FROM RUINS TO PIXELS: USING REMOTE SENSING AND GIS TO ANALYZE, DOCUMENT, AND VISUALIZE ARCHAEOLOGICAL SITES AND ANCIENT ROADWAYS IN CHACO CANYON, NEW MEXICO

by

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To my parents, my Grammy, Florencia, and my puppy Bear

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Abbreviations

ALS	Airborne laser scanning
GIS	Geographic information system
LCP	Least cost path
LiDAR	Light detection and ranging
RT	Random trees algorithm
SSI	Spatial Sciences Institute
SVM	Support vector machine algorithm

Abstract

This thesis project focuses on using advanced remote sensing technology to create a comprehensive 3D model of Chaco Canyon, a significant US National Historical Park and UNESCO World Heritage Site located in New Mexico. There are two primary motivations for this research. The first motivation is that a contiguous 3D Visualization of Chaco Canyon that is available for public viewing does not yet exist. The other primary motivation is to explore an under-documented archaeological site within Chaco Canyon that is vulnerable to becoming fully deteriorated, according to the results of this research. The project is built upon three interrelated sub-research objectives. First, a supervised image classification is conducted on satellite imagery of Chaco Canyon, which is then utilized to identify new archaeological areas of interest based on the spectral signatures of the known ruins and roadways. Second, LiDAR data is used to investigate a concealed site, and then an LCP analysis is performed to model potential travel routes to nearby ruins from the concealed site. To conclude, a 3D visualization of Chaco Canyon is generated using LiDAR point cloud data and high-resolution satellite imagery. By employing cutting-edge remote sensing techniques and GIS methodologies, the product of this project is a contiguous 3D visualization of Chaco Canyon that displays the locations of the major ruins and illustrates the extent of the ancient roadway network. Additionally, this study seeks to support ongoing cultural heritage preservation efforts at Chaco Canyon. The findings will benefit the National Parks Service, associated tribes, conservation groups, and the broader academic and public communities by providing a complete 3D visualization that can be used for educational purposes, preservation efforts, informing public policy, and as a foundation for future archaeological research at Chaco Canyon.

Chapter 1 Introduction

This research project employs a three-pronged approach to achieve its objectives. The first phase of this research is to conduct a supervised image classification on satellite imagery obtained from the Pléiades satellite constellation (acquired from Land Info Worldwide Mapping), which offers a spatial resolution of 30 cm. The findings from the supervised image classification are utilized to identify the location of ancient roadways and hidden structures that the desert landscape may conceal by first defining the spectral signatures of the documented ruins and roadways and then identifying any spectral similarities within the imagery.

The next phase of this research project is the investigation into a concealed structure on the fringes of the canyon. For this step, the history of the hidden structure, called site Bc 53 or Roberts' Site, is examined. This step aims to build upon the supervised image classification completed in phase one and to specifically determine whether the spectral signature of site Bc 53 matches the spectral signature of the nearby documented ruins, which could indicate a shared building material and a possible community connection. The next step in this second phase is to use the supervised image classification results again to assess the overall physical condition of site Bc 53 in comparison to the condition of the other nearby ruins. This second research phase, focusing on site Bc 53, concludes with a LCP analysis investigating a potential connection between site Bc 53 and both the nearby FP Chacoan Staircase and Casa Rinconada community of structures. The least-cost path analysis results provide insights into potential travel routes that ancient inhabitants of Chaco Canyon may have utilized. This analysis also seeks to clarify if site Bc 53 and the Casa Rinconada community are two separate areas or if they should all be classified as the Casa Rinconada community. The information gained from this LCP analysis enriches our understanding of ancient travel patterns, social dynamics, and landscape utilization within the Chaco Canyon region and the American Southwest.

The third and final phase of this research project is to generate a 3D visualization using LiDAR point cloud data and high-resolution satellite imagery. The satellite imagery is wrapped onto the "blank" 3D model to create a realistic 3D reconstruction of the Chaco Canyon sites and ancient roadways that radiate from them. The roadways and structures already documented in the previous Chaco Canyon literature are integrated into the final 3D visualization (Friedman, Sofaer, and Weiner 2021). Additionally, the potential roadways identified during the image classification and the LCP analysis for this project are also illustrated in the 3D visualization. The 3D visualization is made available for public viewing on ArcGIS Online.

By using a multi-layered research approach for this project, including 3D reconstruction, image classification, LCP analysis, and cartographic visualization, this research seeks to uncover new insights regarding the advanced trade, communication, and societal dynamics of the Ancestral Pueblo. The findings of this research contribute to the ongoing efforts of cultural heritage preservation at Chaco Canyon by emphasizing the importance of protecting these archaeological sites from modern threats, such as encroaching drilling and gas production in the area. Understanding the significance of these ruins and the intricacies of the roadway network is crucial for preserving the cultural heritage at Chaco Canyon. This research project builds upon the previous work conducted on the Ancestral Pueblo at Chaco Canyon by cartographically documenting the ancient structures and roadway network in 3D and making it available for public viewing online.

1.1 Background

Chaco Canyon is a US National Historical Park and UNESCO World Heritage Site with an abundance of ancient structures and complex roadways built by the Ancestral Puebloans, also known as the Anasazi, of northwestern New Mexico between 850 and 1200 CE. The overarching topic of investigation is a three-tiered methodology that first conducts a supervised image classification, next examines a specific ruin using an LCP analysis and LiDAR data, and finally generates a 3D visualization of Chaco Canyon in its entirety. This thesis project utilizes advanced GIS and remote sensing technology to complete the necessary analyses and generate the expected final products. This research study concluded by generating a realistic 3D visualization that is publicly available and can be used for a wide range of useful applications. The primary data utilized to complete this research are the LiDAR-derived point cloud of the Chaco Canyon study area and satellite imagery of Chaco Canyon at both the 1-meter and 30 cm spatial resolutions.

1.2 Study Area

This section provides the current physical descriptions of the two study areas for this research. The first study area is Chaco Canyon National Historical Park, which is the encompassing study area for this research project. The second study area is a specific area within Chaco Canyon National Historical Park, called site Bc 53.

1.2.1 Chaco Canyon National Historical Park

Chaco Canyon National Historical Park, located in northwestern New Mexico, is home to an abundance of significant archaeological sites, and it is known for its continuous connection to the Ancestral Chacoan culture. Chaco Canyon is situated within the Chaco Canyon National Historical Park, encompassing an area of approximately 138 km2.

As displayed in Chaco Canyon lies within a geological setting characterized by deep sandstone canyons, mesas, and arid desert landscapes. The Chaco Wash, as displayed in Figure 1,which is a seasonal stream that flows intermittently through the region, has carved this canyon. The elevation of Chaco Canyon ranges from around 1,890 to 1,980 meters above sea level. The canyon is surrounded by a dramatic landscape of red rock formations, including mesas and buttes, which add to its scenic beauty and archaeological significance. Despite its remote location, Chaco Canyon is accessible by road, although the last several miles leading to the park are unpaved. The climate in Chaco Canyon is semi-arid, characterized by hot summers and cold winters. Annual precipitation is relatively low, averaging around about 20 to 25 centimeters per year, with most rainfall occurring during the summer monsoon season. The flora and fauna of Chaco Canyon are adapted to the arid environment and include species such as piñon pine, juniper, and sagebrush. Wildlife in the area includes mule deer, coyotes, rabbits, and numerous bird species. Chaco Canyon is protected as part of the Chaco Culture National Historical Park, which was established in 1907 to preserve its archaeological and cultural resources. The National Park Service manages the park and encompasses both the canyon itself and surrounding areas of cultural and natural importance. Chaco Canyon is significant because it is designated as both a US National Historical Park and a UNESCO World Heritage Site; Chaco Canyon is recognized internationally for its cultural and historical importance. Its inclusion on these prestigious lists underscores its significance as a site of global human heritage.

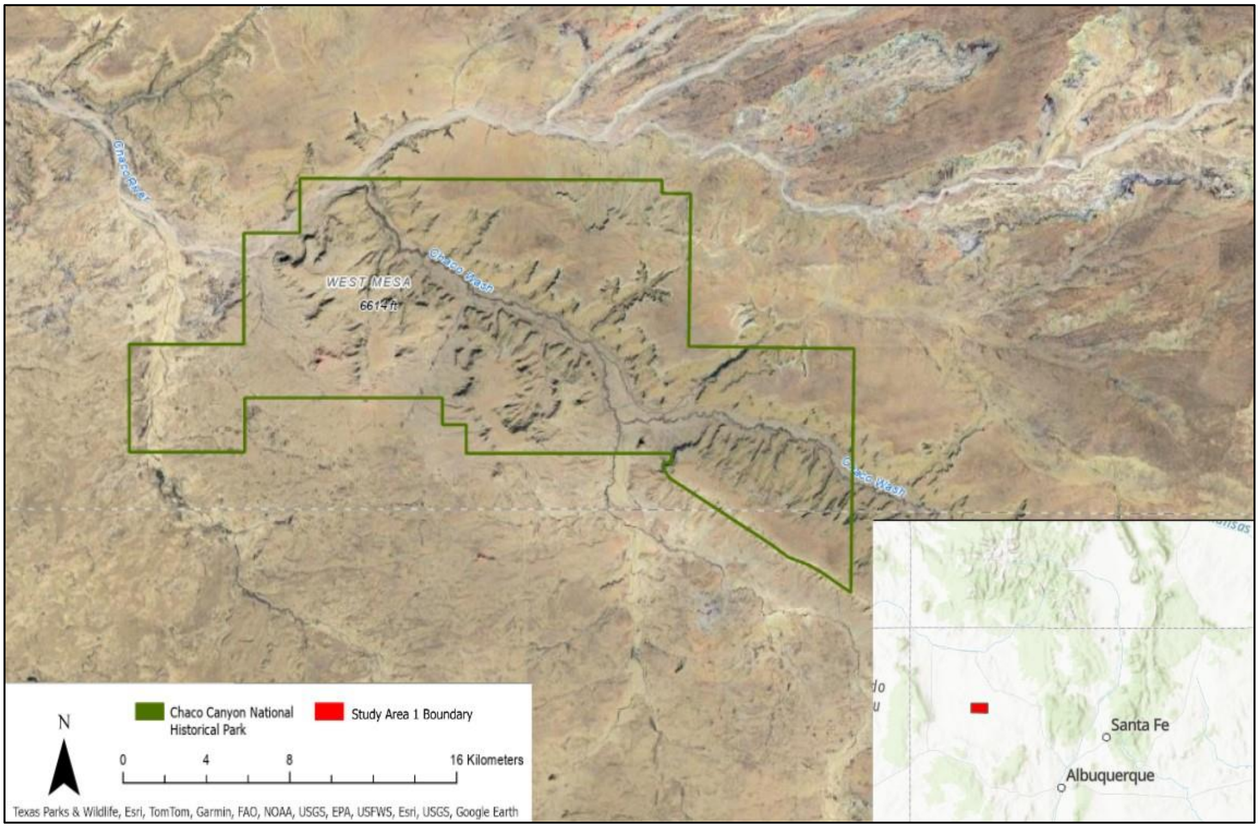


Figure 1. Study Area 1, Chaco Canyon National Historical Park

1.2.2 Site Bc 53

As part of this thesis project, a specific area within Chaco Canyon called site Bc 53 or Roberts' Site is examined in both spatial and societal contexts. As shown in Figure 2, site Bc 53 is located on the south side of the canyon, at the base of a cliff, and is situated across the Chaco Wash from Pueblo Bonito. It is positioned 0.33 km east of Casa Rinconada and the cluster of houses that make up the Casa Rinconada community. Bc 53 is comprised of approximately 21 rooms and four Kivas and was excavated by the University of New Mexico and School of American Research field schools in 1940-1941 under the direction of Frank H. H. Roberts and Paul Reiter. The structure started small and was built larger over a long period of time. Based on the ceramic frequencies found at the site, which primarily consisted of Exuberant Corrugated, Chaco, and Escavada Black-on-white ceramics, it is suggested that the occupation primarily occurred during the last half of the 11th century. Bc 53 is located about 137 meters northeast of Bc 51 and approximately 77 meters southwest of the FP Chacoan Staircase.

Figure 2. Study Area 2, Site Bc 53

1.3 The Anasazi and Chaco Canyon

This section provides the historical context for the research. It includes a description of the landscape and how the Ancestral Puebloans worked with the land and created their homes within the canyon. The section also gives background information about the Anasazi society and their relationship to Chaco Canyon. It concludes by discussing the modern descendants of the Anasazi and Chaco Canyon's role in modern-day culture.

1.3.1 Historical Description of Area

Chaco Canyon was the center of Ancestral Puebloan culture between the 9th and 12th centuries CE, serving as a hub for trade, ceremony, and cultural exchange. The ancient Chaco Canyon landscape was very similar to the climate in the area today, with long and brutal winters that slowly transformed into scorching summertime temperatures. Also similar to today’s climate, the Canyon from the 9th to the 12th centuries was categorized by short agricultural seasons and marginal rainfall (Oswald 2018). While the consistent air desert climate over the past one thousand years has protected many of the ancient structures created by the Anasazi, due to climate change as a result of human behaviors, the area now is experiencing more extreme weather than ever before, leaving the surviving structures and cultural material of Anasazi vulnerable to rapid deterioration. The river or arroyo that flows through the region is called the Chaco Wash and is the same water source that the Anasazi people relied on between the 9th and 12th centuries. While the modern Chaco Wash is the same as the one that flowed through the ancient landscape over one thousand years ago, it has meandered extensively into what it is today. There are numerous archaeological sites in Chaco Canyon located within the Chaco Wash corridor, and the river periodically flows over some of these sites (Allen 2002). However, the amplified impact of climate change, in the form of extreme weather, combined with the natural meandering of the Chaco Wash, poses a future threat that could result in a rapid rate of deterioration for sites directly within the Chaco Wash corridor.

Chaco Canyon is renowned for its remarkable architecture, including massive multistory stone structures known as “Great Houses.” The most famous of these is Pueblo Bonito, which has over 600 rooms. The construction of these buildings required sophisticated engineering techniques, including precise masonry, advanced irrigation systems, and astronomical alignments. Chaco Canyon was a place of major cultural significance and played a crucial role in the development of Ancestral Puebloan society, serving as a ceremonial, economic, and administrative center. Evidence suggests that Chaco Canyon was connected to a vast trade network stretching across the American Southwest and even into Mesoamerica. Goods such as turquoise, shell, and macaw feathers were traded over long distances. There are several structures inside the canyon used for religious ceremonies and astronomical observations, with many of these buildings aligned with solstices and equinoxes. Despite its significance, Chaco Canyon was mysteriously abandoned around the 12th century, with the reasons still debated among archaeologists. Chaco Canyon continues to be a focal point for archaeological research, with ongoing excavations and studies shedding new light on Ancestral Puebloan culture and its significance in pre-Columbian North America.

1.3.2 Site Bc 53 Background

During the initial stages of this research, Bc 53 was thought to be a completely unidentified structure because, in the majority of the maps of Chaco Canyon that define the location of all the known ruins, Bc 53 is not identified. The Chaco Research Archive is one of the only sources that correctly identifies the site on their map of the historical ruins of Chaco Canyon (Chaco Research Archive 2010). In the literature, site Bc 53 is not mapped and is only mentioned a handful of times by other archaeological investigations but not in explicit detail (Watson 2012). Why was this site not correctly identified in the literature? Why is the site so hard to identify, even when using high-resolution satellite imagery? Why are there no modern walking trails surrounding the ruin as all the other ruins have in the area? After some further investigation, some interesting findings transpired. Site Bc 53 was excavated in 1941 by a team directed by Frank H. H. Roberts Jr.; however, the results of the excavation never made it into the published literature (Ditto 2017), leading to no other academic source incorporating the structure on their maps (Chaco Research Archive 2010). In addition, this off-the-record excavation was conducted by students at the University of New Mexico, and the School of American Research field schools were attending a field school, which is where archaeologists first get trained to do field work under the direction of a head archaeologist. Instead of conducting the archaeological survey, documenting the findings, and publishing it in the literature, the only records of the research are confined to photos and field notes. Because Frank H.H. Roberts worked at the Smithsonian as the Director of the Smithsonian Institution River Basin Surveys, the photos, field notes, and seldom artifacts are sitting in the Smithsonian Archives; however, they are fortunately digitized as well (Rappaport 2011). This research aims to officially introduce site Bc 53 into the literature and define the exact location and shape of the ancient structure (Friedman, Sofaer, and Weiner 2021).

There are three main ancient staircases at Chaco Canyon; the largest is called Jackson's Staircase and overlooks the Chetro Ketl ruin. The second staircase, which is referred to as the HP Staircase during this project, is located behind the Hungo Pavi ruin. The final main staircase at Chaco Canyon sits 77 meters southwest of site Bc 53. This ancient staircase built into the cliffside is one of the focuses of the LCP analysis conducted for this research, which will be further referred to as the FP Staircase for the original excavators of the nearby site Bc 53 Frank H. H. Roberts Jr. and Paul Reiter. An LCP analysis on site Bc 53 and the nearby FP Chacoan Staircase is conducted to investigate a possible connection between the site and the staircase with the goal of better understanding the Ancestral Puebloan roadway network and how the Anasazi incorporated their roadways and architecture into the surrounding landscape.

1.3.3 Anasazi Culture and Society

Chaco Canyon is not an easy place to center a civilization, with temperatures in the summer reaching over 100 degrees and below 20 degrees in the winter, especially without the conveniences of modern technology. Despite the challenging climate, the Anasazi culture at Chaco Canyon between 850 CE and 1200 CE was a lively community with ancient roadways that were used to enhance trade and travel as well as irrigation systems for their crops (Judge 1988).

The Anasazi built their enormous and elaborate Great Houses throughout the canyon, with the largest one, Pueblo Bonito, containing over 600 rooms. Different masonry styles of these Great Houses can be dated, reflecting the development of Chacoan architecture. In addition to the Great Houses, the Anasazi also built structures called Kivas. Kivas are round semi-subterranean rooms central to Chacoan architecture and likely served ceremonial and social functions but did not serve as living quarters. These Kivas evolved from earlier pit structures and varied in size and purpose (Judge 1988).

The Anasazi are famous for their ceramic works. Ceramics became a staple over basketware mainly due to their cultural shift away from hunting and toward agriculture, leading to a more sedentary way of life. Ceramics offer several major advantages over basket ware, including that they take less time to construct, are watertight, can be placed directly over fire, and do not age. The style and design of ceramics have evolved heavily over time. Ceramic types can be used to establish temporal sequences, aiding archaeologists in dating sites and understanding cultural changes. Ceramics played a significant role in the lives of the Anasazi, evolving from plain grayware to intricately decorated vessels over their period of inhabiting Chaco Canyon.

The Anasazi used various tools and objects in their daily lives, including hunting, leisure activities, clothing making, and food storage. Until 700 CE, they relied heavily on hunting big game such as elk, mule deer, mountain sheep, and bison. Then, they transitioned to a more settled farming lifestyle, cultivating crops like corn, beans, and squash. Additionally, the inhabitants of Chaco Canyon practiced dry farming and utilized canals and ditches to collect runoff during summer storms.

The inhabitants of Chaco Canyon were also skilled artisans, producing a range of items such as baskets, ceramics, stone tools, jewelry, and ornaments. The Anasazi valued color greatly. Apart from the colorful stones used for jewelry, various minerals were ground into pigments for paints. Hematite (red), limonite (yellow), azurite (blue), malachite (green), and gypsum (white) were ground on stone mortars (NPS 2003). These minerals were then mixed with water or vegetable grease and used to decorate various objects, including wooden items such as arrows. Pigments were also employed to paint murals on plastered walls. Unfortunately, only a few of these murals have survived. The Anasazi engaged in both regional and long-distance trade, importing and exporting goods like ceramics, cherts for tools and weapons, as well as exotic items such as shells from the Gulf of California, turquoise from Cerrillos, New Mexico, and live macaws most likely originating from Mesoamerica (NPS 2003).

Even though the Anasazi lacked formal written language, they utilized rock art, including petroglyphs and pictographs, for communication. Petroglyphs are designs carved or pecked into the rock, and pictographs are designs just painted on the rock, which in contrast, erode quickly over time. These images likely conveyed group/familial affiliation, historical events, and ceremonial or ritual information. Other rock art at Chaco Canyon depicts important events during migrations, songs, stories, and some for the sake of artistic expression.

1.3.4 The Ancient Chacoan Roadway Network

The Chacoan road network is one of the most remarkable and enduring legacies of the Anasazi. These roads, which often span significant distances across the American Southwest, were more than just pathways; they were cultural and ceremonial symbols that connected various communities across the region. The roads connected Chaco Canyon to outlying communities, known as "Chacoan outliers" (Snead 2012). These roads also provided access to resources such as water, timber, and building materials, which were crucial for sustaining the Anasazi population and their construction projects. They facilitated the movement of people, goods, and ceremonial pilgrimages, which, in turn, strengthened the social, economic, and political ties within the Ancestral Puebloan world.

The Anasazi constructed this extensive network of roads that radiated outward from the central hub of Chaco Canyon. The roadways were engineered with precision and intent, often constructed in straight lines over long distances despite the challenging terrain. The roads were vast, between 8 and 12 meters wide, and were often flanked by masonry walls, earthen berms, and edging stones. These roadways also had solid foundations, with the depth of these roads ranging from 10 cm to 50 cm (Vivian 1997a). The construction of these roads would have required substantial labor and resources, indicating their importance to the Anasazi. They were built using various methods, including clearing vegetation, leveling the ground, and creating the foundation for the roads. The road surfaces were often compacted, with some evidence suggesting the use of gravel or other materials to stabilize them. In some areas, the roads were elevated, possibly to prevent waterlogging or erosion, and there are even instances of stairways and ramps being constructed to help the roads traverse steep terrain.

It is difficult to determine the exact timeframe for constructing these roads. However, taking into account the scale and complexity of the network, it is likely that they were built over several generations, possibly spanning the entire occupation of the Anasazi in Chaco Canyon from the 9th to the 12th centuries. The roadways are thought to have assisted with maintaining order within Anasazi society (Vivian 1997b). The roadways' longevity and continued use throughout the Anasazi inhabitance of Chaco Canyon emphasize their significance in the Chacoan world, both as physical connectors and as symbolic representations of the Anasazi cultural and spiritual life.

Beyond their practical use for movement and transportation, the roadways served as an integral part of the Ancestral Puebloan worldview, which holds a deep connection between the landscape and astronomy. The roads served as ceremonial routes and, at times, represented the connection between the living with the spiritual world and the past with the present. The roadways are also thought to have served as a symbolic meaning of relationships in Anasazi society; a solid and clear path represents a stable relationship between groups. At the same time, unkept roads may symbolize a fading connection (Snead 2012). These roads were meticulously planned and constructed, serving as one of the many examples of the engineering prowess and communal efforts of the Ancestral Pueblo.

As one of the descending tribes of the Anasazi, the Apache inherited and adapted aspects of Anasazi traditions, maintaining a deep connection to the land and its significance. The Apache see the landscape as a living entity, where every mountain, river, and landmark held a story and symbolized a piece of their cultural heritage. For the ancient Apache, their movement through the landscape was not merely a matter of efficient travel; these embedded symbolic meanings also influenced their movement. For instance, the ancient Apache often navigated their surroundings based on oral histories and ancestral paths, reflecting the belief that places were not just physical locations but also carriers of cultural memory and spiritual significance. This connection is evident in how places are not just physical locations but are woven into the fabric of Apache identity and spirituality, most likely inherited from their ancestors (Basso 1996). Even for the ancestral Apache, their navigation patterns were influenced by the belief that moving through these places allowed them to honor their ancestors (the Anasazi) and maintain a connection to their heritage.

Modern-day Apache communities continue to have a deep connection and reverence for their ancestral landscape. This bond with the land is a significant aspect of their cultural and spiritual identity. Many modern-day Apache people still hold traditional knowledge and practices related to their environment, viewing the landscape as sacred and integral to their heritage. Traditional stories, ceremonies, and historical practices are often tied to specific places, reinforcing their significance. The Apache's respect for the landscape is also reflected in their efforts to protect and preserve sacred sites, natural resources, and cultural practices that have been passed down through generations.

1.3.5 Descendants of the Anasazi and Chaco Canyon's Role in Modern Culture

Toward the end of the Anasazi residency in Chaco Canyon during the 1100s and 1200s, changes took place in Chaco as new construction in the area reduced and its position as a regional center in the American Southwest. However, Chaco's influence persisted in other regional centers to the north, south, and west, such as Aztec, Mesa Verde, and the Chuska Mountains. As time passed, people gradually moved away from the traditional Chacoan ways of life and ventured into new areas across the Southwest. This migration out of the canyon led to interactions with other groups of people, leading to the transformation of Anasazi culture into the Native American tribes that are seen in the American Southwest today.

The descendants of the Anasazi people of Chaco Canyon almost 1000 years ago are members of the 20 Native American tribes of New Mexico, Utah, Colorado, and Arizona. For the Modern-day Pueblo tribes of New Mexico, the Hopi of Arizona, the Navajo, the Southern Utes, Mountain Utes, Ysleta del Sur Pueblo of Texas, Zuni Tribe, and Jicarilla Apache Nation, Mescalero Apache Tribe, the history of their ancestors, their accomplishments, and traditions are passed down to future generations to maintain the connection to their ancestors. (NPS 2003) Chaco Canyon holds significant cultural and spiritual importance for many Southwestern Native Americans today, as it is a central location along their ancestors' sacred migration paths. It is regarded as a place of reverence and great significance that deserves to be treated with respect (NPS 2024). According to the UNESCO World Heritage Convention, there is evidence that there are ancient roadways and peripheral communities, also with Great Houses, located beyond the current property boundary of Chaco Canyon National Historical Park. However, these outlier roadways and communities were not taken into account during the UNESCO inscription process. Since Chaco Canyon was inscribed on the UNESCO World Heritage List, steps have been taken to slow down its rate of deterioration, such as partial site reburial, defined fencing, and increased park ranger patrolling. Even though there are no current negative impacts directly on the property, there has been an increase in the potential hazards posed by the development of surrounding areas, which includes utilities, roads, energy exploration, extraction, as well as mass transportation projects (UNESCO 2024). Additionally, a law was passed in 2023 that approved a 10-mile buffer zone around Chaco Canyon National Historical Park, meaning that it is no longer open to development. The buffer zone surrounding Chaco Canyon has become a point of contention among various law and policymakers, including tribal councils, the State of New Mexico, the National Parks Service, and the Department of the Interior. Some decision-makers advocate for the buffer zone in order to protect Chaco Canyon as much as possible. However, other stakeholders, such as tribal members from the Navajo Nation, who currently inhabit the area and were allotted these parcels of land many generations ago, do not view this buffer zone as fair. This is because it essentially freezes any land they own inside the 10-mile buffer zone surrounding Chaco Canyon. While the newly passed legislation only controls the federal land inside the buffer zone, and privately owned land is still free to allow resource extraction for profit, the demand has dropped significantly. The oil and gas industry has pulled back its investment into this area due to the new policy, which leaves many tribal members holding land that they have to repurpose or sell now that it will no longer be a reliable revenue stream (Adomaitis 2023).

Despite its importance, Chaco Canyon faces several contemporary threats that jeopardize its preservation and integrity. The region is susceptible to threats from resource extraction activities, including drilling and gas production. These activities can lead to habitat destruction, landscape alteration, and contamination of archaeological sites, posing a significant risk to the cultural and environmental heritage of Chaco Canyon. According to the National Parks Conservation Association, the largest methane hotspot, covering 2500 square miles, is located above Chaco Canyon. This hotspot is a direct result of drilling and gas production in the area. More than 75% of the residents of San Juan County, where Chaco Canyon is located, live within half a mile of gas and oil infrastructure. Additionally, over 91% of the government land surrounding Chaco Canyon National Historical Park is leased to the oil and gas industry by the Bureau of Land Management (NPCA 2023). Additionally, the fragile sandstone formations in Chaco Canyon are susceptible to erosion, which can be exacerbated by natural processes such as wind and water as well as human activities. The effects of climate change, including increased temperatures, altered precipitation patterns, and more frequent extreme weather, could impact the fragile desert ecosystem of Chaco Canyon and its archaeological resources. Illegal looting of archaeological sites for artifacts and vandalism of ancient structures also continues to be significant threats to the preservation of Chaco Canyon's cultural heritage. There is also an important challenge posed to managing and protecting the cultural resources of Chaco Canyon, including archaeological sites and artifacts, which requires significant resources and coordination among various stakeholders, including tribal communities, government agencies, and conservation organizations.

1.4 Project Overview

This thesis research project has three main objectives. First, a supervised image classification is conducted on satellite imagery of Chaco Canyon, with the aim of identifying new archaeological areas of interest based on the spectral signatures of the known ruins and roadways. Second, LiDAR data is used to investigate a concealed site, and then a LCP analysis is performed to model potential travel routes to nearby ruins from the concealed site. For the final objective, a 3D visualization of Chaco Canyon is generated using LiDAR point cloud data and high-resolution satellite imagery. The overarching goal of this research is to support ongoing cultural heritage preservation efforts at Chaco Canyon. The findings will benefit the National Parks Service, associated tribes, conservation groups, and the broader academic and public communities by providing a complete 3D visualization that can be utilized for educational purposes, preservation efforts, informing public policy, and as a foundation for future archaeological research at Chaco Canyon. The findings of this research also inform current efforts to protect this archaeological gem from the encroaching oil drilling and gas production in the area. The knowledge gained from this project not only enriches our understanding of the past but also helps preserve and protect valuable archaeological sites.

There are three primary methodologies for this research project. First, a supervised image classification is conducted utilizing both the random trees and the support vector machine algorithms. For the second methodology, site Bc 53 is further investigated, and a LCP analysis is conducted, with a focus on site Bc 53 and its neighboring sites. For the final primary methodology, a contiguous 3D visualization of Chaco Canyon will be generated, incorporating high-resolution satellite imagery, the LiDAR-derived DEM, and custom symbology to identify the major ruins and ancient roadways.

This research is based on two main pieces of data: the 30 cm and 1 m resolution satellite images of Chaco Canyon acquired from Land Info Worldwide Mapping and the open-source LiDAR data with a spatial resolution of 1 m acquired from OpenTopography. One of the primary goals of this research is to digitally protect the archaeological ruins at Chaco Canyon. "Digitally protect" refers to capturing and preserving the current state of these sites using advanced remote sensing technologies before further degradation of the archaeological sites occurs. Specifically for this research project, a contiguous, realistic 3D model of Chaco Canyon and its archaeological sites is created at a spatial resolution of 1-meter, utilizing high-resolution satellite imagery and a LiDAR-derived elevation model. This 3D model ensures a detailed and accurate representation of the landscape, structures, and ancient roadways. By documenting these sites in a digital format, the current condition of the sites can be safeguarded for future generations. This 3D model "digitally protects" the archaeological sites, allowing for continued study and appreciation of the ruins, even if they are no longer physically visible due to natural deterioration as well as human-caused factors.

1.5 Document Overview

The manuscript begins with an introductory chapter that covers the motivations for this thesis research project and provides background information on the study areas, Chaco Canyon National Historical Park, and Site Bc 53. The second chapter lays the foundation for this research by outlining related work and previous research. It discusses the related literature for the three main analyses: the supervised image classification of Chaco Canyon, the examination of site Bc 53 and its LCP analyses, and the creation of a 3D visualization of Chaco Canyon. The third chapter of this manuscript outlines the research design and methodology for this project. It starts with a brief overview of the overall methodology of the project. The following section delves into the data necessary to complete this research. The chapter concludes with a final section that details the specific methodologies for each of the three main analyses. The fourth chapter examines the results and products created from this research project. It analyzes the results of the supervised image classification, the LCP analysis, and the physical condition and preservation state of site Bc 53. The fifth and final chapter focuses on the conclusions that can be drawn from this research and the objective discussion of the research and its process. It reviews the results, discusses their implications, and explores the limitations of the project and future directions for related research.

Chapter 2 Related Work

In this chapter, the existing literature and previous research on supervised image classification of high-resolution satellite imagery is discussed. Subsequently, the relevant literature on Site Bc 53, as well as LCP analyses in similar archaeological contexts, is explored. This exploration is followed by a review of previous work and research on the creation of 3D models and visualizations of archaeological sites at Chaco Canyon. Additionally, previous research and literature on Anasazi culture and society is examined. Finally, the descendants of the Anasazi today and the role of Chaco Canyon in the modern world are considered.

2.1 Supervised Image Classification

This section discusses the use of supervised image classification in related archaeological research. A previous study conducted by Budge in 1981 is first examined, which employed supervised image classification techniques at Chaco Canyon to map the ancient roadway network and to define the location of the major ruins. Then, a more recent research study conducted by Witts, which also employed a supervised image classification on archaeological sites near Chaco Canyon, is evaluated. Additionally, a research study conducted by Keeney that focused on utilizing a supervised image classification on high-resolution imagery in Alaska to locate new archaeological sites is also reviewed. The limitations of these studies and opportunities for improvement in the use of remote sensing techniques are highlighted. This section also discusses how this thesis addresses the existing gap in remote sensing techniques applied to Chaco Canyon. It introduces a modernized approach that utilizes high-quality multi-spectral imagery, sub-meter spatial resolution, and the advanced capabilities of the Esri platform ArcGIS Pro for completing supervised image classification.

2.1.1 Previous Archaeological Research Employing Image Classification

Previous research conducted at Chaco Canyon has employed an image classification analysis, researchers such as Budge and their team had success using this type of analysis to locate ancient structures and roadways and define the agricultural landscape at Chaco Canyon (Budge 1981). A limitation to much of the research that has been conducted at Chaco Canyon employing a supervised image classification analysis is that they are dated and have not been revisited. While Budge does provide steps for analysis techniques, the workflow is from the 80s and is based on aerial imagery captured in the late 70s, which does not come close to the spatial resolution that aerial imagery today can offer.

In terms of more recent research, Witt's research study was conducted in 2010 on an area near Chaco Canyon called Farmington, New Mexico, which was seeking similar results as this thesis project but was unable to identify any new ancient roadways or the locations of any potential archaeological sites (Witts 2010). One area where Witts' research is lacking is that it is based on very zoomed-out imagery at both 30 m and 90 m resolution to try and encompass the whole Middle San Juan Region. Due to the low spatial resolution, the image classification that Witts conducted did not produce any usable results.

A previous research study conducted by Keeney and their team examined a site in Alaska at a more zoomed-in scale in contrast to Witts' research. Keeney's research study aims to test whether using satellite imagery and other remote sensing technology can help locate archaeological sites associated with mobile hunter-gatherer groups in Alaska's Brooks Range. Using 1-meter resolution IKONOS imagery, Keeney and the team employed both unsupervised and supervised image classifications, revealing a spectral phenomenon associated with archaeological sites, particularly those found under dense willow stands. The Keeney study suggests that supervised and unsupervised image classification methods could help improve survey strategies and the identification of archaeological sites when operating under the right circumstances, such as working with aerial imagery with a high enough spatial resolution to identify the nuances in the landscape (Keeney 2015).

2.1.2 Foundational Literature on Supervised Image Classification in Archaeology

To carry out the supervised image classification for this thesis project, several key literature sources are utilized to guide the process. In this research, a methodology outlined by Keeney in 2015 that uses supervised and unsupervised image classification techniques on high-resolution satellite imagery to locate archaeological features in a cost-effective and efficient manner is referenced (Keeney 2015). This source is a research project conducted by Argyrou and their team in 2023 that highlights the advantages of using supervised image classification on high-resolution aerial imagery in archaeological research. This research also provides background information on previous work done using remote sensing tools to identify areas of archaeological significance (Argyrou et al. 2023). The next source that is utilized for this research is a traditional archaeological research study completed by Gumerman in 1977, which employs remote sensing techniques and aerial imagery at Chaco Canyon National Historical Park to map cultural features such as the ancient roadways and determine the extent and characteristics of the roadways that converge on the Pueblo Alto ruin within Chaco Canyon (Gumerman 1977). Finally, the fourth key literature source is a research study conducted by Witts in 2010, which focuses on the application of remote sensing techniques on similar archaeological sites created by the Ancestral Puebloans.

2.2 Site Bc 53 and Least Cost Path Analysis

This section discusses the previous research and literature gap on site Bc 53, and the previous LCP analyses conducted at Chaco Canyon. The existing literature on site Bc 53 is minimal and inconclusive due to the unsuccessful excavation that essentially destroyed the site. However, by using sources such as the Chaco Research Archive, this thesis project aims to reidentify and map site Bc 53. Additionally, this section presents previous research studies that utilized LCP analysis, such as Alvez's study on the Beaker culture in Northeast England during the Bronze Age and Field's research on Chaco Canyon, which explores the ancient Chacoan roadway network.

2.2.1 Previous Research Regarding Site Bc 53

In terms of the previous research that has discussed site Bc 53, it is minimal and primarily based on only field notes and photos of the site in the Smithsonian Online Virtual Archive (Rappaport 2011). Due to the standard archaeological practices of the time during the initial excavation of site Bc 53, which did not prioritize site preservation for future research, the excavation was somewhat destructive. Additionally, the tools and techniques available in the 1940s lacked the precision of modern tools and methodologies, leading to potential inaccuracies. The excavation was also part of an archaeological field school, which differs from the work of a fully trained archaeological team. The absence of published findings from this excavation has further contributed to the limited scholarly understanding of site Bc 53.

The literature following this excavation only briefly mentions site Bc 53 as being somewhere near the Casa Rinconada community. However, it is never discussed in great detail, and it is seldom correctly identified on the maps in the literature (Ditto 2017). The inconsistencies in the literature and lack of overall information regarding site Bc 53 are the direct result of the failure to properly document the site during this excavation that can never be undone. The majority of the information about site Bc 53 was discovered for this project by using the website Chaco Research Archive, that does an excellent job of mapping and locating site Bc 53, which most of the current literature on Chaco Canyon fails to do (Chaco Research Archive 2010).

Because one of the main goals of this research project is to “digitally protect” the ruins at Chaco Canyon using LiDAR technology to generate a hyper-realistic 3D model, previous research conducted by Guo in 2019 is examined. The research study conducted by Guo was fascinating because it developed and incorporated an algorithm that allows for quick and accurate registration of multiple LiDAR point cloud sites. During this research project, the presented approach employing the newly created algorithm was successfully tested at the burial site in Yaoheyuan, Ningxia, and has been shown to surpass mainstream open-source algorithms in terms of accuracy and efficiency. For this research project an orthophoto generation system was created that automatically generates high precision orthophoto maps, which makes comprehensive digitalization of archaeological sites possible (Guo 2022).

A research study completed by Alvez, focused on the social and economic trends of the Beaker culture in Northeast England during the Bronze Age, using a LCP analysis. The LCP conducted by provided in this research very informative results about the ancient Beaker civilization and their mobility routes. By generating the LCPs that take into account the local topography, this research study was able to model spatial connections between different archaeological sites. The results of Alvez's study show paths that mostly coincide with local variations in the terrain and follow watercourses. This approach has the potential to help archaeologists understand how humans moved during the Bronze Age (Alvez 2016). The main limitation of Alvez's research is that it only utilizes the general topography as the main driving factor for the LCP analysis.

Another research study conducted by Field in 2023 introduces a systematic approach for creating, visualizing, and comparing individual Chaco roadway profiles using LiDAR-derived elevation data. The method presented in this research study utilizes elevation values obtained from LiDAR-derived digital elevation models. The goal of Field's research is to establish a common form of ground-truthing on the Chaco roadways and evaluate its frequency across non-ground-truthed roadways. This approach provides a valuable tool for documenting and comparing ancient roadways using remotely sensed data; it outlines what anomalies to look for in the LiDAR that may be ancient roadways and ruins, especially in landscapes where ground truthing is difficult (Field 2023).

2.2.2 Critical Literature for Site Bc 53 and LCP Analysis

One of the main goals of this thesis research is conduct a comprehensive LCP analysis and investigation of site Bc 53 by drawing upon critical literature encompassing digital archives, LiDAR-based roadway profiling methodologies, 3D visualization techniques, and previous LCP analyses in similar archaeological contexts. The Smithsonian Online Virtual Archives are first used to access the notes, photos, and artifacts list for site Bc 53 to further strengthen the overall background of site Bc 53 (Rappaport 2011). The Chaco Research Archive is also utilized as a source for information regarding site Bc 53 (Chaco Research Archive 2010). The techniques from Field's 2023 research study that introduces a systematic approach for creating, visualizing, and comparing Chaco roadway profiles using LiDAR-derived elevation data is also incorporated into this thesis research to identify the ancient roadways. The methods presented in Field's study utilize elevation values obtained from LiDAR-derived digital elevation models, with the goal of establishing the common form of ground-truthed Chaco roadways and evaluating its frequency across non-ground-truthed roadways. This approach provides a valuable tool for documenting and comparing ancient roadways using remotely sensed data and knowing what anomalies to look for in the LiDAR data, especially in landscapes where ground truthing is difficult (Field 2023).

The 2019 research also conducted by Field is utilized throughout this thesis research project. The study conducted by Field focused on modeling the ancient Chaco Canyon roadway network using a large-scale LCP analysis. Some of the methodologies found in Field's study are adapted to be better integrated into this smaller-scale and more localized LCP analysis for site Bc 53 and the surrounding ruins (Field 2019).

Another key piece of research to this thesis project is the study conducted by Guo in 2022. Guo's research is informative about how LiDAR point cloud data can be utilized to protect archaeological sites digitally, which is very influential to this research (Guo 2022). The research conducted by Guo serves as an essential piece of literature that sheds light on how LiDAR data can be optimally leveraged to “digitally protect” the Chaco Canyon ruins.

Alvez's research project, which employed an LCP analysis on the Beaker culture of Northeast England during the Bronze Age, is the final critical piece of literature to guide this section of the thesis research. The overall goal of Alvez's research is to examine and complete the LCP analysis between significant locations in the Beaker culture and then examine the results through the lenses of social and economic trends in ancient Beaker society. Alvez's research is significant to this thesis project because it clearly outlines how to conduct an LCP analysis in ArcGIS Pro; the clear instructions that Alvez’s provides are particularly useful when carrying out the LCP analysis on site Bc 53 for this project. They serve as an initial template for designing a customized LCP analysis tailored to the specific landscape (Alvez 2016).

2.3 3D Visualization of Chaco Canyon

In this section, the use of 3D modeling and LiDAR in fundamental archaeological research is explored. The aim is to create a 3D visualization of Chaco Canyon by utilizing key pieces of literature that outline comprehensive workflows and successful applications of LiDAR technology in archaeological research. Specifically, research studies conducted by Katsianis, Corns and Shaw, and Carter are examined to provide valuable insights about the application of context-based systems, helicopter-mounted FLI-MAP 400 LiDAR systems, and ALS technology in generating detailed 3D models of archaeological sites. These studies are crucial in guiding the methodology for creating a 3D visualization of Chaco Canyon in this thesis research project.

2.3.1 Visualizing Chaco Canyon and Similar Archaeological Sites in 3D

In terms of the previous research that has been conducted at Chaco Canyon in regard to generating a 3D model from a LiDAR point cloud, researchers, such as Toeppen, have had success generating 3D models of individual sites or a small grouping of sites (Toeppen 2022). One limitation of these individual models is that it is hard to visually understand how these different archaeological sites fit together spatially to create Chaco Canyon as a whole. Additionally, when the model is only limited to individual sites, it can be difficult to visualize the completeness of the Chaco roadway network.

Previous research studies, such as Wills’ 2017 research, have succeeded in generating a complete 3D model of Chaco Canyon, which was subsequently used to conduct a watershed analysis on Chaco Canyon (Wills 2017). The limitation of Wills’ research is that it is a blank 3D model that is not intended to be a visual for the reader; it is explicitly incorporated for conducting the watershed analysis.

Other researchers, such as Carter in 2014, have had success creating 3D visualizations of archaeological sites in Mesoamerica and their surrounding areas in their entirety, employing high-resolution satellite imagery to enhance the visualization (Carter 2014). The only limitation of Carter's research is that the extent of this project is much more zoomed out than what is necessary for this thesis project. The research for this project does, however, incorporate elements from the archaeological research conducted by Carter to generate the 3D visualization of Chaco Canyon for this research project.

A research study based out of Ireland had much success with the helicopter-mounted FLI-MAP 400 LiDAR system, which provides highly detailed 3D models of archaeological sites (Corns and Shaw 2009). The main drawback to this research is the amount of funding that needs to be acquired to conduct this type of research project at such high quality, as well as the use of occupied aircraft to capture the LiDAR data.

2.3.2 Fundamental Archaeological Research Employing 3D Modeling and LiDAR

There are several key pieces of literature that are utilized when creating the 3D visualization of Chaco Canyon. A research study conducted by Katsianis in 2008 explores the application of a context-based system for recording the excavation process across various archaeological projects in Northern Greece. The focus of Katsianis' research is to present a formal data model and a complete digital workflow for documenting the excavation process in 3D at the prehistoric site of Paliambela Kolindros in Greece. The workflow from Katsianis' research can be applied to other archaeological sites to create a 3D model using ArcGIS Pro and other Esri products (Katsianis 2008). Katsianis' research is significant to this thesis project because it goes in-depth and outlines a comprehensive plan about how to create a 3D visualization for an archaeological site using ArcGIS Pro, which can be directly applied to the 3D modeling conducted for this research project.

Another essential piece of literature that is used for this thesis research is a study conducted by Corns and Shaw in 2009, which focused on the Discovery Programme Centre for Archaeology and Innovation in Ireland and how the Programme Centre transitioned from terrestrial-based surveys to digital aerial stereo photogrammetry and then finally adopted a helicopter-mounted FLI-MAP 400 LiDAR system, which provides highly detailed 3D models of archaeological sites. Corns and Shaw's research elaborates on successful applications at sites like Newtown Jerpoint and the Hill of Tara, discussing the efficacy of the new system in data processing, vegetation removal, and field inspections. During this research, the newly generated new methodology is evaluated against the more traditional LiDAR and ground-based approaches (Corns and Shaw 2009). The research conducted by Corns and Shaw is relevant to this thesis research because it provides a professional workflow for creating 3D models of archaeological sites using LiDAR. While this thesis project does not have anywhere near the same funding or equipment as Corns and Shaw's research, it incorporates bits and pieces of the methodologies described by the Discovery Programme Centre for Archaeology and Innovation for generating 3D models of archaeological sites.

The groundbreaking study conducted by Carter in 2014 illuminates the pivotal role of airborne mapping LiDAR technology in archaeological research, particularly in densely vegetated regions like Mesoamerica, signifying a revolutionary shift in the field of archaeology. Carter's research provides a comprehensive understanding of ALS technology, its collection process, and its implications for future research. This research further emphasizes how ALS observations and data are highly customizable to fit the needs of the research project (Carter

2014). Carter's research is essential to this thesis research as it provides valuable information about the significance of remote sensing tools in the field of archaeology. It also sheds light on other similar studies that have employed LiDAR with the ultimate goal of locating obstructed archaeological sites.

Chapter 3 Research Design and Methodology

In this chapter, an overview of the research design and methodology for this project is first provided. The following section in this chapter examines the data utilized to complete this research. The chapter concludes by outlining the methodologies for the three main analyses in this research project: the exploratory analysis of Chaco Canyon, the site Bc 53 analysis, and the generation of the 3D visualization of Chaco Canyon

3.1 Overview

This section outlines the methodology for the following three processes: supervised image classification, the LCP analysis and assessment of site Bc 53, and the generation of the 3D visualization of Chaco Canyon are outlined. These methodologies are separated into three separate workflows, which are further detailed in this section. The first subsection discusses the initial exploration of Chaco Canyon for this project, the process for both the RT and SVM supervised image classifications, and specific investigation into Site Bc 53. The following subsection discusses the workflow for examining the physical condition of Site Bc 53 using remote sensing technologies, as well as how to generate the LCP analysis for the site. This methodology section concludes by explaining the workflow for generating the final 3D visualization of Chaco Canyon.

3.2 Data

This research is based on two main sources of data: high-resolution satellite imagery of Chaco Canyon obtained from Land Info Worldwide Mapping and the open-source LiDAR data package acquired from OpenTopography, as displayed in Table 1. Google Earth satellite imagery, captured by Airbus in 2024 at a spatial resolution of 15 cm, is initially used to explore the Chaco Canyon area as displayed in Figure 3. However, this imagery cannot be exported outside the Google Earth Engine and is only available as a Tile Layer in ArcGIS Pro through ESRI's Living Atlas, which cannot be used for the analyses in this research.

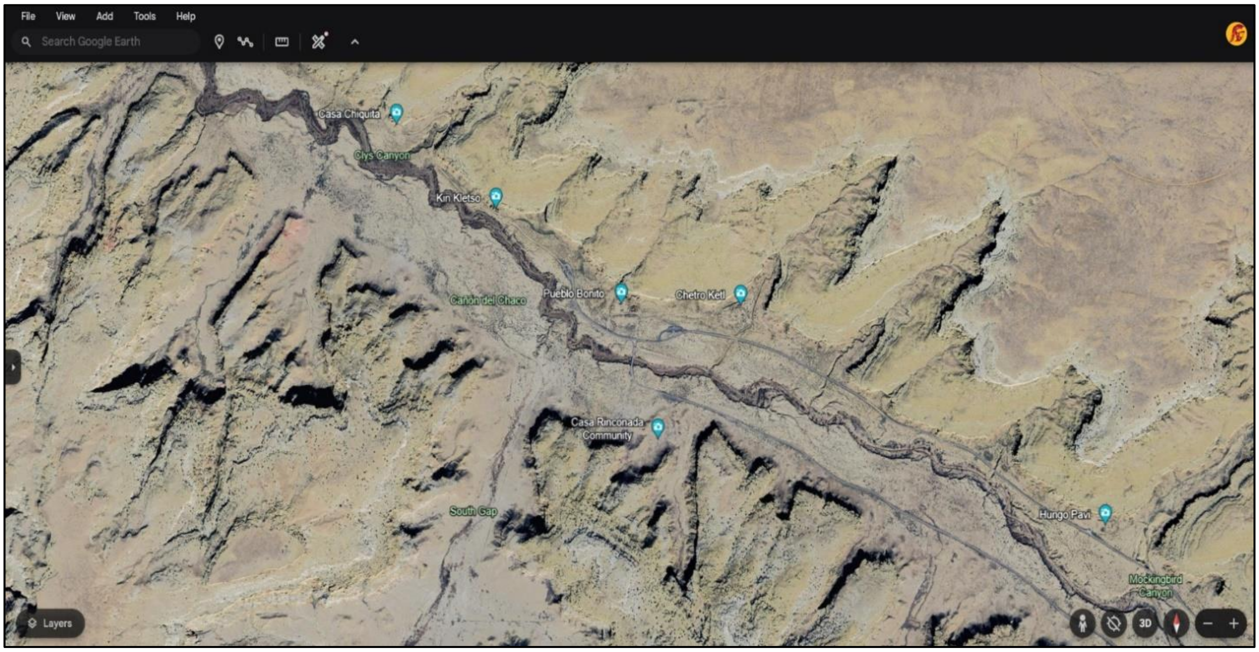


Figure 3. Google Earth view of Chaco Canyon

Alternatively, to complete this research, satellite imagery of the study area at 30 cm and 1 m resolution in both multispectral and panchromatic formats is obtained and is comparable to what Google Earth provides. The multispectral imagery captures all visible light waves as well as near-infrared wavelengths as displayed in Figure 4. This imagery is acquired from Land Info Worldwide, which is based in Denver, Colorado, and has access to the Pléiades Satellite Constellation and is displayed in. Once the imagery is obtained, the imagery is orthorectified to ensure that it is accurately displayed in the correct location in ArcGIS Pro.

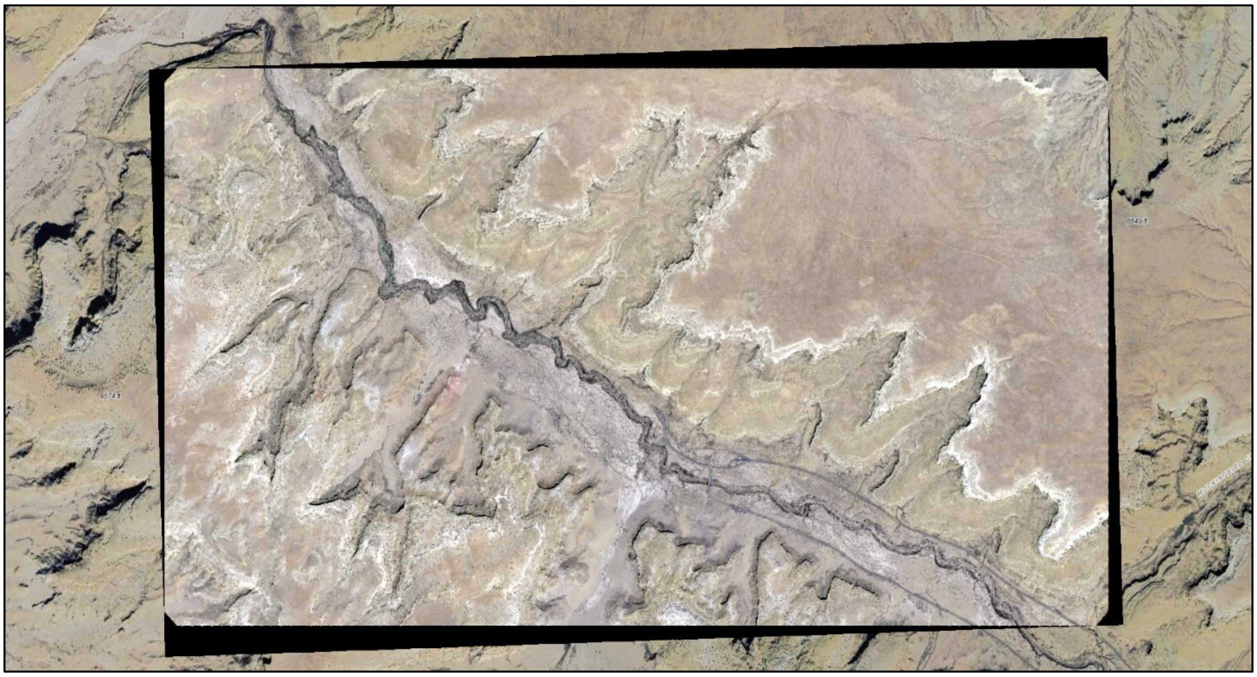


Figure 4. Raw Multispectral Satellite Imagery

The other key data utilized in the research is a LiDAR point cloud and a Digital Elevation Model (DEM) of the study area, which allows for the creation of the most accurate 3D visualization of Chaco Canyon possible as shown in Figure 5. This open-source data package, which includes the LiDAR point cloud data and the DEM derived from the LiDAR, is found available on the website OpenTopography. This data was collected from a previous research study focused on an ancient watershed analysis of Chaco Canyon (Dorshow 2010). Both the LiDAR point cloud and the DEM have a spatial resolution of 1 m, which pairs nicely with the 1 m imagery obtained from Land Info to create a realistic 3D visualization of Chaco Canyon.

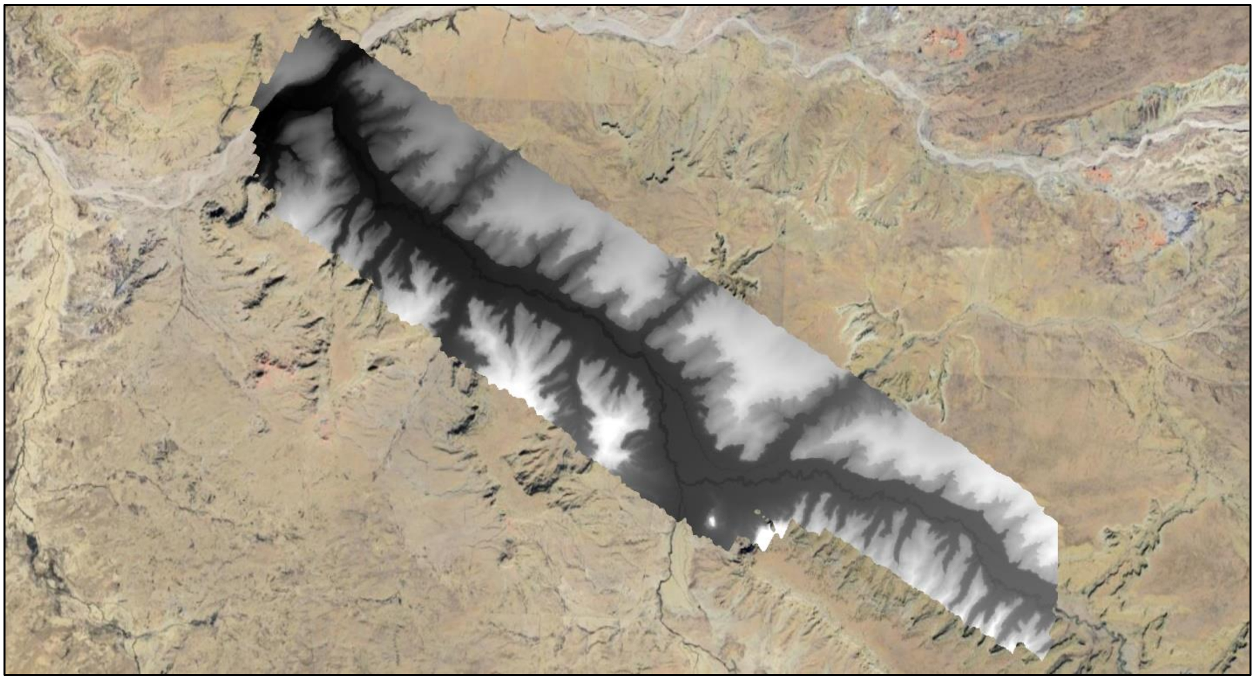


Figure 5. Raw LiDAR-derived DEM

Table 1. Data

Name	Content	Format	Attributes	Precision	Availability	Price
Pleiades Satellite Imagery	Satellite Imagery	GeoTIFF	16-bit pan + 6 band multispectral bundle	Panchromatic/ Multispectral: 30cm; Multispectral: 1m resolution	Private Access; Land Info Worldwide Mapping	$285
Chaco Canyon, NM: Simulating Dynamic Hydrological Processes	LiDAR Point Cloud and DEM (TIN)	.LAZ for point cloud and GeoTIFF for DEM	Total number of points: 298,677,157 pts Point density: 4.46 pts/m2	1m spatial resolution	Open Source; acquired from Open-Topography	Free
Google Earth Satellite Imagery	Satellite Imagery (Source : Airbus Imagery 2024)	Data Layer in ArcGIS Pro found in ESRI's Living Atlas	Panchromatic: 65 cm (nadir) to 73 cm (20^o off-nadir); Multispectral: 2.62 m (nadir) to 2.90 m (20^o off-nadir); 4-band Multispectral: (blue, green, red and near infrared)	15 cm spatial resolution in this area on Google Earth	Open Source	Free

3.3 Exploratory Analysis Methodology

The methodology for this research project begins by first acquiring satellite imagery of Chaco Canyon National Historical Park. An exploratory analysis is conducted utilizing the high-resolution satellite imagery from both Google Earth and Land Info Worldwide Mapping.

The open-source platform Google Earth is first utilized to explore the overall Chaco Canyon study area. When inside the Google Earth platform and viewing the Chaco Canyon study area, the ruins are very identifiable, displaying all the nuances in the structures. The high-resolution imagery that Google Earth uses was captured by Airbus in 2024 at a remarkable 15 cm spatial resolution. During this initial exploration phase, the Bc 53 ruin was first identified, which has a structural outline that is barely visible in comparison to the other nearby ruins, even at a spatial resolution of 15 cm. The imagery cannot be exported outside Google Earth, and it is only available as a Tile Layer in ArcGIS Pro through ESRI's Living Atlas; alternatively, for this project, the imagery acquired from Land Info Worldwide Mapping at both 30 cm and 1 m spatial resolutions are utilized.

Once the satellite imagery is acquired from Land Info, it is reviewed to ensure that the spatial resolution is fine enough to conduct the supervised image classification properly. If the spatial resolution is too coarse, then the ruins and ancient roadways may not be able to be identified. The imagery is then brought into ArcGIS Pro, where it is georeferenced to align with the map in ArcGIS Pro, which has a projected coordinate system set to NAD-83 UTM zone 13.

The next step is to conduct an exploratory analysis of the overall Chaco Canyon study area by completing a supervised image classification. Running a supervised image classification will aid in identifying any areas of interest that the human eye cannot detect by using the unique spectral signatures captured in the multispectral imagery to classify the imagery accurately. The supervised image classification is conducted using 30 cm resolution satellite imagery obtained from Land Info. Two algorithms are run for this research: random trees and support vector machine, which both follow the same workflow. For this image classification, the training samples are broken down into five classes: vegetation, barren, developed, asphalt roads, ancient roads, and ruins. The training samples are then manually identified in the imagery based on these classes. Once the training samples are identified, the Classify Raster Tool is utilized to complete the initial classification of the pixels in the satellite imagery. Following this step, the Reclassify Raster Tool is then used to reclassify the initial classification according to the training samples. An accuracy assessment obtained by generating a confusion matrix for both algorithms is used to determine which algorithm performed the best, classifying the most pixels correctly. The best algorithm is used to complete the rest of this research.

The findings of the image classification are next used in this research to assist with definitively identifying the location of Bc 53. The preservation condition and structural shape of site Bc 53 are also assessed during this step. To conclude this first methodology as displayed in Figure 6, the classification results are examined to identify the structural outline of the major ruins at Chaco Canyon, with a specific focus on site Bc 53 to see if the results were able to distinguish the outline of the structure.

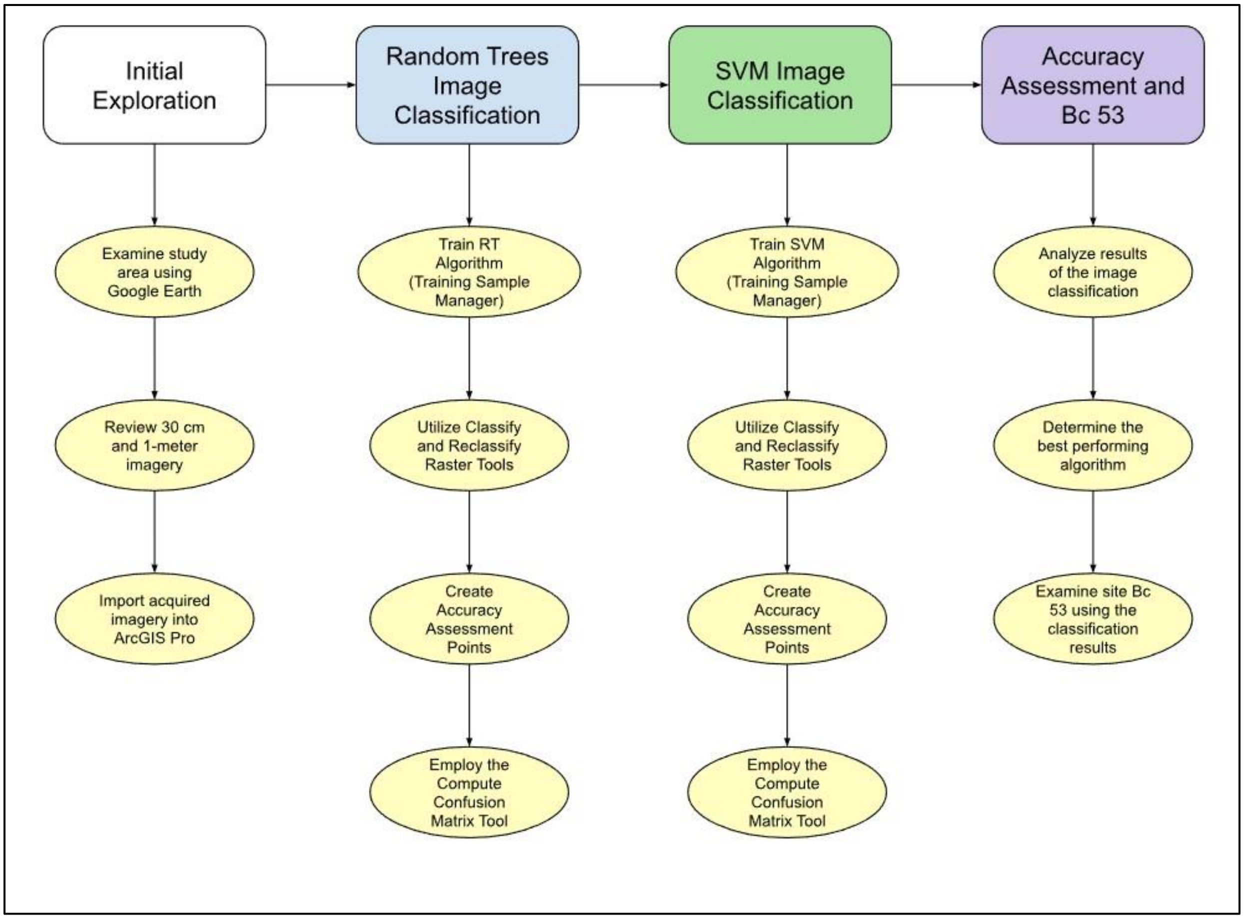


Figure 6. Exploratory Analysis Workflow

3.4 Site Bc 53 Analysis Methodology

The next step in the methodology is to zoom further into the study area of Chaco Canyon and investigate site Bc 53 in more detail. The records and photos pertaining to Bc 53 are first analyzed to begin exploring the site, which is only available for viewing through the open-source Smithsonian Online Virtual Archive. During this step, any other related research that discusses site Bc 53 is examined, with a focus on how it is discussed in the text in relation to the other nearby ruins.

Once a solid foundational understanding of Bc 53 is established, an LCP analysis is conducted with Bc 53 as the focus. The LCPs generated from the LCP analyses connect the FP Chacoan Staircase and Casa Rinconada community with site Bc 53. To begin this LCP analysis, the LiDAR-derived DEM is imported into ArcGIS Pro, and the DEM is first filled using the Fill Tool. The source point for both of the LCP analyses is site Bc 53. The destination for the first LCP analysis is site Bc 51, which is on the edge of the Casa Rinconada community of ruins. Site Bc 51 and the Casa Rinconada community are thought to have been inhabited from the late 11th century to the early 12th century, coinciding with the suggested occupation of site Bc 53 at the end of the 11th century (Chaco Research Archive). Site Bc 51 is selected as one of the destination points for this LCP analysis because it is the closest ruin to site Bc 53. The FP Chacoan Staircase was also selected as one of the destination points for this LCP analysis because, while it is not technically a ruin, it is the closest archaeological area of interest in relation to site Bc 53. Once the source and destination points are defined, the Cost Back Link Tool is utilized to create a raster that defines the neighbor, which is the next cell on the LCP to the nearest source. This newly generated back link raster is essential for determining the direction to move to traverse the LCP from any cell back to the source. The Cost Path Tool is then used to generate the most optimal path between the source and destination. The same workflow is repeated to create both LCPs. These LCP results not only indicate the directness of the most optimal paths, but they also reveal the relationship between the sites based on their proximity and accessibility to one another. This LCP analysis is critical for understanding how the Anasazi navigated the canyon landscape by serving as an educated inference of the most probable routes the Anasazi would have taken to minimize effort expenditure while traveling. This analysis further sheds light on the daily movement locally within the canyon. Understanding these LCPs can also provide insights into the functional significance of various sites. For example, with the FP Chacoan Staircase, by generating these LCPs, it becomes clear that it was a deliberate choice to utilize landscape features to create a rock staircase in the cliffside to connect the long-distance roadway network with the local roadway network within the canyon.

Additionally, the research conducted on local pathways in Chaco Canyon connecting less prominent sites, like Bc 53, is minimal. This LCP analysis utilizes empirical spatial data to identify the most optimal pathways that connect these smaller sites with other nearby archaeological areas of interest. The findings of this LCP analysis can be used as a guide to explore the relationships between other smaller, less prominent sites. The results of the LCP analysis also assist with revealing the true relationship between site Bc 53 and the nearby Casa Rinconada community of ruins. Site Bc 53 does share the same "Bc" prefix as the nearby ruins that make up the Casa Rinconada community of structures (e.g., Bc 51 and Bc 50); however, it appears to be not connected to the community.

To conclude, the physical condition of site Bc 53 is examined using the LiDAR data acquired from OpenTopography with a spatial resolution of 1 meter. To transform the LiDAR-derived DEM into a visible product, a multidirectional hillshade layer is generated using the filled DEM as the input. A copy of this hillshade layer is next generated, and the symbology is changed to an elevation gradient. By stacking the multidirectional hillshade layer and the newly created elevation gradient and then adjusting the transparency, the ruins throughout the Chaco Canyon study area become very distinguishable. The visibility of site Bc 53 is explored and compared in contrast to the other nearby sites. This second methodology is illustrated in the Figure 7 workflow diagram.

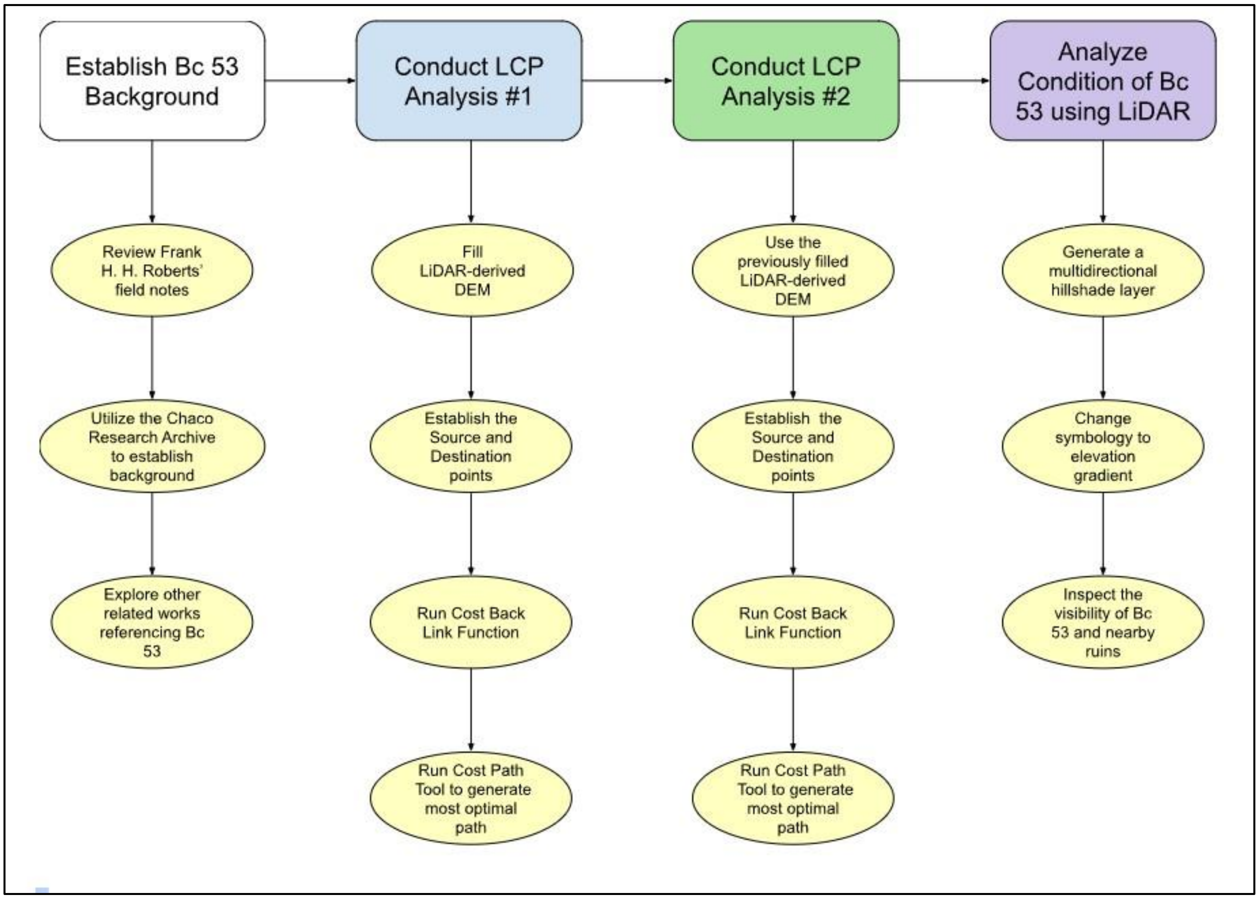


Figure 7. Site Bc 53 Analysis Workflow

3.5 3D Visualization Methodology

The final methodology for this project is to create a 3D visualization of Chaco Canyon National Historical Park. The multidirectional hillshade layer generated in the previous methodology is utilized as the base layer of the 3D visualization. The first step is to convert the 2D map with the multidirectional hillshade layer into a Local Scene, which is in three dimensions. A new 3D scene is generated in the project in ArcGIS Pro. At the bottom of the contents pane in the new Local Scene, ensure that the LiDAR-derived DEM is being utilized as the elevation source for the scene.

A 3D model of Chaco Canyon is created using the LiDAR point cloud data with a spatial resolution of 1 meter. The only visible layer is the multidirectional hillshade layer, which will be used in conjunction with the satellite imagery to generate the most realistic visualization possible. This 3D model is then wrapped with the 1-meter imagery using the Layer Blend technique in ArcGIS Pro to mix all of the contributing layers properly. The transparency and order of the contributing layers are adjusted to achieve the most realistic results.

This step is concluded by finalizing the 3D visualization and incorporating symbology that defines the location of the ruins as well as the ancient roadways. To ensure that the ruins and ancient roadway networks are being correctly displayed in the right location, maps that were created for previous related research are obtained that already have these major ruins and roadways identified. These reference maps are brought into ArcGIS Pro and georeferenced, using known points in both the map and the satellite imagery to make the map distances and locations as accurate as possible. With the georeferenced maps created, line features are created to define the long-distance and short-distance roadway networks, using the georeferenced map as a guide. Point features are then created to define the main ruins at Chaco Canyon, using the georeferenced map as a guide to place the points.

The final generated model is then uploaded to ArcGIS Online for public viewing. The different layers, such as ancient roadways and structures, can be turned on and off by the viewer, as displayed in Figure 9. The 3D visualization allows the user to traverse the Chaco Canyon Landscape, with the ability to tour the major viewpoints digitally at the click of a button. This third methodology is illustrated in the Figure 8 workflow diagram.

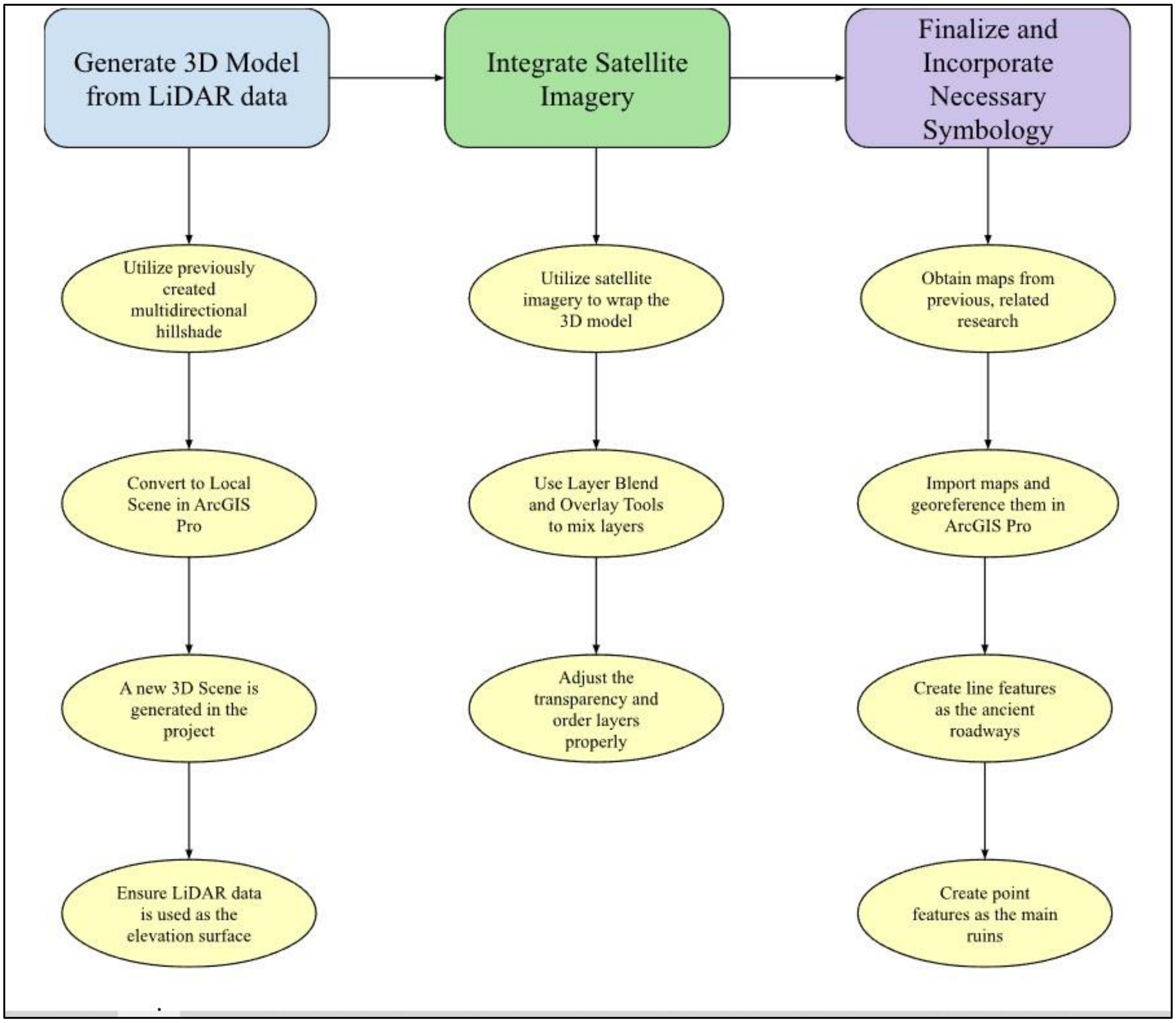


Figure 8. 3D Visualization Workflow

Figure 9. 3D visualization uploaded to ArcGIS Online

Chapter 4 Results

This chapter delves into the specific results of this project. First, this chapter analyzes the results of the supervised image classification that is conducted on high-resolution satellite imagery. The next section of this chapter examines the results of the LCP analysis between site BC 53 and its neighboring sites. The following section investigates the preservation state of Site Bc 53 using both LiDAR data and the results from the supervised image classification. The chapter then concludes by exploring the results of the final visualization, which includes the integration of high-resolution satellite imagery, a LiDAR-derived digital terrain model, and custom symbology.

4.1 Supervised Image Classification

This section analyzes the results from both the random tree and support vector machine supervised image classification. First, the results of the supervised image classification using random trees are discussed. The accompanying confusion matrix provides specific accuracy scores for the image classifications, allowing assessment and comparison of the overall accuracy. This section concludes by exploring the results of the SVM supervised image classification, including its confusion matrix, and finally comparing the two classification products.

4.1.1 Random Trees

As part of the exploratory analysis process for this project, a supervised image classification is conducted on the high-resolution imagery acquired from Land Info Worldwide Mapping. This high-resolution imagery is exhibited in Figure 10 and Figure 13. Figure 10 is a snapshot of high-resolution imagery and displays the Casa Rinconada community of ruins as well as the pathways connecting the sites. The results of the supervised image classification are depicted in Figure 11, where the random trees algorithm is employed. The color scheme used for this classification has yellow representing barren desert, green for vegetation, red for ruins, orange for ancient roadways, gray for asphalt, and purple for developed land. Although this classification misclassified many of the pixels, it still did a decent job of defining and making the ruins and pathways visible.

Figure 10. Satellite imagery at 30 cm resolution from Pleiades Satellite

By using Figure 10 as a reference, the Casa Rinconada community of ruins and the connecting pathways can be easily identified in Figure 11. These results also help assess the condition of site Bc 53, exploring whether it is in a good enough state of preservation to be identified during the supervised image classification.

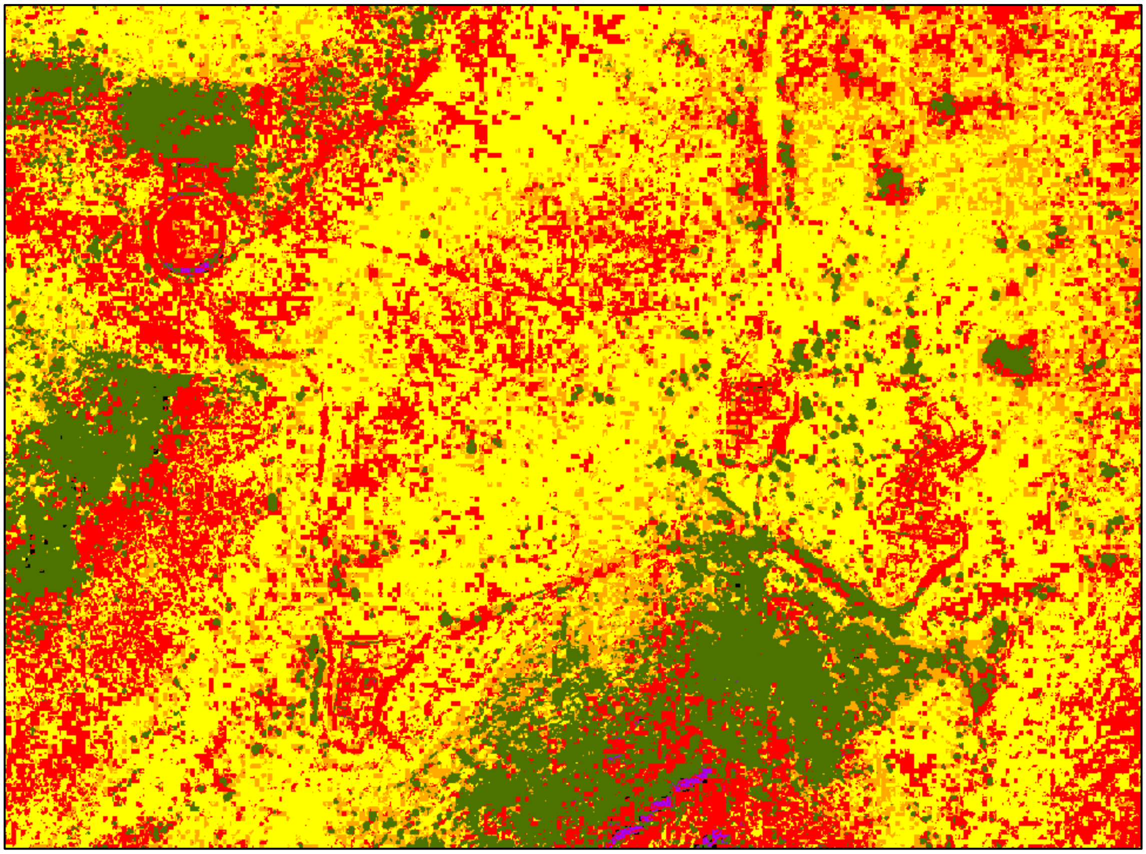


Figure 11. Classification of Casa Rinconada employing the RT Algorithm

To assess the accuracy of the random trees supervised image classification, a confusion matrix, also known as an error matrix, is utilized, as displayed in Figure 12. The confusion matrix assesses the user accuracy, which is also known as Error Type 1 or a False Positive. This Type 1 Error occurs when a pixel is incorrectly classified as another known class. The matrix also assesses the producers' accuracy, which is also known as Error Type 2 or a False Negative. A Type 2 Error occurs when the producers' accuracy does not meet the expectation of the ground truth data. To train the random trees image classifier, 500 random samples of individual pixels were selected through classification results and were manually compared for accuracy against the ground truth data, which is the 30 cm resolution satellite imagery. The matrix displayed in Figure 12 also calculates the Kappa Statistic Index, which is the score for the overall accuracy of the supervised image classification based on the Type 1 and Type 2 errors that were identified. For the random trees algorithm, the overall accuracy score was 0.553408 or 55.3408% accuracy, which means that this algorithm only classified just over half of the pixels correctly.

	OBJECTID *	ClassValue	C_1	C_2	C_3	C_4	C_5	C_6	Total	U_Accuracy	Kappa
1	1	C_1	162	24	0	0	0	86	272	0.595588	0
2	2	C_2	2	44	0	0	0	17	63	0.698413	0
3	3	C_3	0	0	30	0	1	1	32	0.9375	0
4	4	C_4	0	0	2	5	1	2	10	0.5	0
5	5	C_5	0	0	1	0	4	5	10	0.4	0
6	6	C_6	5	2	0	7	0	99	113	0.876106	0
7	7	Total	169	70	33	12	6	210	500	0	0
8	8	P_Accuracy	0.95858	0.628571	0.909091	0.416667	0.666667	0.471429	0	0.688	0
9	9	Kappa	0	0	0	0	0	0	0	0	0.553408

Figure 12. Random Trees Algorithm Confusion Matrix

4.1.2 Support Vector Machine

The other algorithm that is employed during the supervised image classification process was the support vector machine algorithm. Additionally, the input for the SVM supervised image classification is the 30 cm aerial imagery acquired from Land Info, as displayed in Figure 13. The imagery found in Figure 13depicts the Pueblo Bonito ruin, which is the most famous of all the ruins at Chaco Canyon.

Figure 13. Satellite imagery at 30 cm resolution from Pleiades Satellite

To provide a frame of reference, the high-resolution imagery of Pueblo Bonito found in Figure 13 is in the same position as the SVM results displayed in Figure 14. The same color classification scheme is used as the previous supervised image classification employing the random trees algorithm. The barren desert is classified as yellow, vegetation as green, ruins as red, and ancient pathways as orange, purple for developed land, and gray for asphalt (which often gets confused with shadows in the imagery, as displayed later in Figure 19). Comparing the RT results, the SVM algorithm did a much better job as it correctly classified more pixels. The structural footprint of Pueblo Bonito is clearly visible, and the results were determined to be more accurate than the RT results according to the confusion matrices for the two classifications. The SVM image classification results are more useful to this research when determining the shape, size, and location of the archaeological ruins and ancient roadways in Chaco Canyon.

These results also help assess the physical condition of site Bc 53 based on whether it is in a good enough state of preservation to be identified during the supervised image classification.

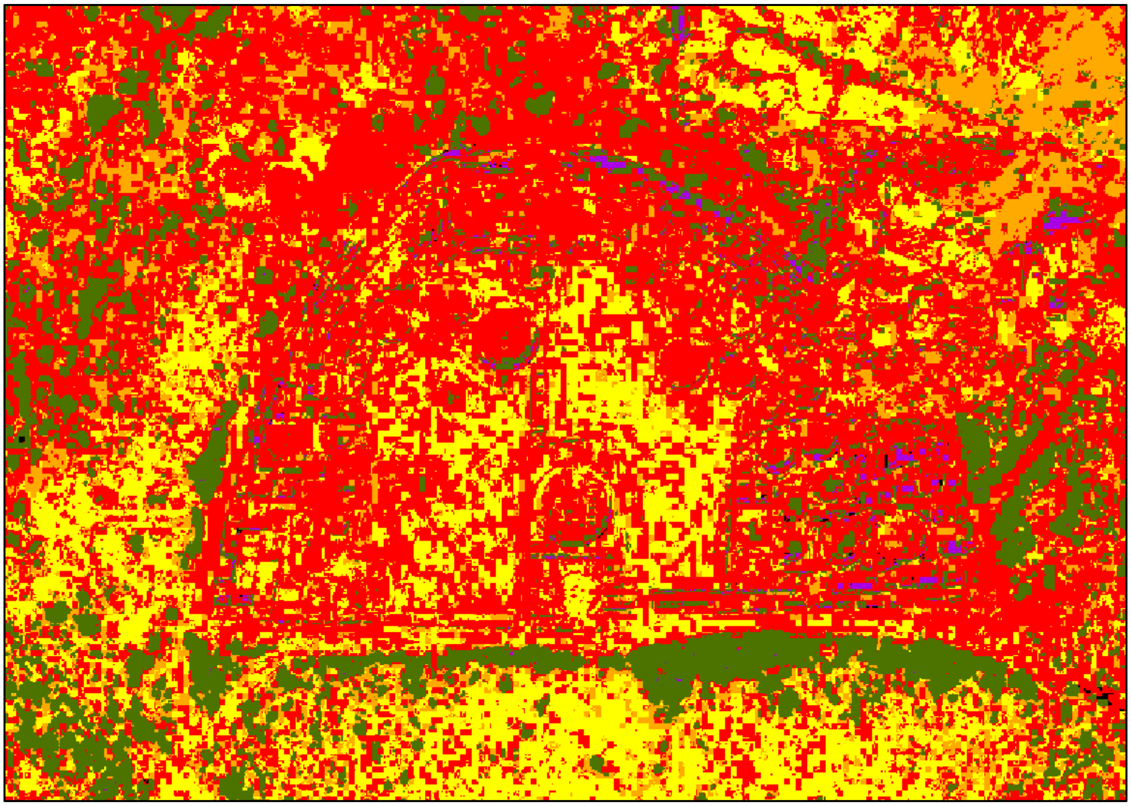
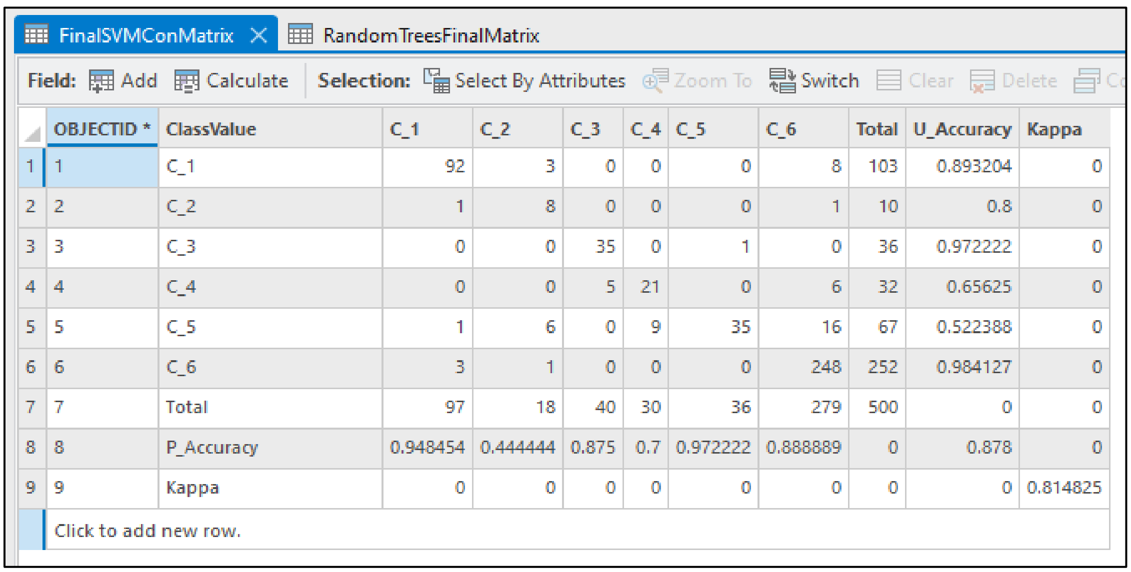


Figure 14. Classification of Pueblo Bonito employing SVM Algorithm

To evaluate the accuracy of the SVM-supervised image classification results, a confusion matrix is generated that compares the classification results against the ground truth data, as shown in Figure 15. To train the SVM image classifier, 500 individual pixels are selected as samples, and each pixel's classification result is compared to the ground truth data, which for this project is satellite imagery with a spatial resolution of 30 cm. The Kappa Statistic, or the overall accuracy for the SVM supervised image classification, is 0.814825 or 81.4825%, which is significantly better than the overall accuracy of the random trees algorithm, which has an overall accuracy of 55.3408%. While 81.4825% is not a perfect accuracy score, the SVM algorithm did classify over 80% of the pixels correctly, making a product that can be utilized to conduct an exploratory analysis of the Chaco Canyon study area searching for any new anomalies, whether ruins or ancient roadways, that are not distinguishable with the naked eye. Because the SVM image classification results have an overall accuracy of over 80%, the majority of the known ruins are correctly classified, as displayed in Figure 14. In addition to being used for the exploratory analysis, the SVM classification results are used to assess the preservation state of site Bc 53. The better preserved the ruin, the more distinguishable the outline of the ruin in the supervised image classification results.



	OBJECTID *	ClassValue	C_1	C_2	C_3	C_4	C_5	C_6	Total	U_Accuracy	Kappa
1	1	C_1	92	3	0	0	0	8	103	0.893204	0
2	2	C_2	1	8	0	0	0	1	10	0.8	0
3	3	C_3	0	0	35	0	1	0	36	0.972222	0
4	4	C_4	0	0	5	21	0	6	32	0.65625	0
5	5	C_5	1	6	0	9	35	16	67	0.522388	0
6	6	C_6	3	1	0	0	0	248	252	0.984127	0
7	7	Total	97	18	40	30	36	279	500	0	0
8	8	P_Accuracy	0.948454	0.444444	0.875	0.7	0.972222	0.888889	0	0.878	0
9	9	Kappa	0	0	0	0	0	0	0	0	0.814825

Click to add new row.

Figure 15. Support Vector Machine Algorithm Confusion Matrix

4.2 Significance of Site Bc 53

In this section, the primary focus is on Site Bc 53 and the LCPs that are generated from Site Bc 53 to its neighboring sites. First, the results of the LCP analysis between Site Bc 53 and the nearby Casa Rinconada community are explored with the aim of revealing the connection between the two sites. Subsequently, the results of the LCP analysis between Site Bc 53 and the FP Chacoan Staircase are examined, and the relationship between the two sites is further investigated.

4.2.1 LCP Analysis Between Site Bc 53 and the Nearby Casa Rinconada Structures

As illustrated in Figure 16, the input raster for the LCP analysis is the LiDAR-derived DEM, which was obtained from OpenTopography at a spatial resolution of 1-meter. The teal cross, which is also visible in Figure 17, represents the location of site Bc 53, while the red circle denotes the position of the Casa Rinconada ruins. These two points serve as the source and destination input points when conducting the LCP analysis in ArcGIS Pro. The primary objective of this analysis is twofold: to determine the feasibility of the paths between site Bc 53 and the Casa Rinconada community of structures and to uncover whether site Bc 53 should be included in the Casa Rinconada community of ruins group or if Bc 53 should be categorized as independent.

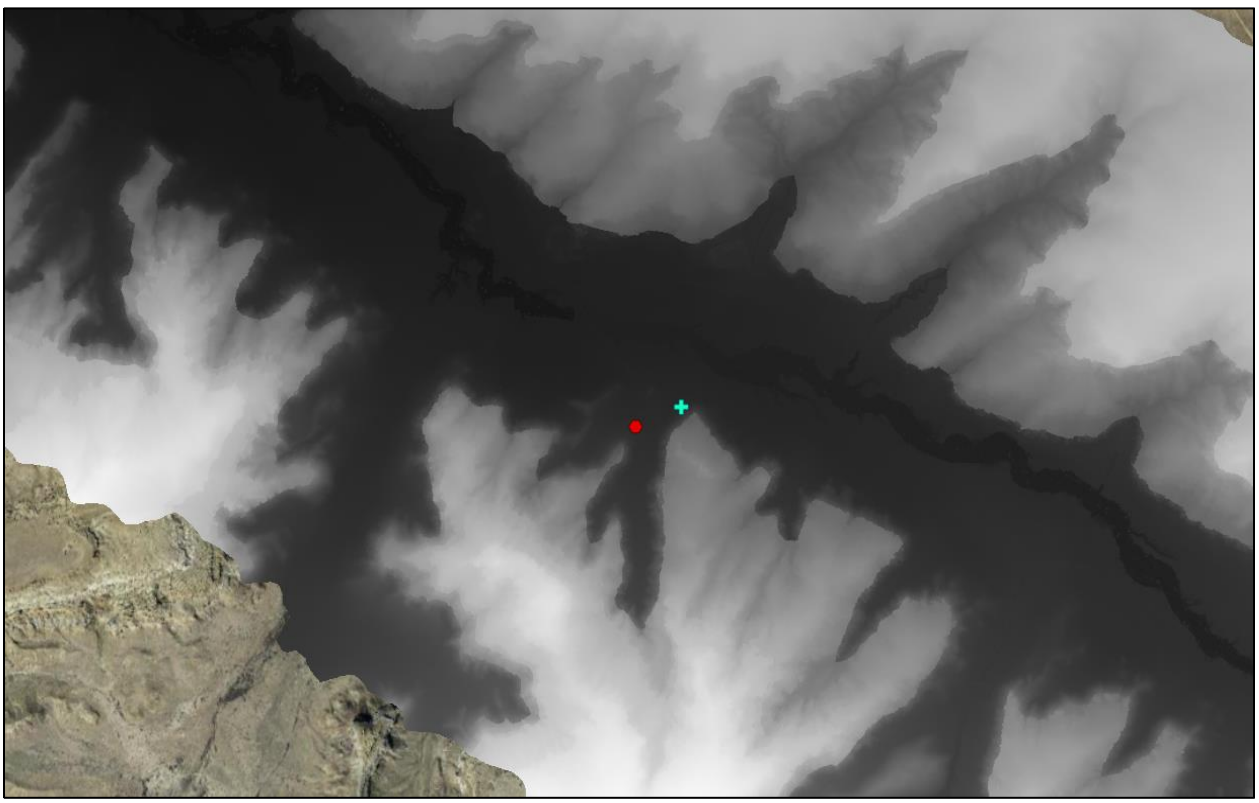


Figure 16. Points for the LCP Analysis and LiDAR-derived DEM input raster

Figure 17 displays the outcome of the LCP analysis, illustrating the path deemed most optimal based on terrain and vegetation conditions, connecting one of the structures within the Casa Rinconada community (site Bc 51) to the nearby site Bc 53. The source point for the LCP analysis is site Bc 53, which is marked by the teal-colored cross. The destination of this LCP analysis is one of the Casa Rinconada ruins, specifically the ruin closest to site Bc 53. The green line identifies the most optimal path between the two locations, and it is based on the terrain at Chaco Canyon. For this LCP analysis, terrain is the main variable driving the LCP analysis because terrain is the primary factor that influenced Anasazi trade routes, short-distance travel networks, and long-distance travel networks.

Figure 17. Least cost path between Bc 53 and Casa Rinconada Community

In the 9th through the 12th centuries CE, the Anasai were limited to traveling by foot, meaning that their pathways, both for long distances and local travels, were heavily impacted by the natural landscape. The Anasazi constructed their road network to align with the natural contours of the landscape, ensuring efficient travel without expending excessive energy on a regular basis. Therefore, terrain was chosen as the main factor for the LCP analysis. Analyzing topography and terrain is a crucial initial step in understanding the movement patterns of the Anasazi people.

However, it's crucial to note that human behavior may not always align with environmental factors alone. Ancient travel patterns could have been influenced by religious or social customs that are not able to be captured by GIS software. Therefore, it's essential to consider a range of external variables, drawing from prior archaeological research on Anasazi society and cultural practices, to further enhance the LCP analysis in future research. Some other variables that were considered for this research were creating barriers around fertile land that were most likely used for agriculture and not travel. Another variable that was considered for this analysis was assigning weights to areas that have been documented to be trade corridors for the Anasazi. It was also considered to customize the LCP analysis to the individuals who were traveling and how their demographics and behavior influenced their travel routes.

The results depicted in Figure 17 suggest a viable route between site Bc 53 and the Casa Rinconada community of ruins. However, due to the indirect nature of the most optimal path, it's plausible that Bc 53 served as a neighboring site rather than being directly integrated into the community itself. Its relatively isolated location beneath the butte further supports this interpretation.

4.2.2 LCP Analysis Between Site Bc 53 and the Nearby FP Chacoan Staircase

Another LCP analysis is conducted between site Bc 53 and the nearby FP Chacoan Staircase, as depicted in Figure 18. Site Bc 53 is marked with the green cross and serves as the source point when running the LCP analysis. A red octagon marks the base of the FP Chacoan

Staircase and serves as the destination point when completing the LCP analysis. The yellow line between the source and destination points is the most optimal path based on the terrain at Chaco Canyon that was extracted from the 1-meter LiDAR-derived DEM. These results suggest that a direct relationship between Bc 53 and the FP Chacoan Staircase is feasible based on the proximity and accessibility between the two sites; however, in order to definitively link these two sites together, more in-depth research that considers more variables than the terrain is necessary.

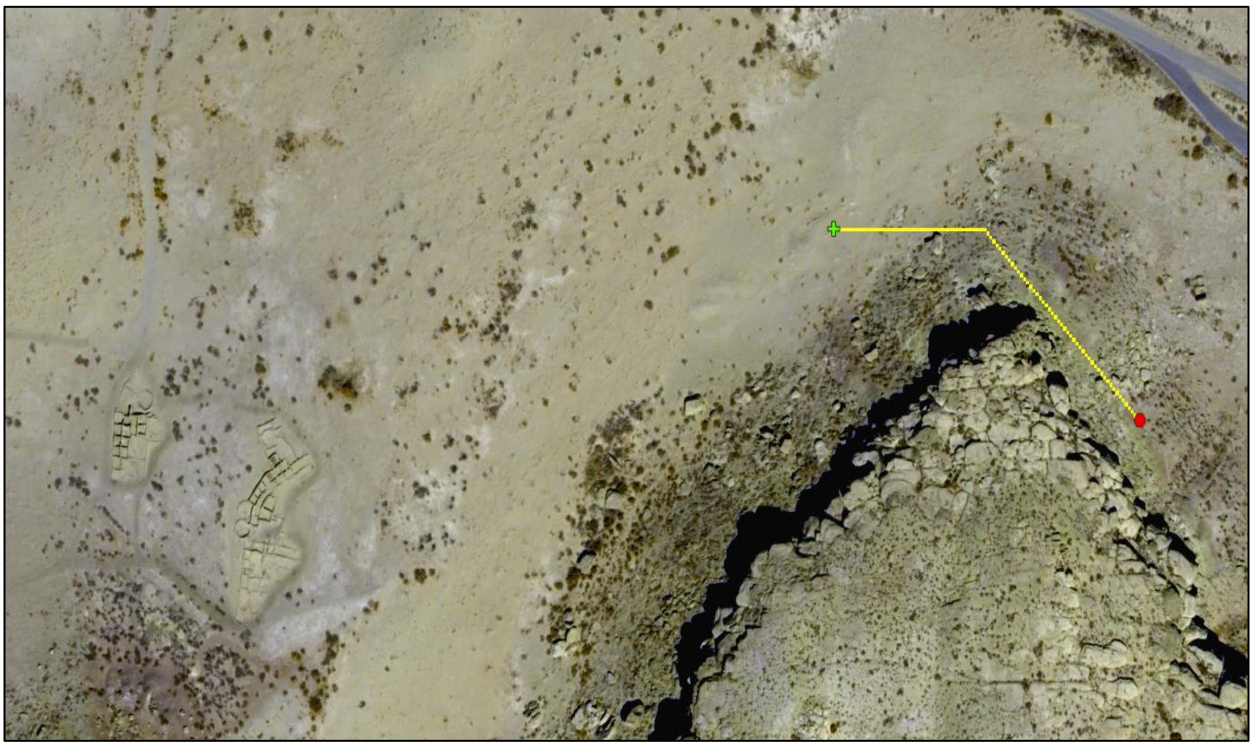


Figure 18. Least cost path between Bc 53 and the FP Chacoan Staircase

The LCP analysis provides valuable insights into the movement patterns and daily travel routes within Chaco Canyon, particularly between various sites and their connections to the ancient roadway network. The LCP analysis reveals the most optimal paths for short, routine travel, offering a complementary perspective on Anasazi mobility distinct from the formalized short- and long-distance roadways. The potential routes identified through the LCP analysis represent the practical routes that individuals may have taken, shaped by the terrain and the need for efficiency in daily activities.

These footpaths, however, differ significantly from the engineered short- and long-distance roadways, which were substantial, labor-intensive constructions designed for durability as well as ceremonial and symbolic purposes. The Chacoan roadways, known for their width and straightness, required considerable resources to build and maintain, reflecting their importance in connecting distant communities and facilitating large-scale movement across the region. In contrast, the potential paths revealed by the LCP analysis may have been created organically through repeated use. They were not intended to be permanent features, which may explain why they are not as visible today as the more formalized road networks.

4.3 Assessment of the Physical Condition of Site Bc 53

This section focuses on using the LiDAR data of Chaco Canyon, as well as the results from the supervised image classification to investigate the preservation state of site Bc 53 in comparison to the other nearby ruins. The section first explores the results of the SVM supervised image classification, specifically examining the location of Site Bc 53 with the aim of seeing if any of the ruins are indefinitely in the supervised image classification. The section concludes by using the LiDAR data acquired for this project to see if any part of site Bc 53 is identifiable, just as the other nearby ruins are.

4.3.1 Assessing Site Bc 53 Using Supervised Image Classification Results

As part of this research, the physical condition of site Bc 53 is investigated utilizing remote sensing technology and advanced GIS techniques. During the supervised image classification of Chaco Canyon in its entirety, almost all of the ruins were successfully identified based on their spectral signatures in the high-resolution imagery, as shown in Figure 11 and

Figure 14. The Casa Rinconada community of structures and site Bc 53 were occupied around the end of the 11th century and therefore should have used the same building materials. The use of sandstone bricks, mud mortar, and adobe in construction means that the spectral signature of site Bc 53 should be identifiable just like the Casa Rinconada community due to the shared building materials. However, when examining site Bc 53, no definitive outline of the ruin could be identified, as shown in Figure 19. The blue circle denotes the area where site Bc 53 is located. These results suggest that the physical condition of site Bc 53 is rougher than that of the other ruins in the area, which were easily identifiable in contrast to the barren desert landscape

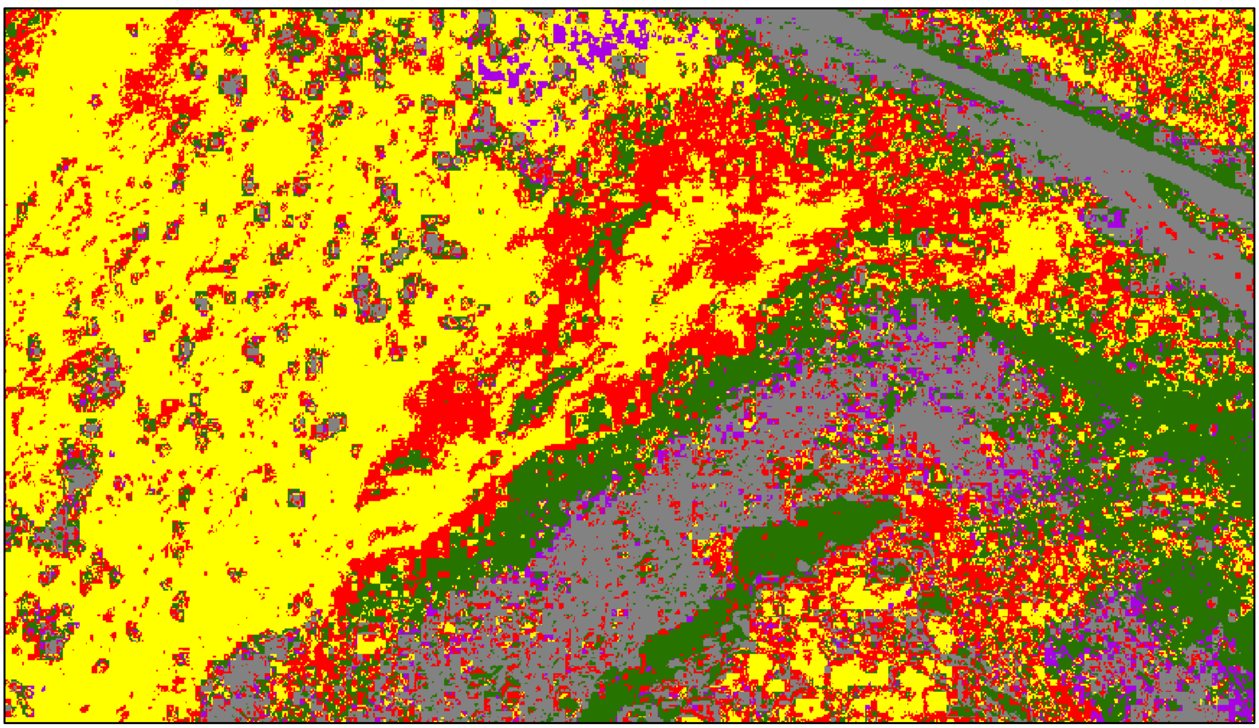


Figure 19. Supervised image classification (SVM) of Bc 53

4.3.2 Assessing Site Bc 53 Using LiDAR-Derived DEM

To validate the findings of the supervised image classification, the LiDAR-derived Digital Elevation Model is also inspected to determine site Bc 53's physical condition when compared to the other ruins at Chaco Canyon. The inspection was carried out at a spatial resolution of 1-meter based on the spatial resolution of the LiDAR data acquired from OpenTopography. As shown in Figure 20, the blue circle represents the area where there should be some evidence of the ruin, but no structural footprint is detectable. In contrast, the nearby Casa Rinconada community of ruins which are identified by the red circles. These results confirm that site Bc 53 is not in good physical condition, as even when examining the LiDAR-derived DEM, it was still not clearly identifiable compared to the other nearby ruins.

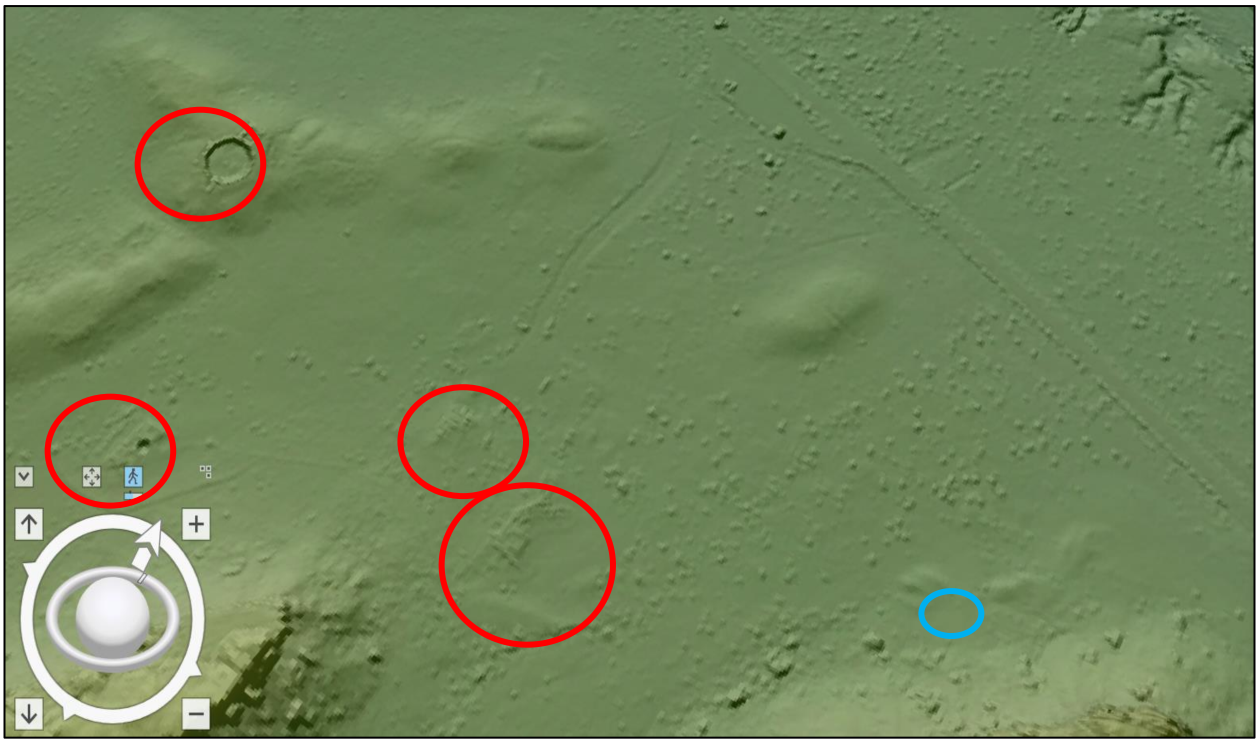


Figure 20. LiDAR-derived DEM of Bc 53 and Casa Rinconada Community

As depicted in Figure 21, the ruins that make up the Casa Rinconada community of structures are easily identifiable in contrast to the barren desert landscape. In Figure 21, the ruins that make up the Casa Rinconada community are identified by the red circles. The blue arrow denotes the main structure of the Casa Rinconada community and is also the most defined ruin in the DEM. This makes sense because it is the most well-preserved of all the Casa Rinconada ruins. Further following this logic, the level of detail and distinguishability of these nearby structures in the DEM can be used as the baseline to evaluate the preservation condition of the nearby site Bc 53. If site Bc 53 is as well preserved as the ruins in the Casa Rinconada community, then the outline of site Bc 53 should have similar discernibility in the DEM.

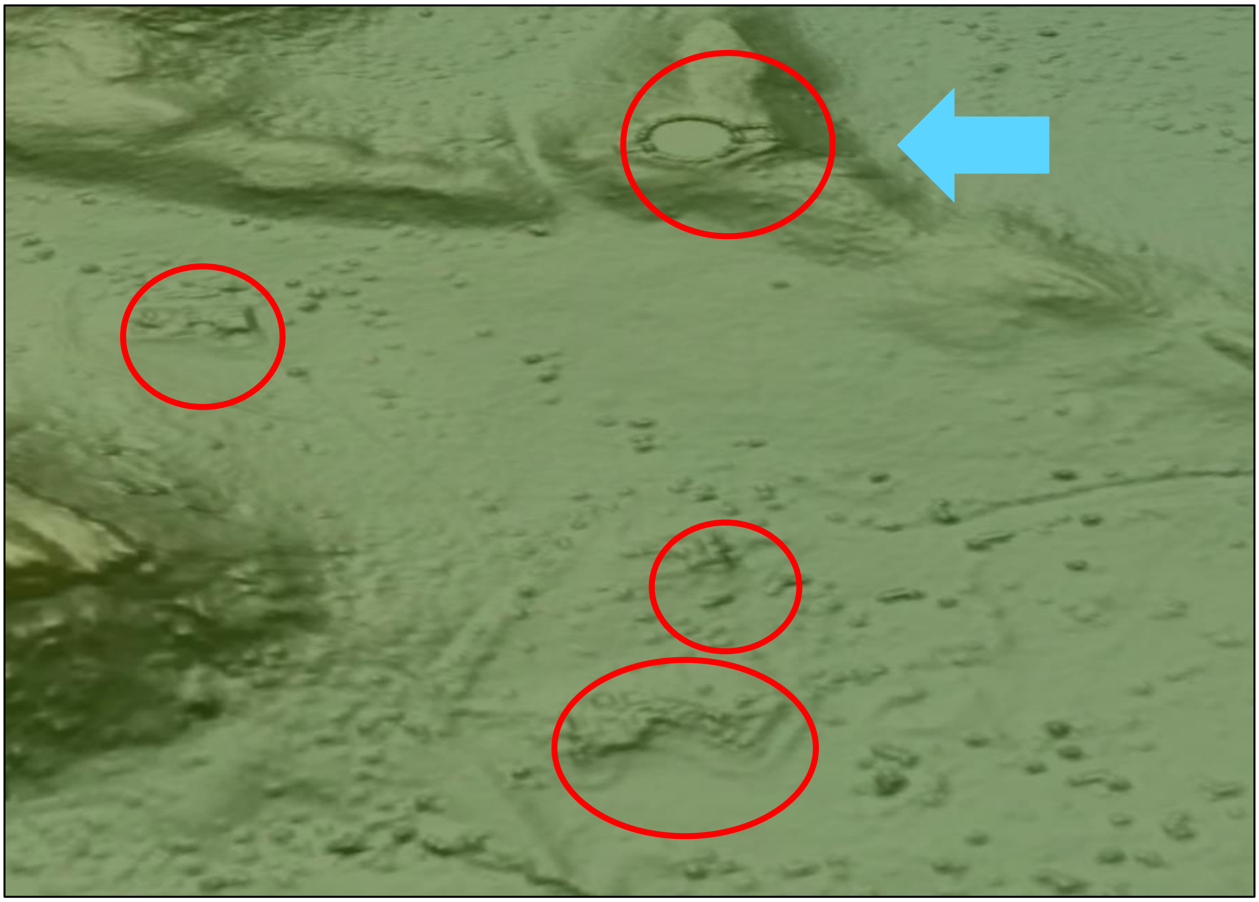


Figure 21. LiDAR-derived DEM of the Casa Rinconada Community

Figure 22 displays a zoomed-in view of the LiDAR-derived DEM focused on site Bc 53 and the edge of the Casa Rinconada community of ruins. As shown in Figure 22, the Casa Rinconada ruins are clearly identifiable and are circled in red. In contrast, site Bc 53 is circled in blue, and the outline of the ruin is not identifiable. In fact, the location of site Bc 53 appears to be one large pit. This could be the result of the initial and destructive excavation that was then backfilled with the excavated sediment after the excavation was completed. This DEM further confirms that site Bc 53 is in poor preservation condition in comparison to the nearby ruins. These results also highlight the need for further exploration into site Bc 53, with the aim of uncovering why the footprint of the ruin is completely unrecognizable in comparison to the other nearby sites and if there are any preservation techniques that can be employed to combat the complete deterioration of site Bc 53.

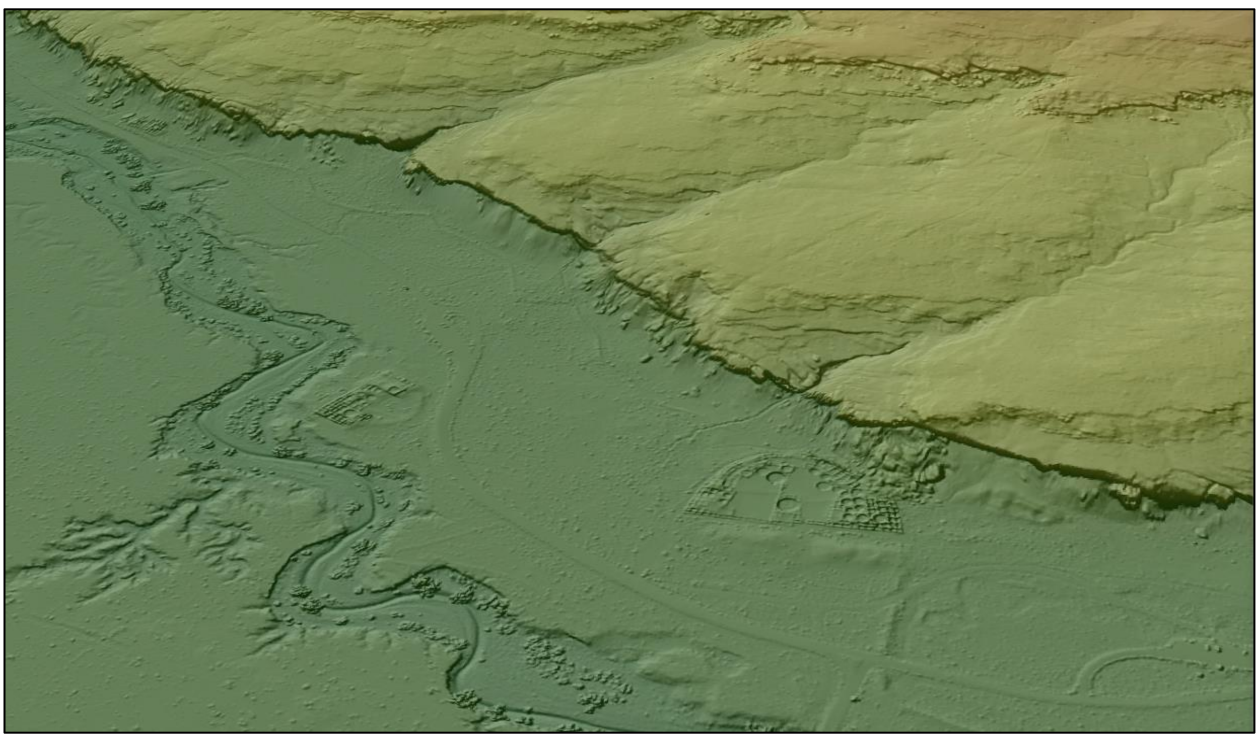
Figure 22. LiDAR-derived DEM of Bc 53

4.4 3D Visualization of the LiDAR-Derived Digital Elevation Model

This final section of the results chapter analyzes the process of generating the final contiguous 3D visualization of Chaco Canyon. It first discusses how the LiDAR-derived DEM is transformed into a usable product for this research. This section then details how the visualization is made realistic by incorporating high-resolution satellite imagery. The symbology of the ruins, ancient roadways, and the LCP analysis results are reviewed. This section concludes by outlining how the 3D visualization was further transformed into a 3D Web Scene on ArcGIS Online for public viewing.

4.4.1 Chaco Canyon Visualized in a 3D Scene in ArcGIS Pro

As displayed in **Error! Reference source not found.**, the 3D scene of Chaco Canyon was created in ArcGIS Pro using the Digital Elevation Model derived from the LiDAR point cloud acquired from OpenTopography. In the forefront of **Error! Reference source not found.**, the Chaco Wash and Pueblo Bonito ruin can both be seen. The previously collected LiDAR data did an excellent job of capturing the nuances in the topography and highlighting the different paths and roadways that may not be visible to the naked eye. This DEM is the input for



generating the 3D visualization of Chaco Canyon.

4.4.2 Combining the 3D Visualization with High-Resolution Satellite Imagery

Figure 23 is a screen capture of the 3D visualization generated in this project facing Pueblo Bonito and Pueblo del Arroyo. A golden star symbol designates the major ruins in the visualization of Chaco Canyon. Figure 24 is also a screen capture of the 3D visualization generated for this research; however, it faces the Casa Rinconada community of ruins and site Bc 53. The orange pathways that are illustrated in both Figure 23 and Figure 24 are the ends of the short-distance roadway network that ends at Downtown Chaco Valley bottom.

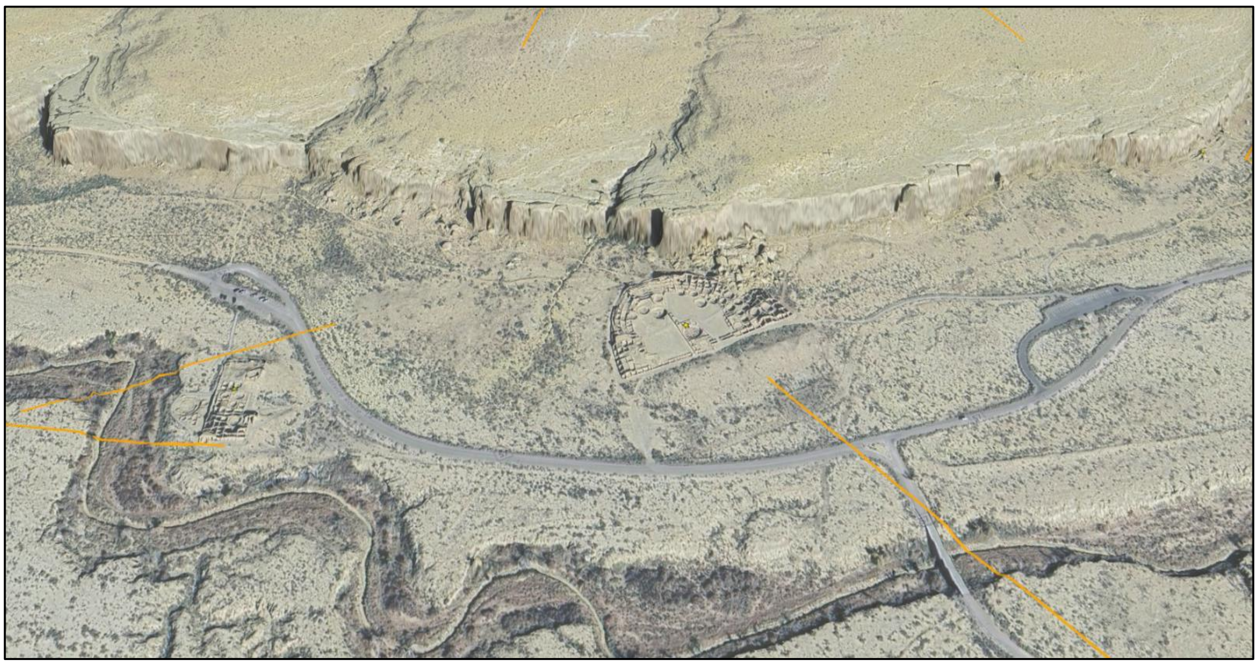


Figure 23. Generated 3D visualization of Chaco Canyon facing Pueblo Bonito

Figure 24. Generated 3D visualization of Bc 53 and Casa Rinconada Community

In Figure 25, the results of the LCP analysis are illustrated along with the source and destination points. The yellow path is the most optimal path between the source, site Bc 53, marked with a green cross, and the destination point, which is the base of the FP Chacoan staircase, marked by a red octagon. The path in purple is the most optimal path between the source, site Bc 53, marked with a green cross, and the destination point, which is the edge of the Casa Rinconada community of structures (site Bc 51) and marked by a red octagon. The orange paths are the edges of the short-distance ancient roadway network, which will be discussed further in the research.

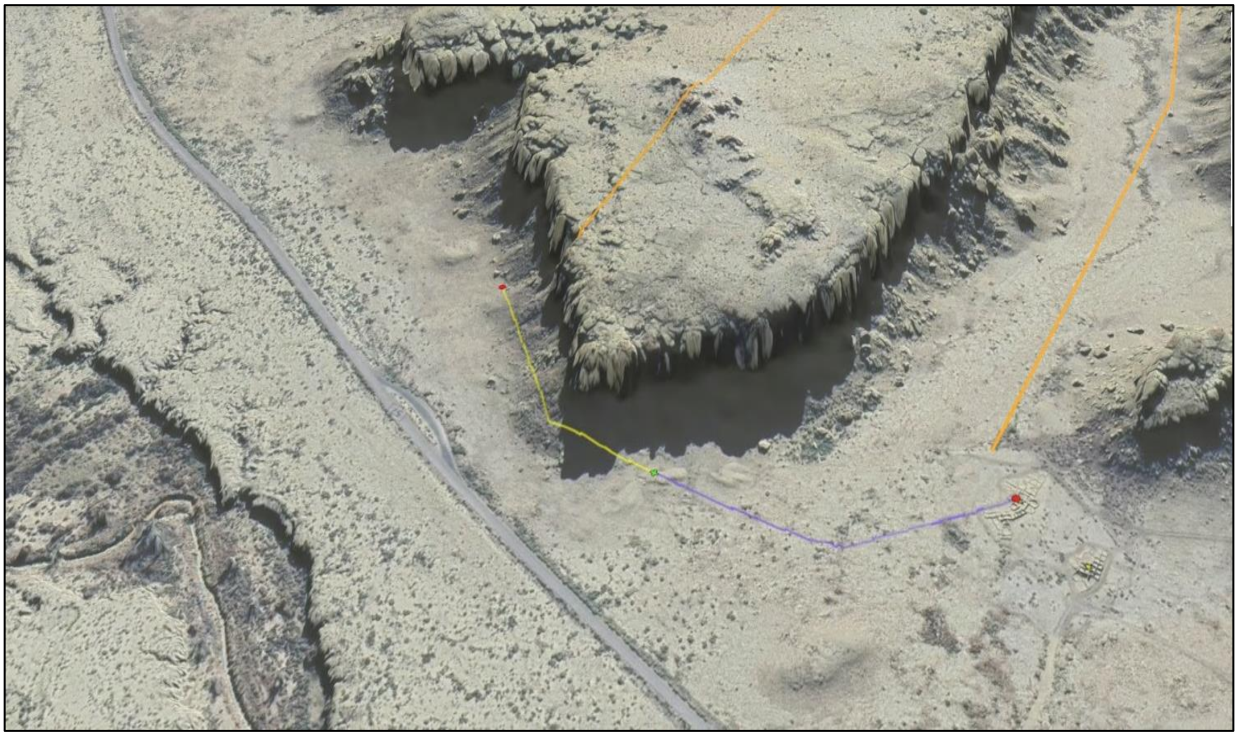


Figure 25. LCP analysis results displayed in the 3D visualization

The 3D visualization is first created by creating the multidirectional hillshade layer from the LiDAR-derived DEM. The 2D map is then transformed into a local scene, which switches the map and all of its layers to a 3D view. The LiDAR-derived DEM layer is then dragged under elevation surfaces to replace the default global terrain. Once the visualization is in 3D, the satellite imagery that is wrapping the visualization can now be adjusted to achieve maximum realism. For this project, the Layer Blending and Overlay tools were utilized in ArcGIS Pro to combine the 3D visualization of Chaco Canyon with the high-resolution satellite imagery (also at a spatial resolution of 1-meter). Figure 23 shows the results of the generated 3D visualization facing towards the Pueblo Bonito and Pueblo de Arroyo ruins, while Figure 24 shows the results of the 3D visualization facing towards the Casa Rinconada community and site Bc 53. The results of the LCP analysis are added to the 3D scene, as displayed in Figure 25, and the major ruins are identified with the golden star symbol by creating individual feature points. In order to visualize the ancient roadway network in ArcGIS Pro, the map created by Lekson in 1988 is used as a reference to illustrate the short-distance roadway network, as displayed in Figure 27, and the long-distance roadway network, as displayed in Figure 28. The map was first brought into ArcGIS Pro as a .jpg file and then georeferenced using common “tie points” that were distinguishable in both the reference map and the satellite imagery for this project. Line features were then created and sketched over the georeferenced Lekson reference map to generate both the short-distance and the long-distance roadway networks as identified in Lekson's research (Lekson 1988).

Figure 26 illustrates the final 3D visualization generated for this research project. It is a zoomed-out view of the Casa Rinconada community of ruins and site Bc 53. In this figure, the short-distance roadway network is depicted as orange-colored trails. Towards the center of Figure 26, the LCP analysis results are depicted along with the major archaeological sites designated by golden stars. The two destination points for the LCP analysis are red octagons, site Bc 51, and the FP Chacoan staircase, and the source point, site Bc 53, is marked by a green cross.

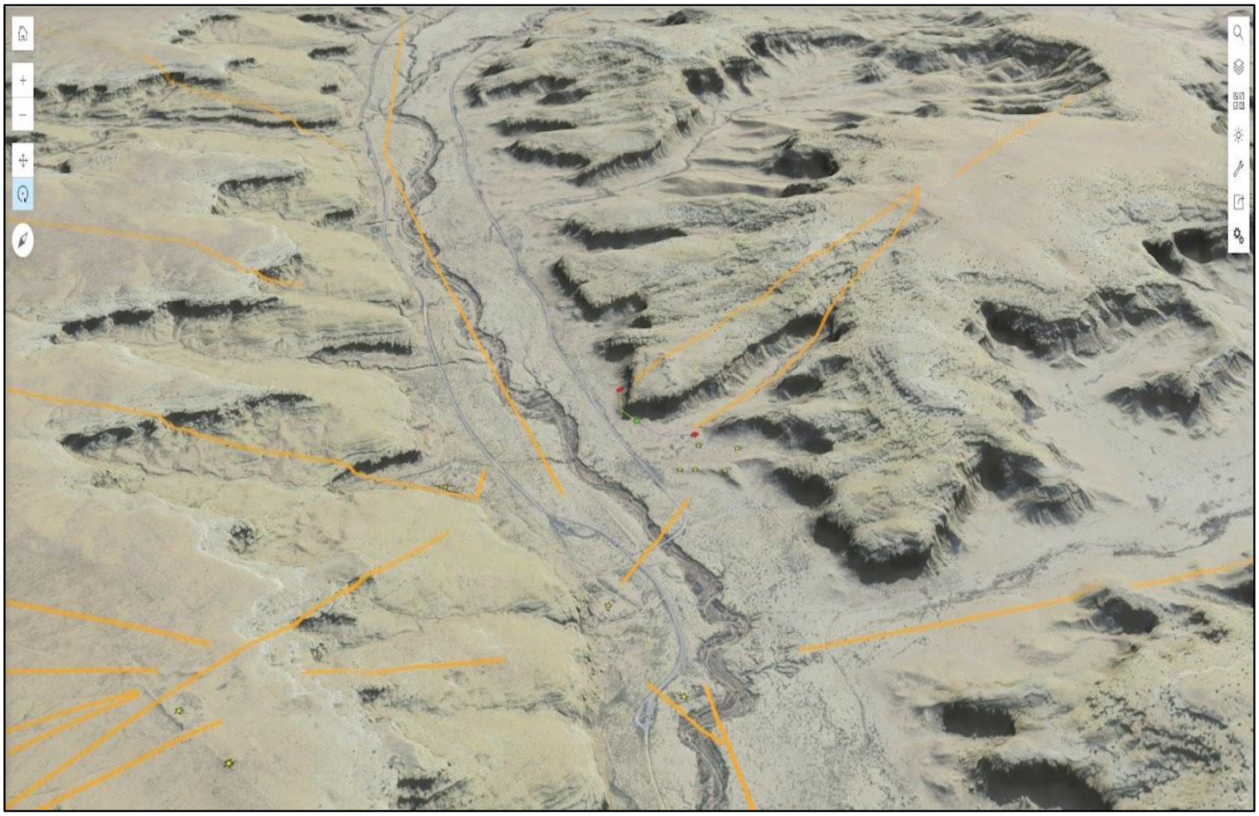


Figure 26. Final 3D visualization of Chaco Canyon zoomed-out

Figure 27 displays an aerial view of the final 3D visualization generated for this research project, focusing on the short-distance roadway network. The short-distance ancient roadway network created by the Anasazi is illustrated in orange, which connects with the long-distance ancient roadway network, which is illustrated in the color teal. Toward the center of Figure 27, golden stars designate the locations of the major ruins in Chaco Canyon National Historical Park. The final features that are depicted in Figure 27 are the elements of the LCP analysis, site Bc 53, which is a green cross, and the two destination points as red octagons, site Bc 51, and the FP Chacoan staircase.

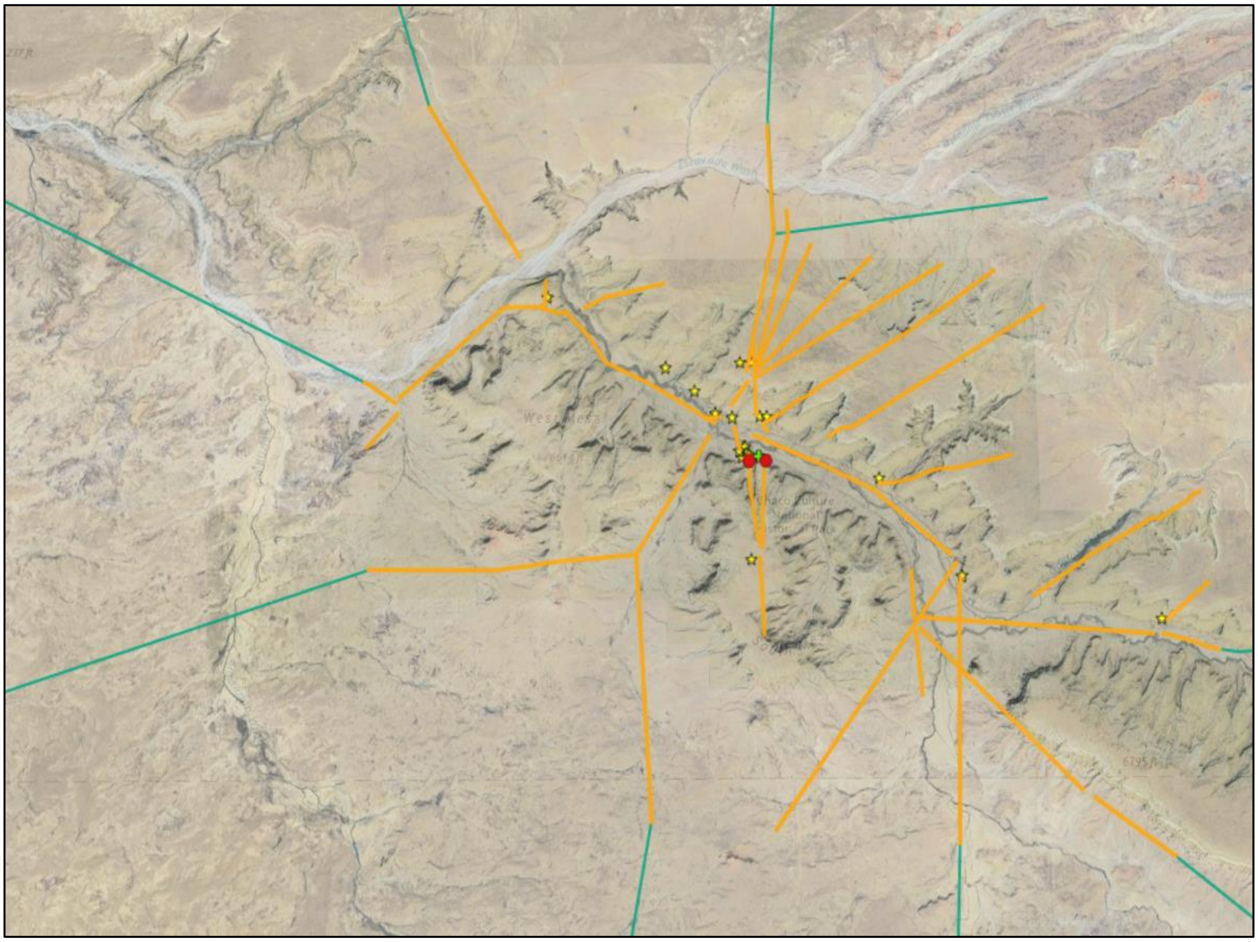


Figure 27. Short distance ancient roadway network

Figure 28 depicts the Four Corners region in the American Southwest and highlights the extensive ancient long-distance roadway network created by the Anasazi. The long-distance road network is shown in teal towards the center of Figure 28. An orange-colored mass represents the short-distance roadway network displayed in Figure 28, illustrating its connection to the long-distance network. In the middle of the orange mass, a red octagon denotes one of the destination points from the previous LCP analysis. Another important feature in Figure 28 is the faded pink roadway network, which actually represents the modern-day highway system in the American Southwest. Remarkably, this modern highway system closely resembles the ancient long-distance roadway network in teal. This similarity is a testament to the impressive ingenuity of the Anasazi and their advanced thinking for their time. The final contiguous 3D visualization of

Chaco Canyon is available on ArcGIS Online as a 3D Web Scene at the following link:

https://www.arcgis.com/home/item.html?id=9d984e5f734f44ef83d9b5fa72e5b88b

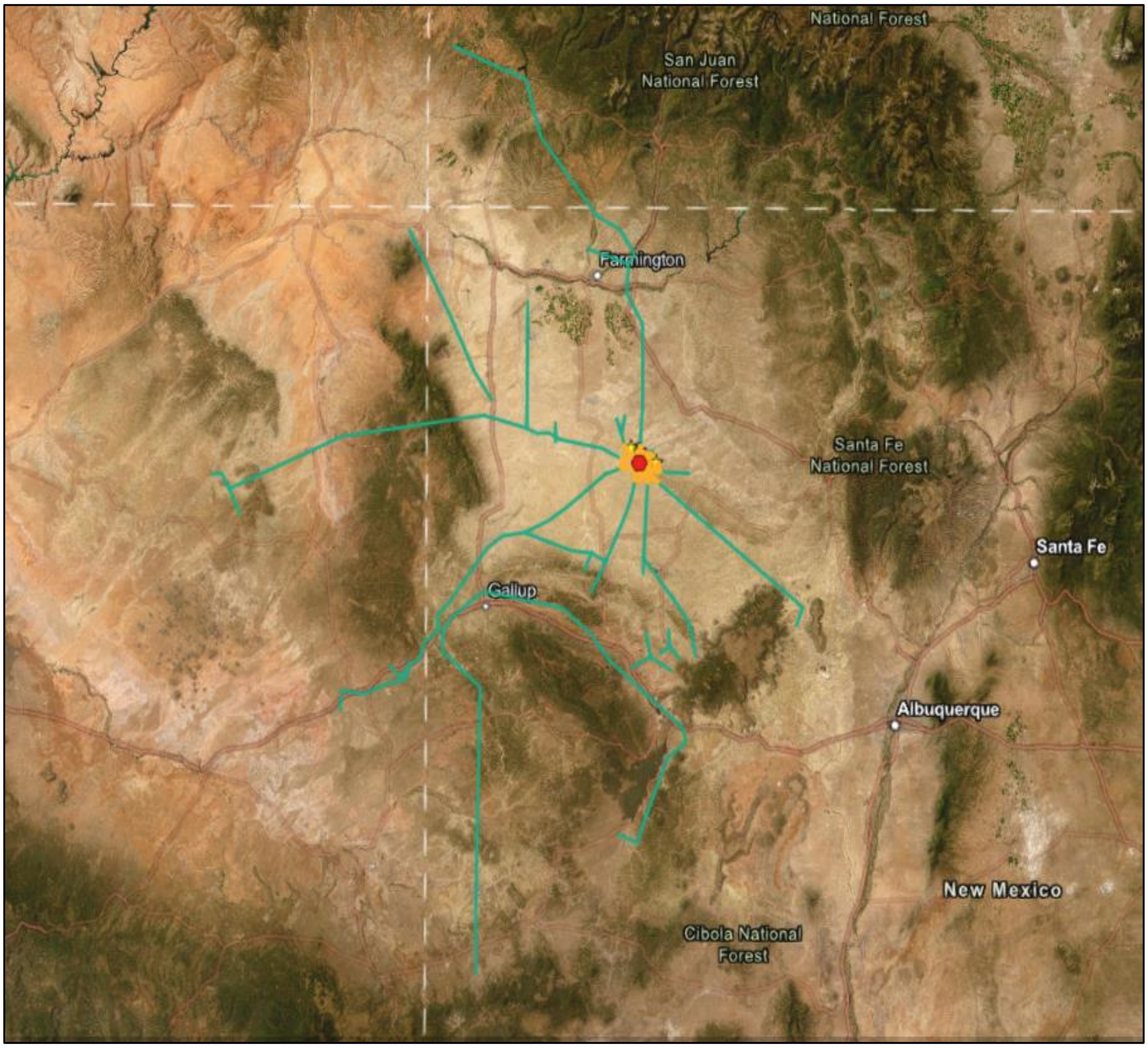


Figure 28. Long distance ancient roadway network

4.4.3 Ethical Implications of the Final 3D Visualization

The decision to make the 3D visualization of Chaco Canyon publicly accessible on ArcGIS Pro raises important ethical considerations, particularly regarding the protection of cultural heritage and the potential for looting. While the visualization has significant educational and research value, it is essential to address these concerns within the broader context of making archaeological site locations publicly available.

One important factor taken into consideration when deciding to make this 3D visualization publicly accessible is the abundance of information about the sites at Chaco Canyon that is already available on widely used platforms such as Google Earth, Google Maps, and the Hybrid Satellite Imagery basemap in ArcGIS Pro. These platforms already provide detailed locations for most of the ruins within Chaco Canyon. These platforms deliberately blur the locations of sacred sites, such as Tsin Kletsin, to protect them from being easily located. The visualization created for this project does not introduce additional risks beyond what is already publicly accessible. This research also ensures that the sacred sites are blurred for their continued protection and privacy.

To further mitigate any potential risks, the National Park Service archaeological team at Chaco Canyon was consulted during the development of this project. Their support highlights the value of the visualization since the National Parks Service does not currently possess a complete, contiguous 3D visualization of the area. This collaboration ensured that the project aligned with the NPS's preservation goals. Additionally, the project proposal was submitted to the Tribal Review Board by the NPS team, which carefully considered its cultural implications. Although certain proposed research activities, such as using a handheld LiDAR scanner to create a 3D model of site Bc 53, required additional discussion and approval, the objective of generating the 3D visualization was deemed acceptable.

Chapter 5 Conclusions and Discussion

In this conclusion chapter, there are two main areas of focus. The first section breaks down the results of the research project and elaborates on their significance. The final section provides an objective overview of the research, identifying major limitations and areas for improvement. This chapter concludes by discussing directions for future research.

5.1 Deciphering the Results

This section provides a detailed analysis of the outputs from the three primary methodologies employed for this research. The first subsection addresses the results of the supervised image classification, highlighting its initial objectives, the achieved accuracy, and the implications of these results for identifying archaeological sites. The following subsection focuses on the analysis of Site Bc 53 and uses the LCP analysis to predict the movement and connectivity patterns of the Anasazi between this site and its neighbors. The final subsection discusses the 3D visualization product, explaining how the generated 3D model integrates terrain data, satellite imagery, and archaeological site markers to create a comprehensive and navigable representation of Chaco Canyon and its ancient roadway networks. The goal of this section is to provide a comprehensive understanding of the research findings and their implications for future studies in archaeological site detection and analysis.

5.1.1 Supervised Image Classification Results

The results obtained from the supervised image classification did not meet the original expectations established at the beginning of this research. The initial goal of the supervised image classification was to create a machine-learning algorithm that could accurately identify concealed ruins with the same building material as the known ruins. If the same building materials were used to construct the hidden ruins as the known ruins, then theoretically, they would have the same spectral signature. Unfortunately, even when trying two separate algorithms, the highest overall accuracy score achieved was just over 80%, meaning that the image classification only classified 80% of the pixels correctly. While the supervised image classification algorithm was not accurate enough to detect unknown ruins definitively, it was still able to detect the known ruins around Chaco Canyon National Historical Park. The objective of the supervised image classification was then adjusted to utilize the results of the image classification to investigate why site Bc 53 was not distinguishable in the image classification like the other nearby ruins.

The results of the supervised image classification were valuable in validating the methodology for using a supervised image classification to identify archaeological sites and ancient roadways. While this initial application of supervised image classification was not perfect, it was able to detect known archaeological sites. This initial research provides an opportunity to enhance the methodology of this image classification process further by increasing the number of training samples and conducting the image classification on satellite imagery with even higher spatial resolution in the future. By enhancing the accuracy and robustness of the supervised image classification, the methodology developed for this research has great potential to identify previously unknown archaeological areas of interest successfully. This classification provides a solid foundation for future research to conduct more comprehensive supervised image classification, particularly as the spatial resolution of satellites and other aerial technology continues to improve, leading to increasingly accurate results with each enhancement in spatial resolution.

5.1.2 Site Bc 53 Analysis Breakdown

The main goal of the LCP analysis was to determine the most plausible pathways taken by the Anasazi between site Bc 53 and its neighboring sites. The LCP analysis results demonstrate the most efficient routes between the project's source point, Site Bc 53, and the neighboring FP Chacoan Staircase and Site Bc 51. These results illustrate the directness of the optimal path between Site Bc 53 and the nearby sites, revealing the relationship between the sites based on their proximity and accessibility to one another. This LCP analysis is critical for understanding how the Anasazi people navigated the canyon landscape because it uses empirical evidence about the landscape, such as slope, vegetation cover, and natural barriers, to determine the most plausible local pathways created by the Anasazi and visualize them.

By mapping the LCPs between Site Bc 53 and the nearby destination points, this project identified the most probable routes that the Anasazi would have taken between individual sites to minimize effort during travel. This LCP analysis illuminates the daily movement of the Anasazi within the canyon and enhances the understanding of the strategic connections between these sites. Understanding the results of the LCP analysis offers valuable insights into the cultural and functional significance of various sites, including the utilization of natural features in their architecture, such as the FP Chacoan Staircase, to connect different roadway networks.

This analysis offers data on potential pathways linking Bc 53 with nearby archaeological sites, providing insight into their relationships, such as their spatial proximity and how the sites are physically connected. Additionally, there is limited research on the local pathways within the canyon that connect less prominent sites like Bc 53. Although Bc 53 shares the same "Bc" name as the nearby ruins of the Casa Rinconada community, the National Historical Park determined Bc 53 to be separate from the Casa Rinconada community of structures. The findings of the LCP analysis conducted between site Bc 53, and the Casa Rinconada ruins (site Bc 51) suggest that the most optimal route between the two sites is not direct. The indirect nature of the most optimal path implies that Bc 53 may have been a neighboring site rather than fully integrated into the community. The relatively isolated position of site Bc 53 beneath the butte supports this interpretation.

The results of the LCP analysis between site Bc 53 and the FP Chacoan staircase indicate that there could be a possible connection between them due to their close proximity and the more direct nature of the most optimal path between them. However, further research that is more robust and considers additional variables beyond just the terrain is required to conclusively establish a link between these two sites.

While the LCP analysis for this research is only driven by the topography that was extracted from the 1-meter DEM, it still provides a solid foundational analysis that can be enhanced to incorporate more variables when determining the most optimal paths. For this research, some other variables that were considered were designating areas in the analysis as fertile land more likely used for agriculture rather than travel. Another consideration was assigning weights to the known trade routes of the Anasazi. The final consideration was to focus the analysis on the demographics and behavior of the Anasazi travelers and how these factors influenced their travel routes. An Agent-Based Model may be better equipped than an LCP analysis to predict ancient pathways based on individual human behaviors and cultural customs. An Agent-Based Model is an alternative advanced GIS analysis that models dynamic geographical phenomena using individual "agents."

When evaluating the preservation condition of site Bc 53 during this research using the LiDAR-derived DEM, it becomes evident that Site Bc 53 lacks any visible outline of the structure in contrast to some of the nearby ruins, such as Bc 50 and Bc 51. This anomaly was discussed with Lori Stephens, the Supervisory Archaeologist at Chaco Canyon, who explained that Chaco Canyon National Historical Park has a team of preservation masons who conduct stabilization work on sites with standing architecture. Site Bc 53 is on the NPS list for cyclic preservation work. However, Lor Stephens explained that there are only a few sections of wall exposed on the west side of the site that are taller than 3 ft high. The limited exposure of Bc 53 is confirmed by the lack of visibility of the structure during the supervised image classification and the examination of the LiDAR-derived DEM for this research. Lori Stephens also addressed the previous question about the absence of public trails allowing access to site Bc 53. She explained that the park management, when establishing the trail system, made decisions about trail placement and accessibility for the public. This balance between preserving and protecting resources and educating the public on these amazing sites necessitates careful consideration of which sites to protect by limiting access and where to create trails through sites that would be open to the public. Specifically, around Site Bc 53, there are no trails at all leading to or around the site, making it essentially closed off to the public.

It is initially alarming that there appears to be a pit of loose soil in the area where Site Bc 53 was determined to be located. However, Supervisory Archaeologist Lori Stephens provided assurance that Site Bc 53 is, in fact, still protected by soil that was backfilled after the initial excavation in the 1940s. Nonetheless, it is exciting that the LiDAR-derived DEM was able to identify this anomaly in the midst of the otherwise uniform desert landscape. While some ruins at Chaco Canyon are left exposed to the elements, such as Pueblo Bonito and the Casa Rinconada structures, the best plan of action at the time to protect Site Bc 53 was to backfill the site. Lori explained that when some sites are excavated and the walls are exposed to the elements, deterioration of the architecture is a significant concern. As a result, many of the excavated sites in the park were backfilled with soil after excavation to protect the remaining structure, and Site Bc 53 was one of these sites.

Additionally, any sites that have standing architecture along visitor trails require a significant effort by their preservation masonry crew to keep the stone and mortar stable and prevent deterioration. The National Historical Park decided that some sites would remain closed to the public, and the exposed architecture would be backfilled to protect them and prevent deterioration of the walls. It still remains unclear why Site Bc 53 was backfilled in contrast to the other nearby “Bc” sites that make up the Casa Rinconada community of structures such as Bc 50 and Bc 51. Unfortunately, now that the ruin is backfilled, it is not possible to evaluate the quality of the archaeological work conducted in the 1940s' without conducting a complete re-excavation. For now, preserving the structure in its current state is the best course of action.

5.1.3 3D Visualization Product and Results

The finalized 3D model of Chaco Canyon is now available to the public on ArcGIS Online as a 3D Web Scene. The visualization was initially created in ArcGIS Pro, then published as a 3D Web Scene, and further edited in ArcGIS Online. The terrain for the 3D model is based on a LiDAR-derived DEM with a spatial resolution of one meter. The 1-meter satellite imagery was used to wrap the generated 3D model, providing a seamless match with the terrain for the 3D visualization. In the visualization, golden star symbols indicate the major ruins, and users can easily navigate from one archaeological site to another using pre-determined “slides” of each point of interest created in the Slide Manager in ArcGIS Online. A green cross identifies Site Bc 53, and the two destination points for the LCP analysis are site Bc 51 and the FP Chacoan Staircase, which are marked by red octagons. Both of the optimal paths determined during the LCP analysis are also illustrated in the final 3D visualization, as displayed in Figure 25. The ancient short-distance roadway network is depicted as orange pathways, aiding in understanding the purpose of these roadways and how they connect with the local pathways within the canyon, as well as with the long-distance roadway network. The ancient long-distance roadway network is illustrated in teal in the visualization and depicts the expansive nature of the Chacoan roadway network spanning across the Four Corners Region of the American Southwest. As displayed by the connection of the orange and teal roadways, it is evident that the Anasazi had a hierarchy of roadways, ranging from local pathways to short-distance travel and extending to long-distance travel.

5.2 Evaluating the Overall Research and Future Directions

This section discusses the main findings and limitations encountered during the supervised image classification, LCP analysis, and 3D visualization processes applied in this thesis research project on the Chaco Canyon archaeological sites. Specific challenges related to the accuracy of the image classification, the limitations of the LCP analysis in capturing culturally specific factors, and the issues of distortion in 3D visualization are addressed. Additionally, potential directions for future research that could improve the accuracy and practicality of these methods are outlined, aiming to contribute to a more comprehensive understanding of the ancient wonders at Chaco Canyon.

5.2.1 Research Limitations

The main limitation of the supervised image classification process during this research was the relatively low accuracy score. While the 80% accuracy of the SVM classification was still useful for this project, it would have been ideal to have achieved a higher overall accuracy score to assist with the intended purpose of this project of definitively distinguishing undocumented ruins amongst the desert landscape. Future research that builds upon this study should work with imagery that offers a higher contrast, which will be better equipped to pick up on all the different spectral signatures in the imagery and to easily distinguish between categories with similar spectral signatures, such as barren desert and ancient roadways. Additionally, if more training data is collected for each category in the ArcGIS Pro training sample manager, it would allow for the image classification to do a better job with class distinction, which ultimately leads to better overall detection accuracy.

The LCP analysis for this thesis research only considered the terrain and did not incorporate other variables, so the results are not as tailored for the Anasazi as originally intended. Due to the limited number of variables in the LCP analysis, the results were not as meaningful as intended, and they failed to consider cultural, social, or religious factors when determining the most likely pathways taken by the Anasazi.

The primary limitation of the 3D visualization is that when the satellite imagery is applied to the generated 3D model, some areas of the imagery become distorted, particularly in areas with steep cliffs or drop-offs. This distortion of the imagery on steep terrain is not a significant problem for most of the major archaeological sites. However, for sites like the FP Chacoan Staircase, which is built into the cliffside, the distortion almost completely obscures the imagery.

5.2.2 Future Research

Even though the SVM image classification was able to correctly identify over 80% of the pixels, future research could improve its accuracy by running the SVM image classification using more training samples and different satellite imagery with even higher spatial resolution. This increased accuracy could help create a machine-learning model that can assist archaeologists in identifying ancient structures and roadways beyond the current boundaries of Chaco Canyon quickly and effectively.

While there are limitations to the LCP analysis completed for this research, recognizing these limitations, and building upon this foundational layer presents an opportunity for future research to incorporate more culturally specific variables or environmental factors. This could lead to a more accurate understanding of the ancient roadway system in Chaco Canyon. Starting with a topography-based LCP analysis establishes a baseline understanding of movement in Chaco Canyon that can be further refined for more in-depth results in future research.

By conducting a brief analysis of Site Bc 53, the aim is to pave the way for future archaeological investigations in similar contexts. These investigations can utilize remote sensing technology and advanced GIS techniques to re-evaluate previously excavated sites for additional insights that may have been overlooked initially. Remote sensing is a valuable tool for archaeologists, providing a wide range of applications to extract data about an archaeological site without physical interaction. Due to the non-invasive nature of remote sensing technology, archaeologists have the opportunity to create digital models of archaeological sites, allowing for efficient collaboration, repeated investigations, and the production of 3D visualizations that can highlight and contextualize archaeological findings a change from prior archaeological excavation methodologies that were more invasive and less sustainable.

The 3D visualization developed for this project can be used for future research, conservation efforts, educational purposes, and to inform policy decisions regarding the management of significant national and international heritage sites like Chaco Canyon. This visualization serves as a solid basis for future research that can delve deeper into the extensive ancient roadway network or map the locations of ancient structures outside the park boundaries that are under threat from modern risks such as encroaching oil and gas drilling. Additionally, the goal of this 3D visualization is to inspire other archaeologists and protection agencies, such as the National Parks Service, to allocate time and resources to create 3D models to "digitally protect" their archaeological sites for future research and exploration.

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