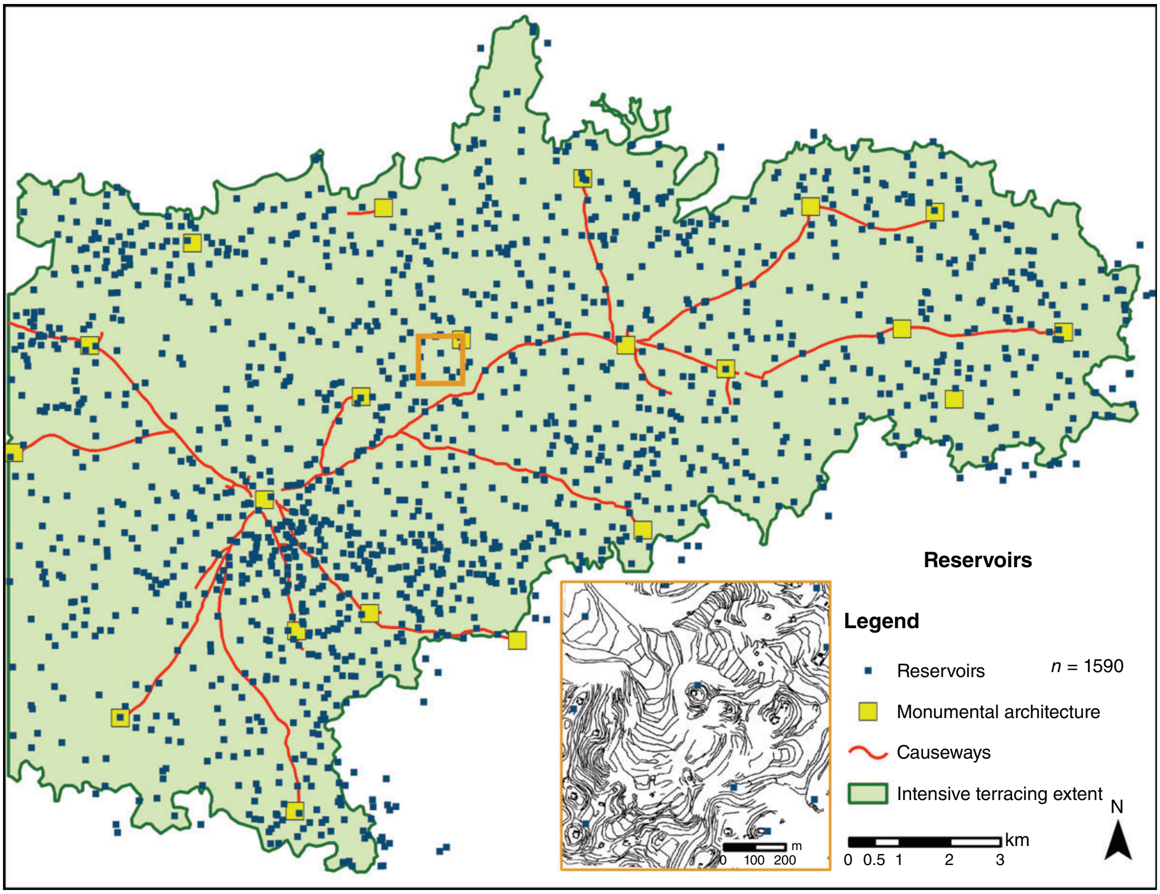

FIGURE 5 | The 1590 reservoirs identified through visual inspection in this analysis are shown above, with Caracol's dendritic causeway system, and with the intensive terracing boundary. Remote survey focused within the boundary of intensive terracing indicated by the green boundary.

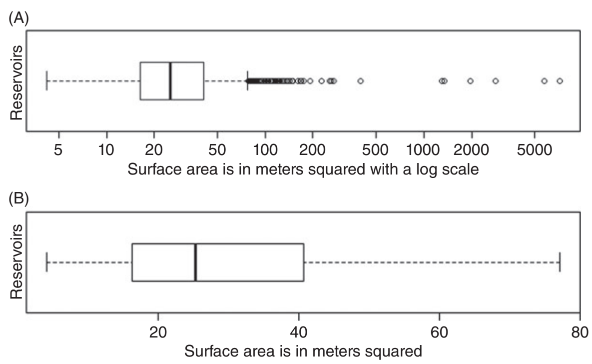

FIGURE 6 | (N = 1590) Distribution of the surface areas of reservoirs at Caracol. There are three distinct groups of reservoirs based on size: those under the box and whisker plot, the set of outliers between 77 and 400 m^2 of surface area, and those outliers with over 1000 m^2 of surface area. (A) All reservoirs at Caracol and (B) Non-outlier reservoirs at Caracol.

Reservoirs constructed with elite regulation in mind would have been built to facilitate that control and would have been constructed to exclude unauthorized use by others. Only the larger reservoirs in the city's center and termini nodes could be easily monitored. In contrast, it would have been impossible for the elite of Caracol to build, control, and monitor the use of each and every single residential reservoir at all times. The large epicentral reservoirs are an order of magnitude larger than the smaller reservoirs with surface areas of thousands of square meters as opposed to hundreds of square meters. The size disparity could suggest that size showcases the power of their owners as proposed by Scarborough[10,18] and Lucero.[7,8] The data presented here suggest that the elite did not possess exclusive control over the majority of water resources at Caracol, but still clearly controlled the large reservoirs near monumental architecture.

The great number (conservatively 1590) of reservoirs at Caracol vastly overshadows the reservoir counts at other sites. The next largest sample of reservoirs at a Maya site is the set of 75 reservoirs found through ground survey at Tikal by Scarborough and

Gallopin.[19] Even these totals may be less than the actual number of reservoirs, especially as small reservoirs less than 20 cm in depth or one or 2 m in cross-section were not considered or recorded. Thus, the reservoir estimate presented in this article underestimates the total number of reservoirs at Caracol.

CONCLUSION

This analysis of LiDAR DEM data from Caracol leads to two primary conclusions. First, the data not only demonstrate significantly more reservoirs than have yet been shown to exist at any other Classic Maya site and second, they also showcase the importance of LiDAR data for archaeological landscape analysis. LiDAR's ability to penetrate the tree canopy to identify the archaeological features preserved beneath it is revolutionizing archaeological survey in heavily forested areas of the tropical world,[68] as has been shown for both the Maya area[27] and for southeast Asia.[69] This new ability to analyze broad landscapes is leading to re-evaluations of urban models[70] and to an increase in landscape-oriented archeological analyses of the Classic Maya.[38] The LiDAR datasets will continue to yield more information and will lead to not only new methods but to new questions requiring more excavation. Archaeology now possesses a tool that enables the detailed study of entire ancient settlements. LiDAR makes possible the identification of small features over large-scale areas. Using LiDAR survey data, previous survey maps, multiple visualization methods, and ground-truthing of 105 reservoirs; this research identified 1590 reservoirs at Caracol.

Significantly, this research also provides data on the nature of elite power. Caracol's reservoir density and distribution suggest that the elite did not control all, or even most, of the water storage features at this site. Instead, residential water features were widely distributed and decentralized. The Caracol population utilized reservoirs for water catchment and did so at a level that would have required inordinate elite supervision to permit elite control. As such, Caracol's abandonment cannot be tied to the failure of elite water control mechanisms.

The built landscape at Caracol demonstrates the way its residents responded to their environment. Lacking a local source of water, they relied upon rainfall. The creation of reservoirs and the heavy use of agricultural terraces[29] are the two interdependent technologies that the inhabitants of Caracol constructed and depended upon for their survival. The people who lived at Caracol shaped their environment until it fulfilled their needs. They built hundreds of square kilometers of agricultural terraced fields and created hundreds or possibly thousands of residential reservoirs to provision their city. This water management system in its totality may provide inspiration and lessons for our own water issues today.

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FURTHER READING

Caracal Archaeological Project (currently associated with University of Nevada, Las Vegas) publications are available at http://www.caracol.org/drs-chase/publications/.

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