Beyond Elite Control: Water Management at Caracol, Belize.

A thesis presented by

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Beyond Elite Control: Water Management at Caracol, Belize

Abstract

Scholars have argued that the ancient Maya elite controlled water and surrounding populations both ritually and literally by maintaining large central reservoirs. This research assesses those claims using data from Caracol, Belize - one of the most intensively investigated Classic Maya cities. The Maya of Caracol had no rivers or natural pools of water; they were entirely dependent on rainfall. To conserve water, the ancient Maya built reservoirs, rectangular features that were lined with stone and plaster or clay, to catch rainfall. Using a 200 square kilometer Digital Elevation Model created from LiDAR (Light Detecting And Ranging), it is possible to not only confirm a heavily modified ancient landscape that was covered with agricultural terracing and residential settlement, but also to study ancient water capture. While the Caracol Archaeological Project had mapped approximately 100 reservoirs, analysis of the LiDAR data through the use of visualization algorithms revealed 1400 reservoirs at Caracol, more than 10 times the number that had been identified by traditional on-the-ground survey. These algorithms will help future investigators identify reservoirs in these datasets. Reservoirs are located throughout the landscape next to households, on hillsides, in valleys, and even among the terraces. All residences had a water source close by. These data demonstrate how the Maya of Caracol were able to successfully negotiate a waterless environment. The decentralized distribution of Caracol's reservoirs further demonstrates that control of water was not the source of elite power - at least in this ancient city.

Table of Contents:

List of Figures:

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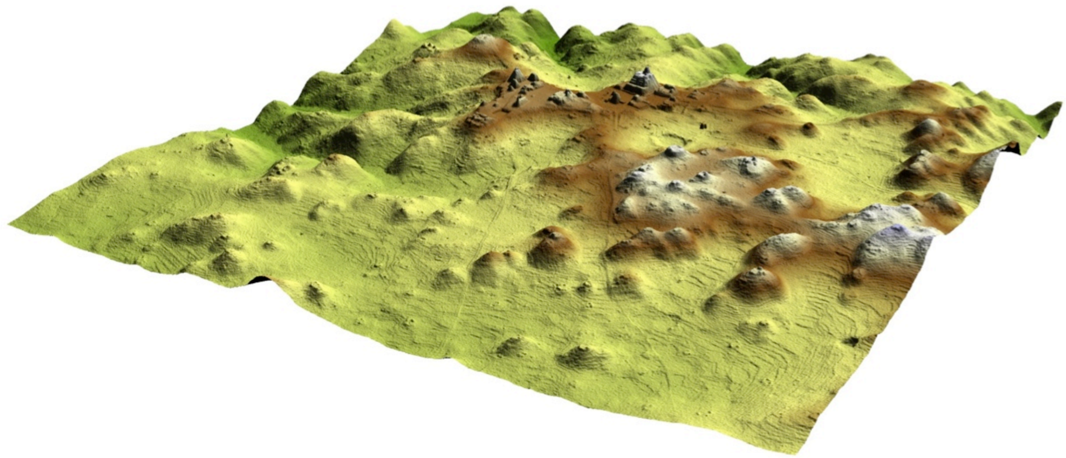

Figure 1: 2.5D of the Caracol epicenter based off of the LiDAR DEM data.

Chapter I: Introduction

Problem

Water is critical to human existence. Regardless of time period or location, humans depend on water for drinking and to provide sustenance. The availability of quality water, as well as the impact of climate change and human activities on water supply, has contemporary significance and urgency. A current response to issues of freshwater sustainability is the establishment of UN-Water, an inter-agency United Nations group focused on drinking water, sanitation, health, and the impact of factors such as urbanism, pollution, and climate change (World Water Assessment Programme 2009). Water is not only a key factor to be addressed in any archaeological reconstruction of past interactions between humans and their environment, but may also elucidate present human adaptations and potentially impact planning for the future. Thus, it is to be expected that water resources and water management would be critical to considerations of archaeological cultures such as that of the ancient Maya.

The managerial requirements of water control have been hypothesized to be influential in the rise of elite status and state-level societies (Wittfogel 1956, 1957). Scholars have also emphasized the ritual significance of water (Lucero 2006). It has been argued that control over water resources and rituals may have led to the formation of the Maya elite (Lucero 2006; Scarborough 1998). Correspondingly, the Classic Maya collapse has been tied to a series of great droughts that depleted water resources leading to social and ecological instability (Gill et al. 2007). It is argued that when rainfall and elite-controlled water capture mechanisms could no longer provide sufficient quantities of water, the Classic Period Maya civilization collapsed (Lucero 2006).

Research on ancient Maya water management systems (Lucero and Fash 2006) has focused on a variety of features such as *chultuns*, “bottle-shaped limestone cysts,” (Dunning 1994), raised field agricultural systems (Harrison and Turner 1978), and constructed landscapes (Scarborough 1998). Information about water storage derives predominantly from site centers (Scarborough 1998; Scarborough and Gallopin 1991; Crandall 2009) where large reservoirs, humanly constructed water catchment features that are often rectangular in shape, are generally found in close proximity to palaces and temples. The difficulty of survey and excavation in the rainforest concentrates research on these readily visible areas, emphasizing them over their peripheries. New survey techniques, such as LiDAR (Light Detection And Ranging) conducted at Caracol, Belize (Chase et al. 2010), permit us to survey the rainforest floor remotely through the jungle canopy, thus enabling the study of water management systems within larger settlement survey areas.

Figure 2: An image of the largest Caracol reservoir, and the only one that still holds water today. It is located in the city's downtown area.

Most Classic Maya cities were constructed away from natural water sources. All of these cities utilized reservoirs or other features related to rainwater catchment and storage. Reservoirs were humanly constructed rectangular features. They were dug into the ground and then lined with stones and covered by a layer of plaster or clay to seal in the water. At Caracol, these water collectors were often located near Maya households on the high points of hills and among their fields and terraces. The lack of easily accessible ground water and the prevalence of rainfall created a water system focused on maximizing the amount of water stored after the rain. These reservoirs are now located under a thick jungle canopy through which it is difficult to conduct ground based survey.

Figure 3: A smaller reservoir located near residential housemound groups in the 2012 Caracol archaeological project field season.

While LiDAR provides a window through the jungle canopy into past landscape modification, actual identification of reservoirs is difficult given the small size and depth of many residential area reservoirs. Given the fact that these features are often feed by drains or slopping surfaces, silting and erosion has also taken place since ancient Maya times, meaning that reservoir edges are often irregular and the reservoirs themselves are often filled in with soil and become more shallow than they would have been in antiquity.. Vegetation has also grown around and within these reservoirs, large trees can destroy these features with their gargantuan roots and smaller jungle brush obscures the reservoirs from ground survey. As such, these features are difficult to see on-the-ground without more overgrowth removal than traditionally takes place during survey. At Caracol, they are not visible in either aerial photographs or satellite imagery. This makes remote identification of reservoirs a very challenging problem. One method of remotely inspecting reservoirs that is newly available is close visual inspection of the LiDAR derived images. While time consuming, it is substantially faster than on-the-ground survey. Unfortunately, there are currently no mechanisms to identify any Maya archaeological features without human visual inspection. Development of a "smart" algorithm to the LiDAR DEM data for reservoirs would greatly enhance the speed and accuracy of reservoir identification, and could have applicability to other areas of computer visualization/machine learning (Zou and Nagy 2006; Beymer and Poggio 2012). Another potential computer science line of inquiry lies in finding ways to create images to facilitate the accuracy and speed of finding reservoirs by hand. The focus of this dissertation, therefore, is two-fold: to resolve the issue of ancient Maya water control at Caracol, Belize and to establish a methodology/technological tool to identify water capture features.

Hypotheses

Sites lacking nearby bodies of water, such as Caracol, needed reservoirs for water storage. An examination of the spatial contexts of the reservoirs can be used to test the extent of centralization in the control of water resources. Two opposing hypotheses are proposed for testing.

Hypothesis I: Elite Control of Water Resources: The elite controlled key water resources and derived a significant part of their political and ritual power from this control (Lucero 2006a). This hypothesis would be supported if reservoirs are found only in association with site epicenters, monumental architecture, and/or elite residential units.

Hypothesis II: Distributed, Non-Elite Control of Water Resources: Given the focus on shared resources and identity at Caracol (Chase and Chase 2009), 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 associated with both elite and non-elite residential units.

Figure 4: Dr. Arlen Chase standing next to a reservoir associated with the raised plaza group behind it.

Materials and Methods

Using ArcGIS on the LiDAR DEM (Digital Elevation Model) already acquired from the Caracol Archaeological Project (Chase et al. 2010), this research located Caracol reservoirs and studied their distributions. Reservoirs were identified through visual inspection using different lighting schemes (Devereaux et al. 2008) to identify reservoir-like depressions, rectangular and within a range of depths that varies with the length and width of the depression, and record their coordinates. In addition to visual inspection, several other techniques were employed including the use of an algorithms coded in Python and executed in ArcGIS 10. While identifying large rectangular site-center reservoirs is simple, smaller settlement reservoirs are substantially more difficult to identify with certainty. On-site ground tests with a GPS and comparisons with previously mapped reservoirs were used to hone my ability to find reservoirs and to establish error ranges for my remote identifications. Spatial analysis of reservoirs was undertaken to determine whether they are concentrated in epicentral areas – locations with monumental architecture in the center of the site – and thus elite controlled or broadly distributed in a fashion indicative of non-elite use and control.

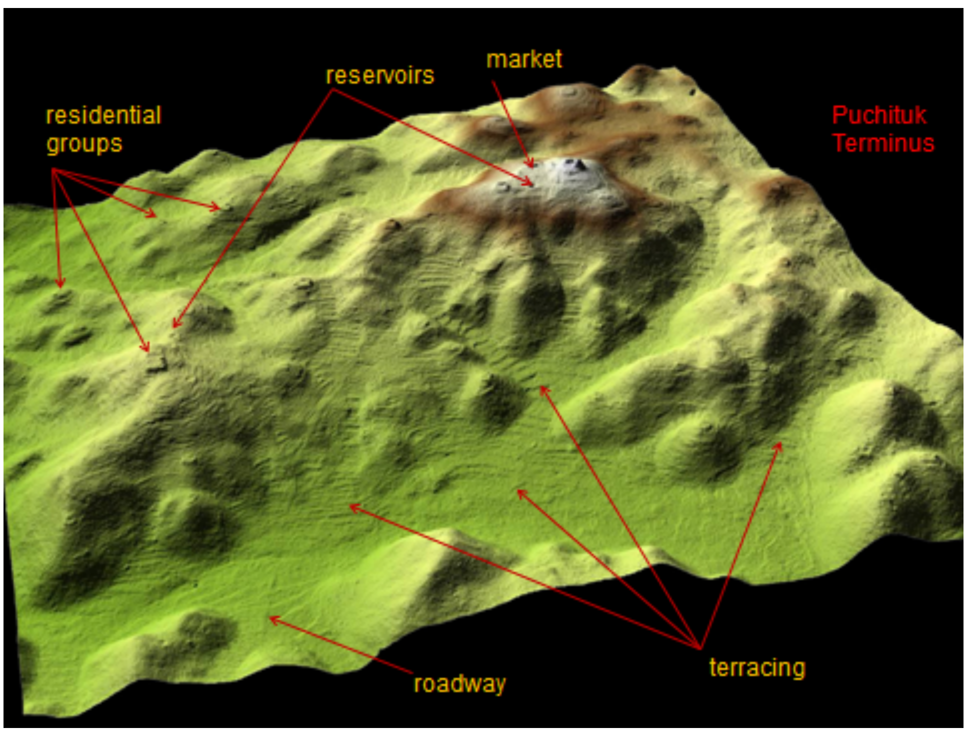

Figure 5: LiDAR 2.5D image showing archaeological features. This image shows the Puchituk Terminus. The arrows point out features within the data including residential groups, a market, roads, terraces, and reservoirs.

Significance

This research provides concrete data on the control of water resources, presumably quality water suitable for drinking, and provides alternatives to augment visual inspection for feature identification. My research does not support restrictive, centralized elite control of water resources. It adds to current knowledge on the sustainability of Maya water resource systems and assesses the role of water conservation in the rise and fall of Classic Maya civilization at Caracol. Caracol's adaptation to its local environment may also have contemporary applicability. The creation of an algorithm or the creation of new visualizations to aid in the identification of reservoirs could also be useful, not only to future archaeological analysis of LiDAR datasets, but also to other studies of computer pattern recognition.

Chapter II: Water and the Ancient Maya

Wittfogel's Hydraulic Hypothesis:

Various factors have been suggested as prime movers in the origins and development of ancient complex societies. These range from warfare (Carneiro 1970; Webster 1975) to population pressure (Boserup 2005) to trade (Sabloff and Renfrew 1975) to environmental factors (Meggars 1954). In 1957 Karl Wittfogel published *Oriental Despotism: A Comparative Study of Total Power*. His approach focused on water management and its effects on social complexity. Despite subsequent critiques, his work has become a standard hallmark to be addressed in considerations of complexity – in both the Old World and the New. Wittfogel (1955, 1957:23-27) proposed that powerful despotic governments rose to political and social prominence through their use of public works projects revolving around irrigation. The need to manage these water features, particularly in arid environments, allowed for the creation of an elite within societies. These elite then solidified and magnified their control over society through the creation of more elaborate and better water management features. Complexity can therefore arise based on the need to organize water features for the general public. Wittfogel believed that large-scale canal and irrigation systems could only have arisen through a powerful governing body. The managerial class was created by a need for water management systems, dispute settling over water rights, and the need to schedule water availability in an economy of scale. In this sense, water became the source of their power.

Subsequent thought and publication about water management has provided counter-examples to Wittfogel's basic arguments. Archaeologists have documented examples of complex irrigation systems existing without a complex system of government – in some cases showing complex irrigation systems were maintained by fragmented populations without the need for a centralized authority to dictate management of the entire system, as was the case in Samarkand (Stride et al. 2009). Others have shown that small-scale water systems under local or family jurisdiction often preceded large political organization and management of large-scale irrigation systems, suggesting that at least small water systems arose and preceded social complexity (Adams 1981), at least partially contradicting Wittfogel's assertions that a managerial government was necessary for the construction and maintenance of hydraulic systems. Additional case studies suggest that other factors may be equally or more important than water management in the evolution of social complexity. Billman (2002) assesses Wittfogel's hypothesis in the context of the formation of a managerial elite in the Southern Moche State. He notes that,

> "Analysis of the development of irrigation and political centralization indicates that the managerial requirements of irrigation were probably relatively unimportant; rather, I propose that warfare, highland-coastal interaction, and political control of irrigation systems created opportunities for leaders to form a highly centralized state" (Billman 2002:372).

Although Wittfogel's premise that large and complex water systems required governmental management and oversight has fallen out of disfavor, at least in its purest form, his theory still stands as the Prometheus of water management theory and no text on ancient hydraulic systems can be authored without mentioning his foundational work. And, in fact, tenets of his thesis remain in current analyses. They are important to consider in this work as one hypothesis supports Wittfogel's theory and the other provides a counter-example to it.

Water and IHOPE Maya:

IHOPE (Integrated History and Future of People on Earth) is a worldwide initiative looking at how studying the past may be used to better understand the present and impact the future (Costanza et al. 2007). The particular emphasis of IHOPE is on exploring the complex relationship between humans and their surroundings. Access to water clearly has an impact on understanding these relationships, particular in places with large population build-up such as at Caracol.

Maya Water Management:

While water control and access to water are important to considerations of Classic Period Maya power and organization, analysis of water in the Maya area has focused less on Wittfogellian water management than has been the case in the Old World. In his description of urbanism, Gordon Childe stated that

> "it is impossible to prove that the Mayas owed anything directly to the urban civilizations of the Old World. Their achievements must therefore be taken into account in our comparison, and their inclusion seriously complicates the task of defining the essential preconditions for the Urban Revolution" (Childe 1950:9).

The Maya did not have despotic governments formed by the creation of large water projects. However, the large reservoirs at any given site are often located in the city center, and theories about elite control over water management are common. Scarborough (2003:11) in his book *The Flow of Power* describes Maya water management as a decentralized system where "absolute elite control was never possible", yet elite control over these centralized reservoirs and a series of elaborate public rituals held societies together as "regal-ritual" states (Lucero 2006a, 2006b; Sanders and Webster 1988:524-527). The form of water control in Classic Maya cities is quite unique and has no absolute parallel in the rest of human history.

Water and Classic Maya Cities:

> "Why Caracol is situated where it is cannot be answered with any certainty or simplicity. Fifteen kilometers away by air, and many more by land, lies the Macal River; eight kilometers south of the site's epicenter lies the Retiro sinkhole. No other permanent bodies of water are closer to the site nucleus. The Maya who once lived at Caracol instead constructed innumerable reservoirs" (Chase and Chase 1987:1).

Many Classic Maya cities are located in places that we might today consider uninhabitable or undesirable for habitation. These cities, while within a sub-tropical environment, were often located at a distance from natural water resources. As a result, the ancient Maya built reservoirs for water storage. Many Classic Maya cities evince large centrally constructed reservoirs adjacent to the monumental architecture in site centers.

Cases for elite control over water resources have been advanced with evidence from Tikal in Guatemala. At this site, rainwater storage was accomplished by the use of reservoirs that provided water sufficient for the yearly four-month dry season (Scarborough and Gallopin 1991:659). All of the large reservoirs were located near the epicenter of downtown Tikal; any reservoirs in the surrounding areas appeared to be miniscule by comparison. Based on the grandeur of the central reservoirs and the detailed civic planning exemplified by the construction of those reservoirs and their drainages among the major plazas, Scarborough and Gallopin (1991) argue that the elite built and managed access to these water sources. This control over these reservoirs, they argue, resulted in elite control over the populace of Tikal.

Other scholars, however, such as Estella Weiss-Krejci and Tomas Sabbas (2002), have argued that research into Maya water management has been conducted with far too great an emphasis on the reservoirs near the monumental architecture of the city centers. Weiss-Krejci and Sabbas sampled sixteen small depressions in northern Belize that could have been reservoirs and found evidence that four of them had in fact been used for water storage. They also noticed that at Tikal there are over 65 depressions similar to the ones that they had analyzed. Based on their analysis the shallowest and smallest depression they studied could still have provided drinking water for 94 people year round if they used 2.8 liters of drinking water per day (Weiss-Krejci and Sabbas 2002:353). This would imply that the small reservoirs at Tikal should not be overlooked when scrutinizing water management at the site. Scarborough (1998) defended the focus of his analysis on the epicentral water sources at Tikal and suggested the futility of studying the small depressions.

> "… the inability of the known small tanks to hold enough water through more than one dry season after a not uncommon extended period of drought (over two years) prevented these households water holes from providing the necessary risk reduction when compared to the truly huge catchments and reservoirs associated with the largest centers" (Scarborough 1998:144)

At present, researchers in water management disagree on the importance of household reservoirs. The spectacular and prodigious sizes of the water catchment and storage reservoirs in Tikal's downtown area overshadow the potential usefulness of residential water management. However, the smaller reservoirs should not be ignored in analyzing water storage. In fact, it has been calculated that Tikal's epicentral reservoirs hold six months of emergency water rations while the other catchments in residential households brings the total emergency water rationing time up to 18 months (Gill 2000:266). Unfortunately 18 months does not cover the necessary time to outlast the extended period of drought that Scarborough decided would be necessary for the small reservoirs.

Water and Elite Control:

Vernon Scarborough and Lisa Lucero provide the primary contemporary theory on the water management practiced by the Classic Maya, and it emphasizes elite control over water. In his 1998 article Scarborough discusses the importance of water storage in order to provide water resources during the dry season. He also places importance on the civic architecture that turned the monumental portion of Tikal into a large catchment for its six great reservoirs. He argues that the Maya accretionally added water catchment technology to their sites over a long time period and without an overall plan, eventually making their water management system successful through extensive trial and error. While water storage was not limited to the site center, the reservoirs and other storage mechanisms of the Maya living outside of the city center were not robust enough to handle more than one dry season. Scarborough also views the reservoirs in the epicenter of Tikal as important ritual and political statements about the power of the elite. Reservoirs are tied to views of a watery underworld, and the lack of natural water makes control over water an important social and economic factor.

Lucero (2006a, 2006b) expands upon Scarborough's initial idea that the elite gained power through these centralized reservoirs. Her general theme is that certain members of Maya society built these large reservoirs and received disproportional gain from them, forming the societal elite (Lucero 2006a:181). Once this elite had gained power they constructed elaborate water rituals to maintain good ties with the supernatural powers in order to assure future successes in their water management scheme. "[A]t nonriver major centers like Tikal, Calakmul, and Caracol rulers' maintenance of artificial reservoirs combined with their knowledge and performance of associated rituals facilitated dry-season nucleation at centers and lessened the need for hinterland farmers to build their own reservoirs” (Lucero 2006b:117).

Lucero (2006a) uses three main points to support her analysis of the importance of reservoirs in creating and maintaining a political structure for Maya society at Tikal. The first is that the large reservoirs are located in the site centers, an indication that they were associated with the civic architecture and the elite. The second is that while larger reservoirs would have been supported by labor from many individuals, residential reservoirs would have been too difficult for a small group to maintain, especially when compared to the ease of using the central reservoirs. The third is that water lilies were used ethno-historically to gauge the purity of water in a reservoir; and, water lilies are a common symbol of Maya nobility and elite status. She concludes that elites controlled society through their use of water rituals, sacred knowledge, and distribution of water resources. While part of her argument was predicated on a limited sample of settlement data, it also employs concepts, such as “regal-ritual,” that are debated and favor an elite-centric approach to the Maya (see Sanders and Webster 1988 for an application of the regal-ritual model as well as Chase, Chase, and Haviland 1990:499 and Chase and Chase 1992:307 for a critique of the this application). Thus a consideration of water resources has impact not only on the nature of elite power, but also on the degree to which the elite controlled basic resources.

Water and the Classic Maya Collapse:

Water is often central to theories of the collapse of the Classic Maya. Some of the original monocausal theories posited drought and the resulting lack of water as the cause of a mass exodus away from these Classic Period cities. Each of these cities had been founded in a location lacking natural year-round water resources. In the case of Caracol, there is no flowing water for at least fifteen kilometers (Chase and Chase 1987). While lack of water no longer acts as a monocausal cure-all explanation for the Classic Maya collapse, it still plays a large role in most modern collapse theories.

One such theory is Yaeger and Hodell's (2008) analysis of the Maya collapse. They discuss recent paleoenvironmental data uncovered throughout the Maya lowlands and its impact on the Maya collapse of AD 750-950. One of the major points of this article is that the 'collapse' occurred throughout the Maya lowlands, but it did not occur in the same manner at all sites; some sites prospered during the collapse. In fact, the Classic Maya collapse occurred over a very large timespan. One of the main issues with dating collapse events is that radiocarbon dating suffers three flat zones on the calibration curves (Yaeger and Hodell 2008:194). These dates correspond with AD 680-760, AD 790-880, and AD 900-950. This means that radiocarbon dates for the collapse are less precise and cover a larger time swath. While theories of the collapse have moved away from monocausal factors, drought is seen as complicating the economic, political, and social issues, which ultimately lead to societal collapse.

Regardless of the actual causes of the collapse, a lack of natural freshwater resources at most, if not all, Classic Maya cities certainly provided no aid against environmental change and drought. Richardson B. Gill (2000) discusses the potential for drought as a major factor in collapse, focusing on the ancient city of Tikal in his water-deprived collapse theories. According to his calculations, the epicentral reservoirs of Tikal would have been able to supply the city for six months of drought. In conjunction with the large central reservoirs, there were also many residential reservoirs, which would have allowed the total emergency water supply to last up to 18 months (Gill 2000:266). Gill's argument seems to agree with Scarborough's assertion that Maya civic planners considered watersheds in the construction of the epicentral Tikal reservoirs. The effort required in rebuilding the site epicenter accretionally as Scarborough's model seems to suggest would mean that reaching the optimal water catchment system would require more initial planning; it would be difficult for the large reservoirs to have been constructed and changed incrementally. Drought was certainly a major issue for the ancient Maya, and the construction of Classic cities, such as Tikal, can give us insight into the civic mindset of the people who once lived there and include the degree to which planned systematic water catchment versus accretional household-based planned systems.

A consideration of drought, in conjunction with reservoir construction and elite control, has led to an intriguing view of the collapse that revolves around water, rituals, and the supernatural. According to Lisa Lucero's book *Water and Ritual: The Rise and Fall of Classic Maya Rulers* (2006a), the Classic Maya elite gained their power and prestige by constructing reservoirs and providing the water therein to others. They were granted a special position in society, and gained sacred power gained by virtue of their rituals with the supernatural forces that provided them water. When drought parched the reservoirs and the rituals could no longer bring rain and precious water, the commoners who had depended on water from the reservoirs of the elite abandoned those elite because their rituals had failed. Lucero's argument revolves around the importance of epicentral reservoirs; her model does not address residential reservoirs.

As noted above, most scholars now suggest that multiple factors were involved in the Classic Maya collapse. However, modern theories often focus on climate change – particularly drought - as one of the major factors leading to the collapse. Lucero's (2006a, 2006b) and Scarborough's (1998) theoretical frameworks suggest, first, that power of the elite Maya was based on their control over water resources in lands devoid of natural water sources and, second, that Classic Maya society was built around the centralized elite control all of water. When the water was scarce due to drought and the elite lost their ability – or possibly 'mandate from heaven' – to control the distribution of water, they lost control over the society. Since their rituals were no longer effective there no longer existed a reason to follow them.

This model may be tautological; even if society was not organized around ritualized power over water, it could still have collapsed due to economic, political, or social issues arising from the stresses associated with a prolonged drought. However, perhaps most importantly, if reservoirs were spread throughout the landscape in sufficient number to accommodate the entire population of a given site, this distribution could obviate the need for central water control, implying that water ritual might not be completely under elite purview the model of elite control of water fails when it can be proven that water catchment features were widely distributed outside of the spatial purview of Maya elites; the elite control hypothesis is based on an incomplete, core-focused dataset and it falls apart when Maya cities are viewed holistically.

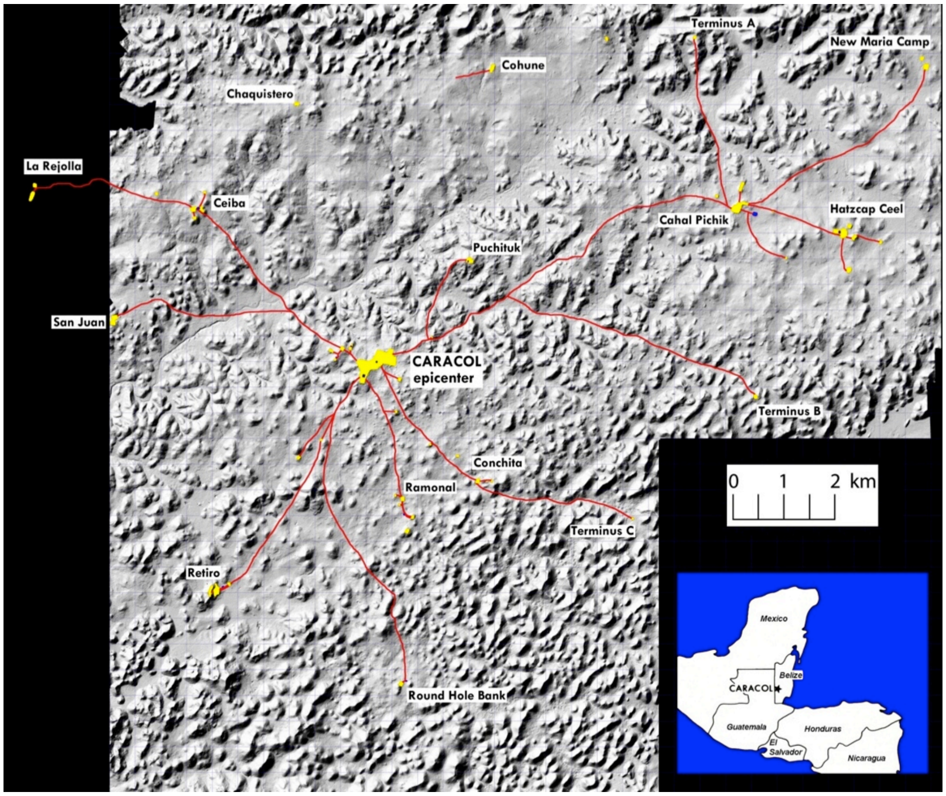

Figure 6: Caracol hillshaded terrain model with epicenter and causeways leading to the termini groups, marketplaces and elite palace groups with large epicentral style reservoirs.

Chaper III: Caracol

Caracol is located in the Maya Mountains in modern day Cayo District, Belize. Epicentral Caracol is over four kilometers from any natural freshwater resource, a spring at the Guatemala-Belize border (Crandall 2009:3), and over 15 kilometers from the nearest riverine source of water, the Macal River (Chase and Chase 1987). The site is located in its own archaeological reserve in the middle of the Chiquibul National Park. The six square miles of archaeological reserve was initially formed at the request of Linton Satterthwaite after his archaeological survey of the site in the spring of 1951 (Satterthwaite 1951:30); however, the reserve has subsequently been substantially expanded. Based on the standing stelae he observed and on mapping in the site center, Satterthwaite (1951:30) suggested that that Caracol was a ‘class 2’ Maya site. Caracol is now known to be substantially larger in size and importance as has been shown by the research and investigations of Arlen and Diane Chase (1987, 1994, 2007) of the University of Central Florida.

A logger named Rosa Mai discovered Caracol in 1938 (Satterthwaite 1951:26). However, the credit for its discovery often goes to A. Hamilton Anderson who was sent to investigate the ruins with H. B. Jex of the Forestry Department (Satterthwaite 1951:26). At that time, Anderson was colonial official in charge of the Jubilee Library. He went on to become the first Commissioner of Archaeology to what was then the Royal Crown Colony of British Honduras. In the spring of 1950 Linton Satterthwaite was recruited by the commissioner to conduct reconnaissance of Caracol as a possible candidate for his house-mound project (Satterthwaite 1951:21). Satterthwaite conducted initial excavation and mapping of the site; however, his real interest lay in the monuments he discovered around the site. At the end of his excavations in 1953 the monuments were divided between the University of Pennsylvania Museum and the British Colonial Government (Satterthwaite 1954). After that initial excavation in the 1950s, the site lay largely undisturbed, except for some minor work by Anderson (1958, 1959). After his series of surveys and excavations in the early 1950s, Satterthwaite did not return to continue excavations at the site. He did create an initial site map, but it only includes the site epicenter (Beetz and Satterthwaite 1981). It would take over thirty years before the true geospatial extent of Caracol would be perceived.

In December of 1983 Arlen and Diane Chase undertook a preliminary site survey (Chase and Chase 1987:6). Although, their initial pre-season demonstrated that Caracol had been undervalued, it is doubtful that the Chases realized during their first field season in 1985 that they would continue to excavate at Caracol annually for almost 30 years. The site has proven to be a source of great archaeological data on the Classic Maya. Not only is Caracol one of the most intensively excavated Maya sites, along with Tikal in Guatemala, but it has a unique civic system built around its role as a "garden city" (Chase and Chase 1998). The ancient people who lived in and around Caracol went to great lengths to alter the natural landscape and they covered every valley, slope, and hill with agricultural terraces. No other Maya site has as many documented terraces as Caracol. Intensive agriculture, however, has been suggested elsewhere in the Maya Lowlands (Harrison and Turner 1983). It is interesting to note that Satterthwaite (1951:30) himself noticed the abundance of terraces in his initial survey. Paul Healy undertook additional settlement work in what was perceived to be the outskirts of Caracol (Healy et al. 1983). However, the extent of the terrace system has only recently been fully established (Chase et al. 2010).

Aside from the terrace system of agriculture, Caracol also provides a new model for the display of wealth that may have applicability elsewhere. Symbolic egalitarianism, a term created to describe the distribution of elite goods at the site (Chase and Chase 2009), distinguished the site from its Classical Period counterparts. At Caracol, goods that at other sites were considered exclusively elite wares have been found in non-elite residential contexts, but in smaller quantities. This archaeological trend at led to the creation of this model of symbolic egalitarianism, where the elite shared their fine goods with the rest of society, albeit in smaller quantities. The argument is that the elite decided not to restrict all goods and share them to create cultural cohesion at the site that acted as a control mechanism whereby the elite maintained power by sharing the fruits of that power. It is interesting to note that Caracol's collapse occurred only after the elite had ceased the practice of symbolic egalitarianism and began hoarding their valuable items (Chase and Chase 2009).

The distribution of reservoirs at Caracol is in keeping with the idea of Caracol as both a garden city and a society built upon symbolic egalitarianism. Although the largest reservoirs are located in the site epicenter and near the termini groups – outlying marketplaces and residential palace groups with larger than average reservoirs – at the ends of the site's causeways, there are hundreds of smaller reservoirs located near plaza groups, households, and among the terraced hillsides. This distribution of water – and its implication that the elite did not centrally control the resource – fit into the model of symbolic egalitarianism where the elite did not limit distribution of wealth or, in this case, water. The elite in the epicenter and among the termini groups may have had more wealth and larger reservoirs, but they did not have a monopoly on that wealth and water. Reservoirs belonged to local individuals, families, or extended family groups. While the reservoir system at Caracol is important, it is exceedingly difficult to map and to demonstrate. Residential area reservoirs are often small and not easy to identify without either excavation or extensive clearing. It is only with the advent of new remote sensing technology that the full extent of the water management system becomes apparent.

Chapter IV: Technological Wonders

Computer Science and Archaeology:

Archaeology is the ultimate cross-disciplinary science. Virtually all aspects of archaeology employ tools, techniques, and methodologies from other disciplines. Key breakthroughs in archaeological science have often come from these synergies. The introduction of radiocarbon (C^{14}) dating revolutionized archaeology by providing an absolute timeline for ancient events and features. Less radical perhaps, but equally important have been laser electronic distance meters that greatly increased efficiency in surveying sites and digital cameras that provided easy and effective records of archaeological finds. Computer applications in archaeology have permitted more detailed and quicker data analysis leading archaeologists to pursue more quantitative as opposed to qualitative research, enhanced graphic and digital publication abilities that have provided quicker presentation of research findings, geographic information systems that provide the opportunity to view human landscape modification, and virtual reality applications that have provided near first-hand experiences of both excavation and ancient cultures. The greatest advances of this century are likely to be in the areas of computer vision and pattern recognition.

Computer vision and pattern recognition are key fields in Computer Science. While many papers focus on the identification of people or facial recognition (Zheng et al. 2011 and Yin et al. 2011), while these specific patterns are not particularly relevant to archaeologists this area of research is important to archaeology. Of particular interest in this paper is the ability to generate electronic identifications of patterns that can be seen by the human eye, but that we cannot currently identify in this manner. Development of such tools would simplify complex analysis providing greater reliability, speed, and coverage than can now be done by hand or by eye. Such tools would have applicability beyond the field of archaeology.

The Caracol LiDAR (Light Detection And Ranging) Dataset:

Various kinds of remote sensing have been used in archaeological research in the Maya area. In particular, satellite imaging has been used (augmenting traditional aerial photography) to indicate the locations of Maya sites and structures (Saturno et al. 2007) However, due to the dense sub-tropical canopy, none of these remote sensing techniques are able to effectively show detailed aspects of ancient landscape modification. LiDAR, Light Detection And Ranging, rectifies this situation by penetrating the jungle canopy. Lidar is a remote sensing technology utilized to measure the distance. A LiDAR emitter sends out laser pulses. When those pulses reach a surface such as a leaf on a tree or the ground, they bounce. This sends those laser pulses back to the emitter. The emitter can then measure the distance the laser traveled based on the time it took for the laser pulse to hit the target and bounce back. When each measurement is combined with a GPS reading and taken from the same elevation, the pulses can be recorded as a point of latitude, longitude, and height. This allows for LiDAR to create a spatial map of x, y, and z values. The small wavelength of laser light also means that laser pulses are able to pass between the leaves of the rainforest canopy, bounce off of the ground, and return to the emitter. When enough measurements are made, LiDAR can be used to see beneath the trees.

However, this data in its raw point cloud form does not allow easy analysis. In order to be of use, raw LiDAR data needs to be formatted into a Digital Elevation Model

(DEM) or another data type. A DEM is simply a grid of x (latitude), y (longitude) points where each pair of x's and y's gives a z value (elevation).

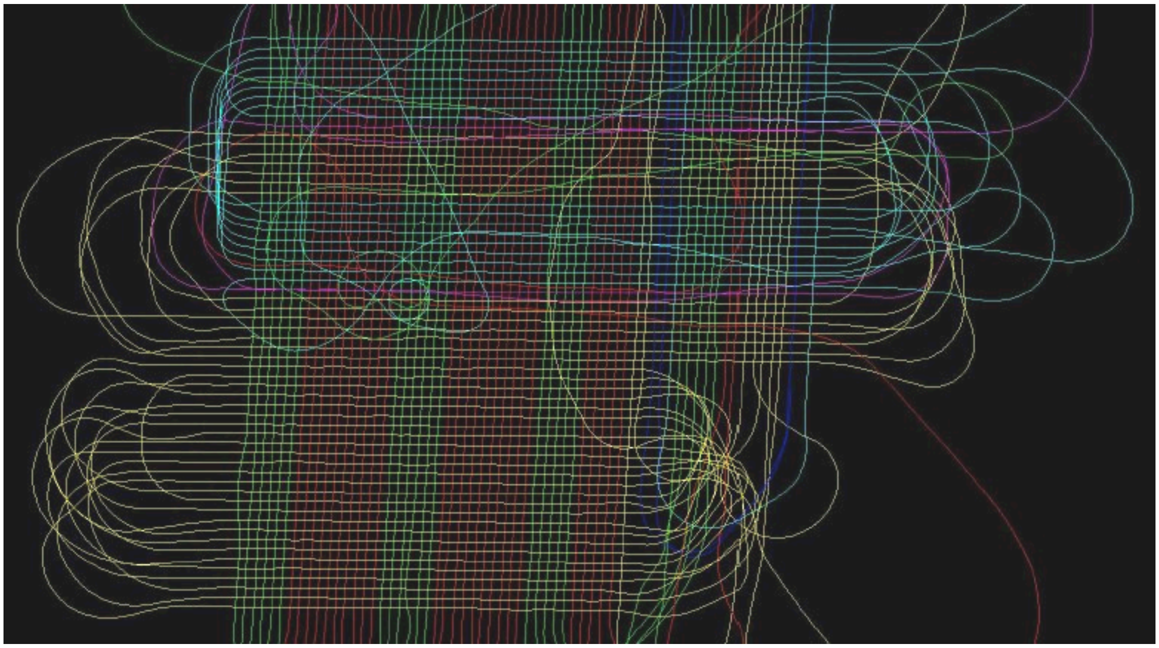

Figure 7: The grid of flight paths of the airplane taking LiDAR points.

Through a NASA space archaeology grant, the LiDAR data for Caracol was collected by a flight undertaken by the National Science Foundation's National Center for Airborne Laser Mapping (NCALM) (A. Chase et. al 2011:390). The plane flew 800 meters above the forest canopy of Caracol (D. Chase et al. 2011:63) and flew in two sets of parallel lines in order to create a grid flyover pattern (See figure 7 above). The flight was undertaken during the driest part of the dry season in order to minimize the density of leaves in the forest canopy (Chase et al. 2010:28). To conduct the LiDAR survey, a Cessna flew over the site for with 9.24 hours of laser measurement time between April 26th and April 30th 2009; "the survey used an Optech GEMINI Airborne Laser Terrain Mapper (ALTM)" (A. Chase et al. 2011:390-391). Through the use of the Airborne Laser Swath Mapping (ALSM) system, the LiDAR could record transects that were 1,500 ft wide in a single pass (Chase et al. 2010:28). Overall, the flight collected over 4.28 billion measurements, which translates into 20 points per squire meter of ground surface (D.Chase et al. 2011:63). On average 1.35 points per square meter were able to penetrate the forest canopy and reach the ground surface below (A. Chase et al. 2011:391). The resulting data was processed using ArcGIS 9.3 and Surfer 9.9 in order to produce a 199.7 square kilometer DEM, Digital Elevation Model (D. Chase et al. 2011:64). The actual processing of the data from its raw form took approximately three weeks (Chase et al. 2010:28). The end result of this LiDAR data collection was a survey dataset of which only 13 percent had been previously mapped (Chase et al. 2010:28).

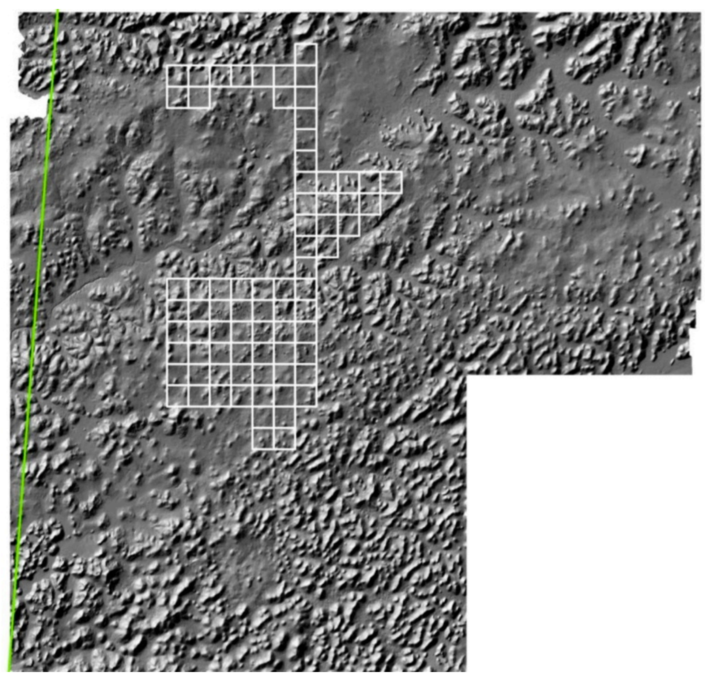

Figure 8: The grid cells on the Caracol LiDAR hillshaded terrain model represent the extent of the Caracol Archaeological Survey before the LiDAR data was taken.

Significantly, the LiDAR-derived DEM shows both large and small structures, raised platforms, terraced fields, causeways, and reservoirs. By utilizing LiDAR data it becomes possible for the first time to demonstrate the extent of the ancient landscape modification throughout the 200 square kilometer survey area. However, identification and classification of features within the LiDAR dataset requires a separate set of skills. Interpretation of remote sensing images requires the interpretation of a bird's eye view of the landscape. 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.

It was the goal of this research to develop an algorithm to identify features in the Caracol dataset that can be seen by the human eye, but are time-consuming to accurately identify in this manner. Unfortunately, reservoirs, the subject of this thesis, while of extreme interest to archaeologist, are perhaps the most difficult features to identify because of their varying shapes and sizes. As is the case with most research, the most interesting problems are the most difficult to solve. In the subsequent sections, several attempts were made to identify reservoirs. The best end result; however, came not from an attempt to automate reservoir detection but from the application of visualization techniques to facilitate the manual identification of reservoirs. Using different depictions of the data, the reservoir count was increased by a factor of 5 over the original 270 reservoirs identified with the naked eye.

Chapter V: Methodology and Research Results

Methodology:

Earlier fieldwork had recorded reservoirs in all mapped areas of the site and suggested that there were approximately 5 reservoirs per square kilometer (Chase and Chase 1996, 1998). Previous research also outlined the capacity of the epicentral reservoirs (Crandal 2009). However, mapping was incomplete as residential reservoirs are frequently small, irregular, and obscured by overgrowth. A holistic study of the water management system at Caracol therefore requires a fuller identification of the location and distribution of reservoirs at the site. This necessity led to the current thesis with two LiDAR-based sub-projects, one based on visual inspection and confirmation, which indirectly led to the second, described in a subsequent section, on algorithm augmented identification.

The visualization project contained three basic steps: 1) location of a sample of known reservoirs within the LiDAR DEM to determine the basic signature of those features; 2) visual identification of other possible reservoir features with the same signature throughout the 200 sq km area; and, 3) confirmation of identifications through previous mapping and new ground-checking.

The initial method employed for finding reservoirs relied on matching up sections of the hand-drawn site maps from survey projects from the 1980s through the 1990s. Reservoirs noted on the survey maps were located in a hillshaded terrain model, a terrain relief model which simulates a raking light source onto the underlying DEM. This initial stage of reviewing archival maps and comparing them to the various hillshades (Devereaux et al. 2008) were useful in determining key reservoir characteristics.

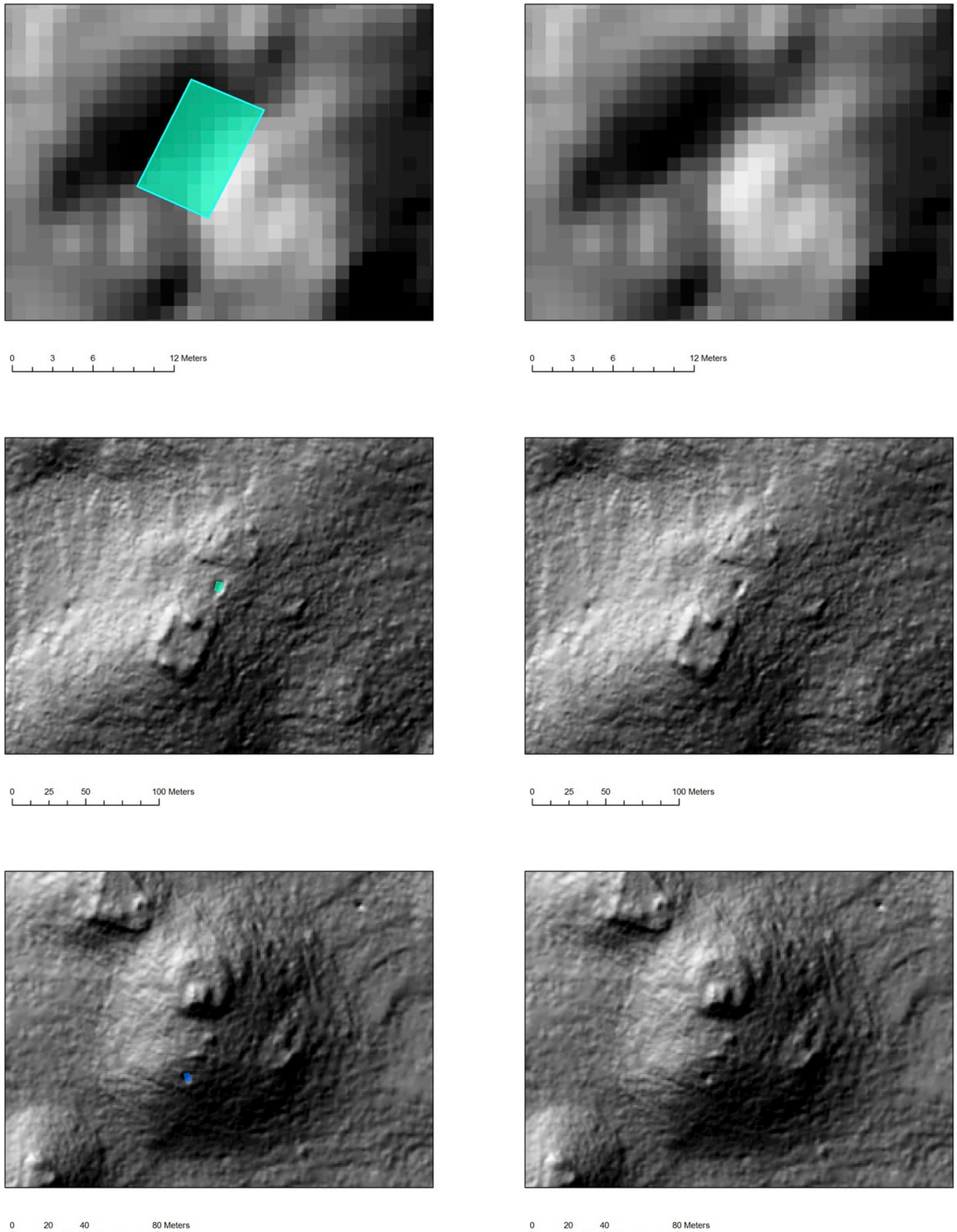

Figure 9: top reservoir #5, middle reservoir #22, and bottom reservoir #270. Each of these images is of a hillshaded terrain model image created from the LiDAR DEM data. The left image includes the outline of the reservoir in the image. The right side contains the image without the outline of the reservoir.

With a light source from the NW, raised features will be illuminated (light) on their NW sides and shaded (dark) on their SE sides. This signature describes features such as platforms, house mounds, and causeways. Sunken features, on the other hand, will be shaded on their NW sides and illuminated on their SE sides. This signature describes features such as reservoirs (see illustration above). Monumental architecture and other structures were relatively easily identified.

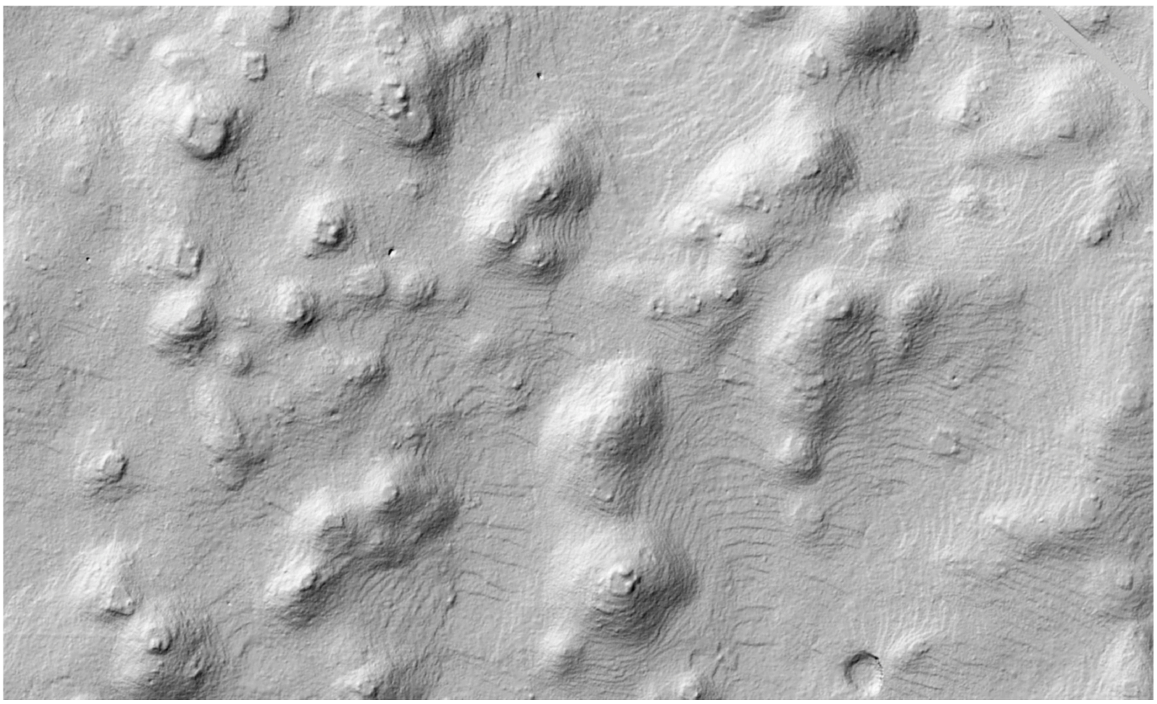

Figure 10: A hillshaded terrain model of 1.19 square kilometers with the Machete group in the upper-left.

The visual trick required to search for reservoirs was to look for semi-rectangular shapes with the characteristic signature of an anti-mound, a depression. The location of reservoirs in conjunction with other features was also taken into account. Patterning in the data made it clear that the reservoirs tended to be located near housemound groups, and they were more likely to be located near the higher elevated portions of hillsides. The majority tended to be located where they would have had cleaner watersheds, although a few reservoirs are located in the middle of terraced fields and where drainage may have made the water less potable for human beings and more suitable for agricultural purposes. The next stage of investigation involved the identification of new reservoirs using the skills developed based upon the analysis of the initial mapped sample.

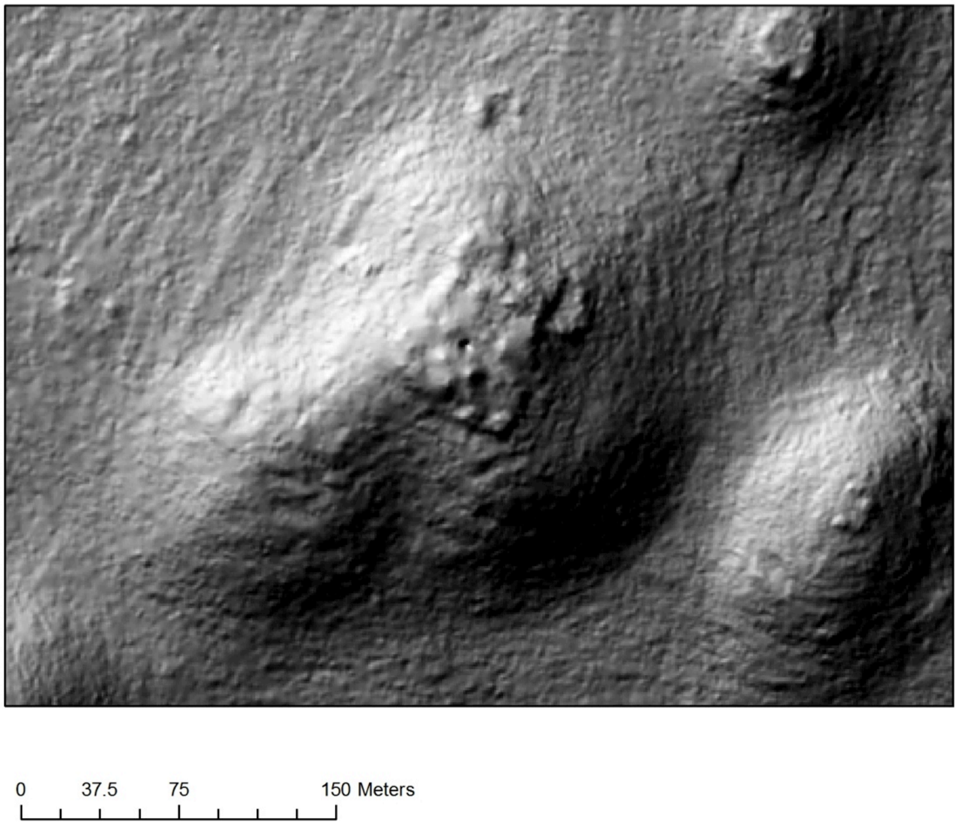

Figure 11: Ramonal *chultun*, this depression in the center of an elevated group in the middle of the image is not a reservoir. It is a bottle shaped limestone cyst. It is nearly indistinguishable from a reservoir, except in the original ground-based field surveys

As the search was conducted, many features were noted. Some of these features, while similar to reservoirs, had distinctive qualities to them. The naturally forming depressions in limestone called *chultuns*, "bottle-shaped limestone cysts," (See figure 11 above for *chultun* image in the LiDAR hillshaded terrain model) 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 (1843, Vol. 1:231) as well as subsequent research (Dunning 1994). Thompson (1887) studied sixty *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* were used to store food. Through experimental archaeology Puleston (1971) discovered that *chultuns* had the perfect conditions for the storage of ramon fruits. The Maya at Caracol appear to have used these features as early burial places (Hunter-Tate 1994). 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 would seem likely that the Maya at Caracol did not use *chultuns* for water storage. Other features such as caves can also look like reservoirs, but they can be separated out because they are too large, too deep, or lack the semi-rectangular nature of the reservoirs (Weishampel et al. 2012). On some locations within the LiDAR data, looters' pits can look like reservoirs. These features can usually be distinguished by their indistinct outlines and disturbed and bumpy surface. Furthermore, they are usually found in locations where reservoirs are not generally located, such as in the middle of a structure. Finally, other features such as open tombs can be seen in the data that are nearly indistinguishable from reservoirs. 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-degree sides. Thus, a very detailed inspection of the data is necessary if possible; in many cases it may be impossible to accurately identify a feature in the hillshaded image without ground checking.

With these false positive features in mind, a systematic search through the entire dataset was conducted. To do so, a square kilometer grid was established over the entire two hundred kilometer dataset. For each of these squares an integer value, a whole number, corresponding to the square was created. The numbers were initialized to zero, with a zero signifying that square had not yet been searched. After searching that square, the number was changed to a one. Clearly marking previously inspected locations in the grid permitted a systematic search over the entire dataset. In order to avoid false positives, the elevations of features were also double-checked. By employing these basic methods using the description of reservoir appearance in the hillshaded relief model noted above, 270 reservoirs were identified.

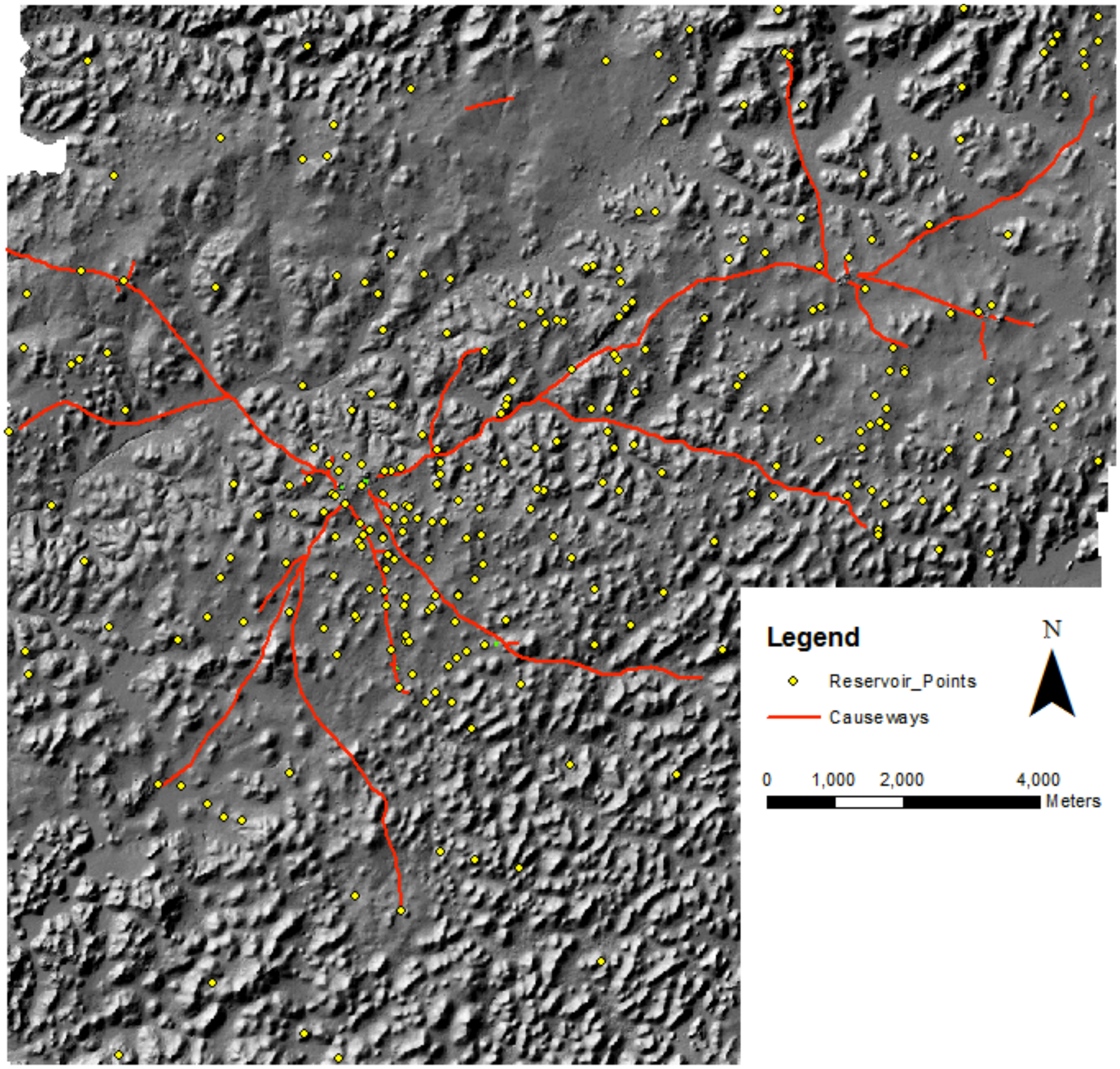

Figure 12: This image shows the 270 reservoirs identified through visual inspection on top of the hillshaded terrain model and the causeway system.

Building an Algorithm:

Visual inspection permitted a 466% increase in reservoir count (from 58 to 270 reservoirs). However, the process was painstaking; in addition, visual inspections could not effectively locate all reservoirs. The next goal was to try and find a method of remotely sensing the reservoirs and identifying them within the dataset. The LiDAR DEM has 1-meter resolution, which meant that each cell value represented one square meter. The largest reservoir at the site has a length of 42 meters, and on the other end, a few had been identified which had only 1 meter in side length, however the number of these small reservoirs in the sample is far lower than the actual number at Caracol. A one meter square reservoir fits into a single cell value within the LiDAR DEM and would appear as a single pixelated value when investigated on a computer screen. The depth of reservoirs also varied from several meters to less than 50 cm (no reservoirs in the current data-set have a depth less than 20 cm and the majority are deeper than one meter). This range in features and the fact that the majority of the reservoirs fell on the smaller end were the two main issues that need to be overcome in order for the algorithm to work.

Feature recognition is a difficulty problem and one of the most optimal solutions is to build up statistical models based on thousands of examples. Unfortunately, with only 270 reservoirs I did not find the two thousand or so I would have needed to perform a proper statistical analysis algorithm to find reservoirs. Instead, my efforts were focused on developing a process for identifying reservoir-like features. Reservoirs tend to have sloping sides and a generally rectangular shape. Thus, my initial algorithm combed the DEM to find reservoir-like depressions.

PRE, the Python Reservoir Extractor:

The initial version of PRE used a relatively simple algorithm. It hunted for a downward slope, then at least one square of the reservoir's relatively flat bottom, followed by the upward slope out of the reservoir. As it calculated the upward slope, it also counted backward on the downward slope to attempt and find the rim of the reservoir. It performed calculations like this for the x and y direction and then unified the results to show the outlines of potential reservoirs. This algorithm seemed like it would work, and even managed to successful outline several test reservoirs; however, when it was attempted on a sample dataset, it came up with too may reservoirs. In subset of data initial tests were conducted on, the algorithm identified over 6,000 possible reservoirs. Among these were housemound groups and terraces that did not sufficiently slope. It appeared that algorithm was insufficiently discriminatory.

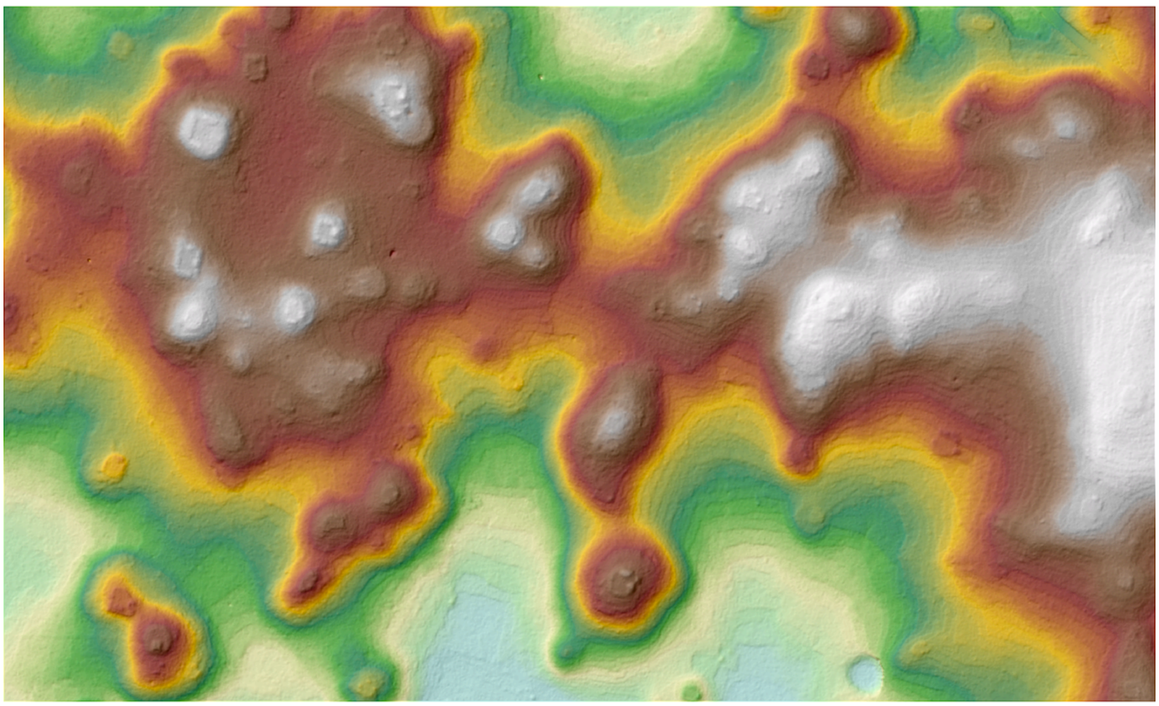

Figure 13: A hillshade of Machete (upper left) placed on top of an elevation model.

The subset of data utilized for this test was from the Machete group and surrounding area at Caracol. It is a neighborhood of raised house groups about 1.19 square km in size (850 meters NS by 1400 meters EW). I had identified 11 reservoirs by hand for the group from the initial hillshaded terrain model, 5 of which were from the initial site survey. This also made it seem highly unlikely to me that there were 6,000 reservoirs.

Further analysis of the results showed that these “reservoirs” were often no more than one cell large and they were often less than 20cm deep. In many cases, the data selected did not seem to be anything intentionally human-created like the reservoirs I was looking for. The final issue was that where I knew there was a reservoir from previous visual inspection; the algorithm would find one or several smaller sub-reservoir(s) within the large actual reservoir.

Seeing that my initial PRE algorithm was not sufficiently discriminating, I used an out-of-the-box set of hydrology software provided in ArcGIS’s Spatial Analysis package to find sinks. The sink algorithm takes as an input a modification of the DEM. The first step is to run a flow analysis on the data in order to identify in which direction a cell would drain. When the sink is piped in this flow model, it then traverses every x, y pair in the dataset and compares the cell it is on with all 9 of its neighbors, above, below, right, left, and its four diagonals. If the cell is the lowest of all its neighbors, then it is recorded. Else if, another cell shares its height value, then it runs that cell. If all cells checked in this recursive method are all below their neighbors, then the group of cells is recorded. Else, there is a neighboring cell with a lower value; the current cell is not recorded. The recorded results are then returned in an image of the same size and resolution as the initial DEM.

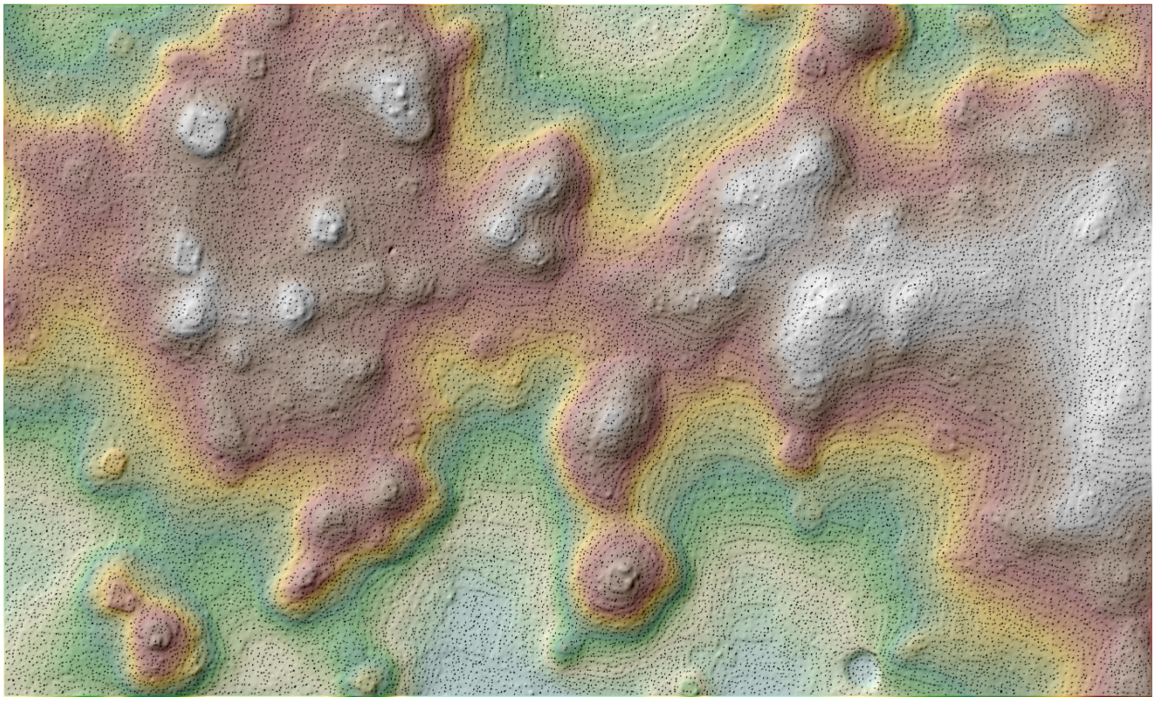
Figure 14: Machete where all 30,632 black squares represent a sink.

The initial results of this sink algorithm were quite startling. It found over 30,000 sinks. These sinks were even more detailed than those discovered by the initial PRE algorithm. Plazas had sinks in them and the terraces were littered with sinks, far more and smaller depressions than could be reservoirs. My next step was to see if I could reduce the number of sinks found to try and see if there would be an effective way to alter the DEM to smooth out the data for the initial PRE.

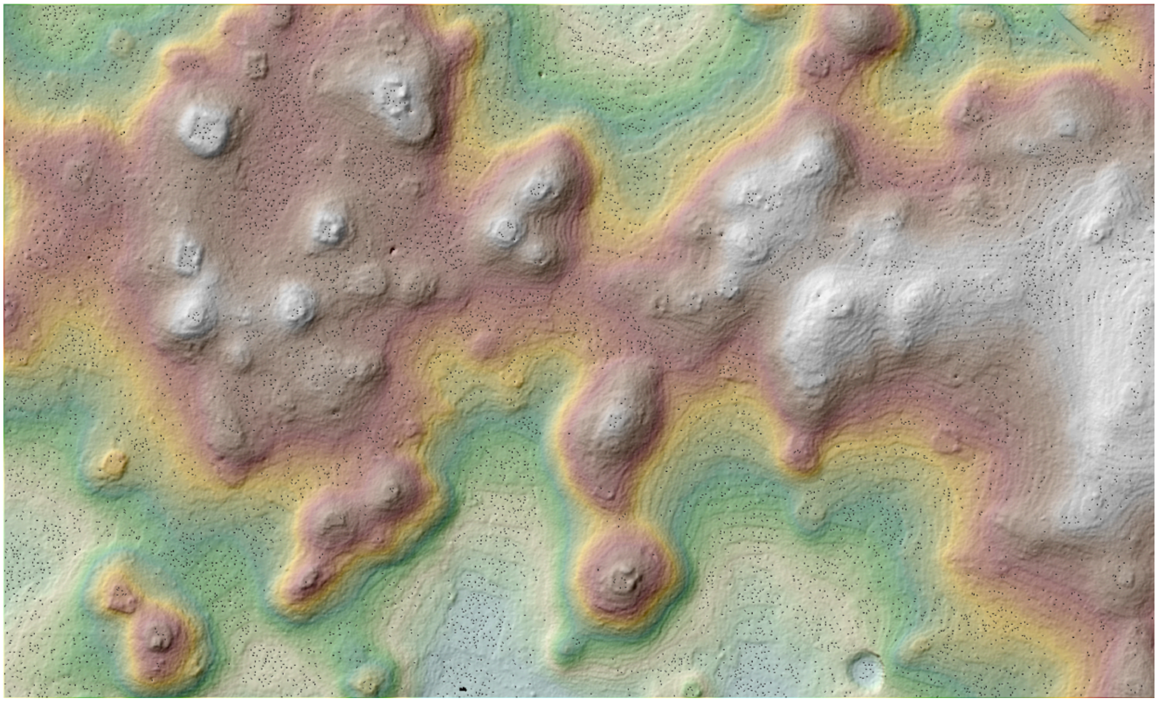
Figure 15: Machete where all sinks with 2 meters of fill or less are filled in. There are still 6,210 sinks in this image. (Sinks are represented by dark pixels)

The first tweak was to use the sink data to fill in the algorithm. This fill method ran sink, but took each sink to be a glitch and tried to fill it up to a specified z value. I did fill for 2-meters, 4-meters, 8-meters, and then, after viewing the results of the previous three, on 32-meters. Running the sink algorithm again did not have the expected results. All four of these fill operations produced the same number of sinks in the resulting image: 6,210. At this point the previously identified reservoirs all had at least one sink in them, but there were still too many false positives. Another direction was needed.

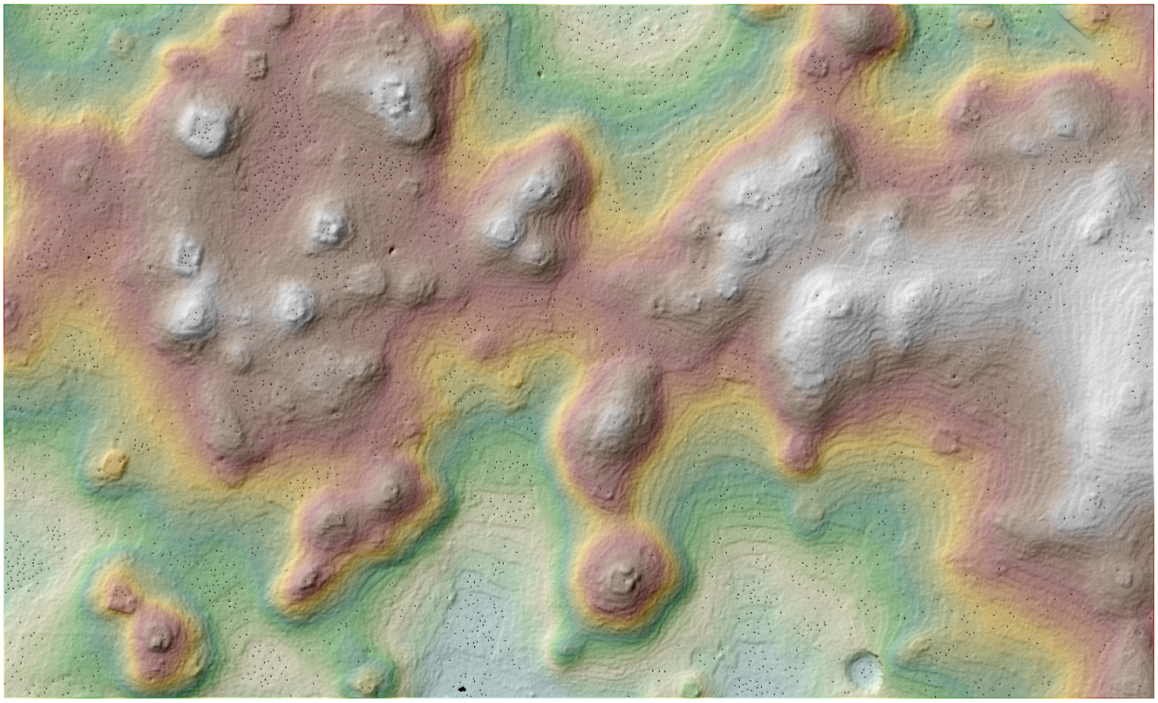
Figure 16: Machete with a single low pass filter applied to the underlying LiDAR DEM before looking for sinks. There are still 1,732 sinks in this image.

As a result of trying to fill in the sinks, I instead decided to run a low pass filter over my data set in an effort to eliminate some of these smaller sinks by averaging them away. This method reduced my total number of sinks to 1,732. Unintentionally, this erased one of my smaller known reservoirs from the dataset. In an effort to see how much further the number of false positives could be reduced, I tried running the low pass filter again and then found the sinks. That time I had 865 sinks. I tried it for a third time and had 507 sinks, but by that point only one of my visually identified reservoirs was still showing up. As I investigated the sinks, it seemed that many of them could not have been reservoirs, at the same time a several of those hundreds of values in the fields turned out to be reservoirs.

Looking at this data was not easy and it was quite difficult to tell if something was a reservoir or not. I also realized that looking for sinks or sloping features did not seem to be working well with this method of data analysis. As a result, I began to make a modified version of PRE with the intent that it would be able to help me see the reservoir features.

As I thought about the problem, I realized that what I wanted was the average change in height. I could take the current cell and an annulus (donut) around it. By taking the mean of the cells in the annulus and subtracting the current cell's height value from that mean I could produce an image that might help me find reservoirs by showing me where the landscape was both higher and lower than average. After coding this up and running it in ArcGIS, it turned out that this method worked brilliantly.

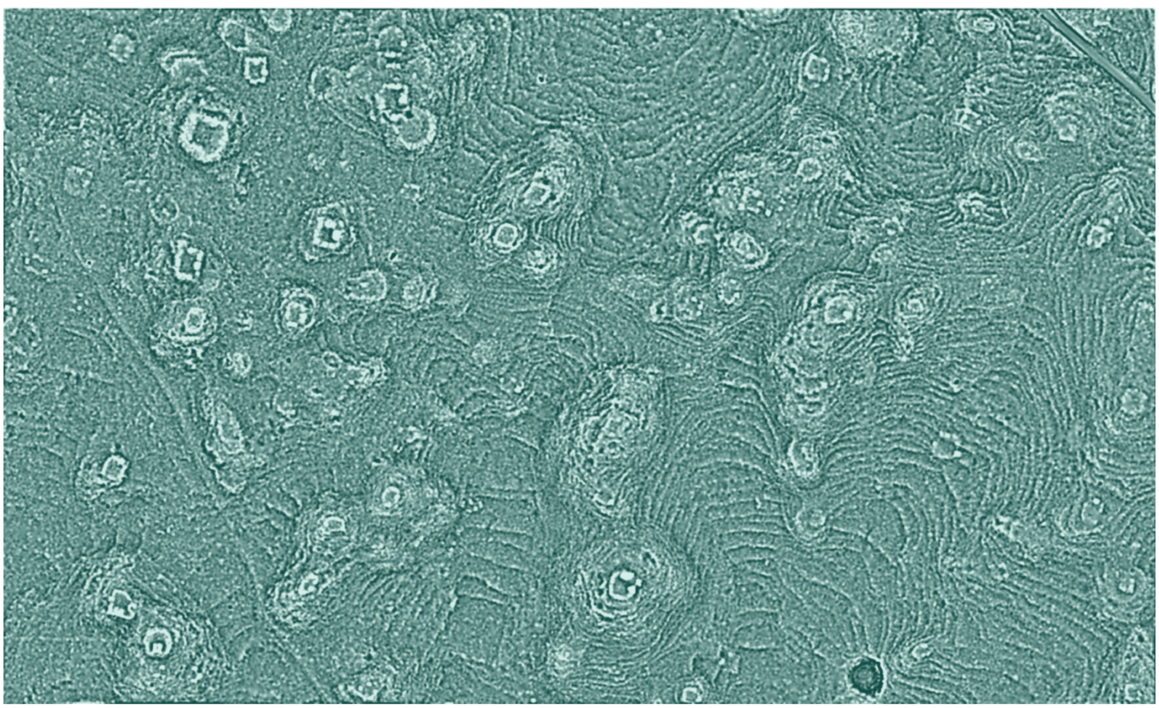

Figure 17: Machete after the application of the algorithm in the above paragraph.

I could see the structures very clearly because they were higher than the expected value of the annulus around them in the computer enhanced image. I could see the terraces incredibly well because the cells beneath the terrace wall had lower than expected values and the spaces on top had higher than expected values, creating a double line. There are also depressions that could be reservoirs that are clearly visible as low values in the image, but are not as clearly visible as the structures or the terraces. It is also possible to make out the causeways, the white roads of the ancient Maya. In fact, a new causeway was discovered that had not already been previously identified. This method seems to have extracted all of the archaeological features from the image. In fact, this method appears to mimic the mechanism used by the human eye (Róka et al. 2007).

While this method works very well and will make future identifications of reservoirs easier, it is unable to automatically identify reservoirs. Based on the lack of ability of the sink and initial PRE model to work, it would seem like the best course of action would be to continue manually pulling data out of the DEM, but using this visualization scheme to aid in identification. It should be mentioned that research after coming up with this algorithm show it to be similar to edge detection used in visualization problems. Algorithms of that type are based on the manner in which the retina of an eye perceives an image (Róka 2007:33-34). Analysis of the resulting image from my "edge detection" algorithm helped to uncover several reservoirs that had been missed both by the ground based survey and by my survey of the LiDAR DEM.

Results:

Because the new image makes it easier to see features I decided to retest an old data segment using this new visual aid. Using Machete's 1.19 square kilometers as the sample, I re-searched it for reservoirs. The results were astounding. I found a total of 58 reservoirs. The initial ground survey of the area had only found five reservoirs that I could locate on the LiDAR DEM and my first visual search over the hillshaded terrain model added only six more reservoirs. That led to a grad total of 11 reservoirs from previous analysis. With this new image I was able to go from 11 reservoirs to 58 reservoirs in a 1.19 square kilometer grid.

Not only were these new reservoirs located near plaza groups and hilltops, they were also distributed among the terraces and the slopes of the hills. This is how the reservoir count could increase so significantly. However, this new tally is also an underestimate. No possible reservoirs less than 20cm in depth were included and although one or two small two meter square reservoirs were found, there are certainly been more of those small reservoirs hiding in the dataset that were missed due to their small size. In data with one-meter resolution, features of around one meter in size are difficult to identify. The cells are the same size as the features and as such they appear more pixelated as they are magnified. With this in mind, the increase in reservoirs discovered was by 527%. If the total number of reservoirs discovered previously by visual inspection was multiplied by this increase, it should allow for a good lower bound on the number of reservoirs at Caracol that can be extracted with this detection method.

There were 270 reservoirs found visually and if that number could be universally increased by 527% then that would mean that the estimated number of reservoirs at Caracol is 1423. That number should be considered lower bound for the number of reservoirs at the site based on the difficulty of finding the very small reservoirs in the dataset. This would mean that Caracol had at least 1423 reservoirs. Significantly, the distribution of reservoirs has now also become clear. Households 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 in the sample analyzed never exceed 120 meters.

Usability:

Analyzing the LiDAR DEM data through these new visualization tools helped increase my reservoir total. However, I had no knowledge of how well these images would work for individuals who had not spent the past two years looking at this dataset. This led to a usability experiment in the style of computer usability analysis from visualization. In this experiment the goal was not to prove the superiority of one image over another. Rather the experiment was designed to try and figure out how the images aided in remote identification of reservoirs. These usability experiments are also not designed to get statistical results. They only test three to five people in order to shed light on how easy a system is for non-specialists to use. Whoever designed the system has biases that are not necessarily shared with people who have never seen the system before.

I found five archaeology majors and minors, and they looked at three different types of images and tried to find reservoirs. At the end of the experiment they rated the images and gave feedback on how well they felt the images worked. The first image was a grey-scale hillshaded terrain model, the second image was a colored elevation and hillshaded image, and the third image was an edge detection image. For each individual all three images were of three different locations within the data. This was done to prevent issues where two images of one location would be skewed due to the tester having previously seen the image. As each individual tried to identify reservoirs, he or she discussed his or her mental process of reservoir identification. The end result is a subjective set of views about the images that gives me an idea about how well they work for individuals who have not worked with this kind of data before.

While this feedback, including only five subjects, is not statistically significant, it has given me new insight on reservoir analysis. The first thing to note is that some individuals preferred the colored image and detested the edge detection image while others detested the colored image and preferred the edge detection image. No one seemed to mind the grey scale image, but there was a common critique that it was difficult to find reservoirs on the slopes of hills. The edge detection image was considered very difficult to look at but also very useful for finding possible reservoirs. People tended to find more reservoirs on hillsides in this image than in the other two. The color image had its own set of problems, all of the participants wanted there to be a finer distinction of colors, and many of them found the image appealing but had difficulty finding reservoirs in this image. It is worth noting that people seemed to be very good at judging which images they had a higher accuracy in when identifying possible reservoirs. Individuals gave the images that they had the highest accuracy in better usability scores, and they gave the images that they had the lowest accuracy in the lowest usability scores. Even so, there is no overall trend in which type of image is the easiest or the hardest to use. Testers as a whole did not show any image preference trends. Between the five scores for each image type, all of the images received about the same score.

However, that is not to say that images did not have their uses. Each of the images seems to have a reservoir detection niche. The color image was very good for eliminating very deep depressions such as cave entrances and showing the testers the overall nature of the landscape. The grey scale image seemed to be the best image for finding reservoirs on the flatter slopes in the data, and it seemed to give the testers a better idea of how many terraces there were in the landscape. Lastly, the edge detection image seemed to be the best for finding many depressions to investigate on hillsides, but the shear number of depressions on the flat terrain made it very difficult to look at. The edge detection image also received feedback on how it easily presented the outlines of structures, roads, and terraces. All in all these visualization all seem to have their own roles to play in identifying features in this archaeological landscape.

Future Research:

Through the use of visualization methods and algorithms it should be possible to expedite the process of manually extracting data from the LiDAR DEM. After analysis of the entire dataset, about 200 square kilometers, there should be sufficient examples of plaza groups, structures, causeways, reservoirs, caves, *chultuns*, and terraces to create statistical algorithms to extract these features. Future research would involve the creation and testing of these algorithms by training them on the examples within this dataset. As a result future LiDAR data may be easier to transform from a raster into a classified vector useful for asking and answering spatial questions.

Chapter VI: Conclusion

Hypothesis:

Based on analysis of the LiDAR DEM of Caracol, it seems that the Caracoleños did not have the regal-ritual society centered on water described by Scarborough (1998) and Lucero (2006a and 2006b). The distribution of the reservoirs across Caracol, along with the variety of sizes and shapes, would imply a lack of standardized elite control over the reservoirs dispersed among the terraced landscape.

Two types of reservoirs can be seen in the data. Large reservoirs are found near the epicenter and termini groups. They do not exhibit any particular standardization of size and shape, but rather were constructed based on factors such as catchment size, labor availability, and the social requirements of reservoir construction. Most are not dug into the ground, but rather are truly constructed features.

The smaller reservoirs have a general similarity in size and shape, but exhibit a great deal of variance. One possible explanation for this variability could be that family units built reservoirs for their personal use. That would mean that the reservoirs would be limited in scale, and that there was no centralized reservoir contractor or other controlling factor to standardize the size of the small reservoirs. The distribution of these reservoirs across the landscape would also seem to make elite control over these water sources untenable at best.

Reservoirs constructed with elite control in mind would have been built to facilitate that control and would have excluded unauthorized use by others. To some extent, epicentral and termini reservoirs do this, possibly by providing more sizeable bodies of water that could be exploited at a time of severe drought. However, it would have been impossible for the elite of Caracol to build, control, and monitor the use of each and every single reservoir. Only the larger reservoirs in the city's center and nodes could be easily monitored. By the same token, the large reservoirs are an order of magnitude larger than the smaller reservoirs, which would suggest that their size showcases the power of their owners. With this in mind, it would seem that the spatial data points to a model where the elite did not possess exclusive control over all of the reservoirs at Caracol, just those that were located near their palaces.

Implications/Discussion:

The great number (270 by visual inspection and 1423 through estimation based on computer-assisted reservoir search) of reservoirs at Caracol vastly overshadows the reservoir counts at other sites. Even these totals may be less than the actual reservoir count. Small reservoirs less than 20cm in depth were not considered or recorded, and reservoirs that are small such as only one square meter in area do not always register on the LiDAR DEM. Thus, the estimate presented in this thesis is actually an underestimate of the total number of reservoirs at Caracol. The most detailed analysis of reservoirs to date by Scarborough and Gallopin (1991:661) describes only 75 reservoirs. Reservoirs are clearly located in association with non-elite, residential constructions located outside the epicenter of the site. The LiDAR fly-over of Caracol permitted a survey of 200 square kilometers to take place in only a few days (A. Chase et. al 2011:388). Other reservoir analysis depends on terrestrial survey data that had been painstakingly accumulated over many seasons. It is unnecessary to continue extoling the virtues of LiDAR data and its ability to quickly generate archaeological datasets. With this great survey data, water management at Caracol can be analyzed at a far greater scale than has been possible in the past. The number of reservoirs discovered is a whole order of magnitude beyond previous analysis. The future of landscape archaeology and settlement survey in the Maya area will be revolutionized by future LiDAR datasets and their ability to shed insight on ancient settlement beneath the engulfing jungle canopy.

The number and distribution of small reservoirs at Caracol implies that the elite at Caracol did not monopolize control over water. The lack of natural water sources at most Classic Maya cities coupled with the prevalence of water catchment features at those sites and with this data sample suggests that Caracol's water management system may not have been unique, but rather may have been common practice. Caracol has already helped to alter urban views of the Classic Maya with its system of agricultural terraces embedded among its dense settlement as a "garden city" (Chase and Chase 1998) and in its substantial population size of over 100,000 people at AD 650 (A. Chase et al. 2011) secure its place as one of the larger Classic Maya sites. While some might argue that Caracol is "unique" in the amazing quanity and aray of its anthropogenic features, usch as reservoirs and terraces, I would suggest instead, that the technology and algorithsm used in this thesis when applied to other areas in the Maya world, will lead to similar discoveries and a greater appreciation for the acheivements of the ancient Maya – particularly for their genius in creating their own brand of tropical urbanism. Why would similarly sized sites such as Tikal, which also lacked natural water, not have practiced the same set of landscape intensification techniques as its neighbor? The number of household reservoirs at Caracol raises the question of how important and prevalent

Even after 25 years of ground-based surveys, the LiDAR data at Caracol identified numerous new reservoirs. It is true that many additional reservoirs were added due to the larger survey area; however, the number of reservoirs was more than quadrupled in the areas that had been previously investigated based on the visual analysis alone. Earlier survey efforts at other sites likewise may have missed many of the smaller reservoirs that could have provided the average citizen freedom from an elite controlled water program. With the number of smaller reservoirs greatly outnumbering the number of large reservoirs, the results of this research renew interest in the possibility that these smaller reservoirs were far more important to the average citizen of these polities than the large epicentral ones.

The built landscape at Caracol demonstrates the way the Maya responded to their environment. Lacking a local source of water, they were forced to rely upon rainfall. The creation of reservoirs and the heavy use of agricultural terraces are the two key technologies that the inhabitants of Caracol constructed and depended upon for their survival. Both features showcase the need and ability of Caracol's residents to adapt to an environment lacking in water. The people who lived at Caracol chose a hydraulically marginal environment, but shaped their environment until it fulfilled their needs. They went to great effort to build hundreds of square kilometers of terraces and to create hundreds of reservoirs. From Caracol, we can extrapolate how other Maya cities may have been sustained.

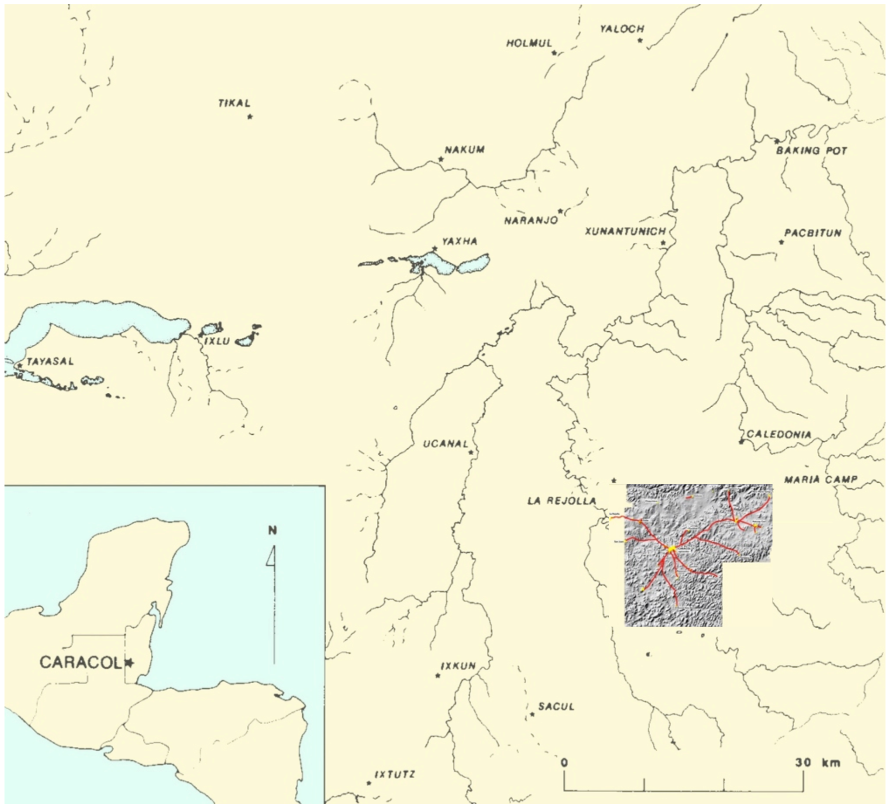

Figure 18: Image of sites near Caracol in Belize and Guatemala. Sites are placed on the map as individual points, but the *sacbeob*, causeway, network around Caracol shows that the sites were not in fact dots on a map. What does the landscape underneath the rainforest canopy actually look like? Are some disparate site points actually part of the same city? Hopefully more LiDAR data will allow us to find out what the landscape between sites looks like.

Conclusions:

This analysis of LiDAR DEM data from Caracol leads to two primary conclusions. In terms of methodology, it is clear that computer-enhanced images and computer-assisted pattern recognition have much to offer archaeology. These techniques increase the ability of researchers to identify key features. Additional work will be necessary to fully develop these tools for widespread use. The data not only demonstrates significantly more reservoirs than have been shown to exist at any other Classic Maya site, it also showcases the importance of new technology and the application of techniques from computer science to archaeological datasets. When it becomes more financially feasible for smaller projects, LiDAR's ability to see beneath the tree canopy and bring out the archaeological features preserved beneath it will revolutionize survey in the Maya area (A. Chase et al. n.d.), and in doing so will lead to more re-evaluation of urban models and landscape archeological analyses of the Classic Maya. This dataset will continue to yield more information about this Maya urban center and will lead to not only new methods of data extraction but new questions requiring more excavation to answer questions about settlement patterns and the lives of the average people. Landscape archaeology now possesses a tool that will permit the study of archaeological places beyond the epicenter. Sites are no longer dots on a map in Mesoamerica. This research more than quadruple from 58 to 270, and then quintupled from 270 to 1423, the number of reservoirs at the site and there exits the potential for its future use in other datasets and perhaps for other features not anticipated by its creator.

The second conclusion bears on the nature of elite power. Caracol's reservoir density and distribution indicate that the elite rulers of Caracol did not control all of the water storage features. Although the Maya built their cities in places devoid of natural flowing water, they utilized reservoirs for water catchment and did so at a level that cannot be tied to elite supervision and control.

This research has demonstrated that water control was decentralized, and shows how water was captured and controlled. In addition to modifying the landscape with agricultural terracing and a radiating causeway system, the Maya of Caracol developed an internal system of water management. Not only was each household situated such that there was easy access to markets and fields, but there was also ready access to water.

Households either had their own reservoirs at the sides of their plazas or within close proximity within the surrounding fields. In most cases reservoirs were within 120 meters of any settlement. Water was not the source of elite power; rather, water resources were household or neighborhood based. This thesis adds to the discussion of human-environment interactions showing how the Maya of Caracol were able to establish and maintain a large urban center and successfully thrived within their waterless surroundings.

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