ARCHAEOLOGICAL SITE VULNERABILITY MODELING FOR CULTURAL RESOURCES
MANAGEMENT BASED ON HISTORIC AERIAL PHOTOGRAMMETRY AND LiDAR

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GIS has been utilized in cultural resources management for decades, yet its application has been largely isolated to predicting the occurrence of archaeological sites. Federal and State agencies are required to protect archaeological sites that are discovered on their lands, but their resources and personnel are very limited. A new methodology is evaluated that uses modern light detection and ranging (LiDAR) and historic aerial photogrammetry to create digital terrain models (DTMs) capable of identifying sites that are most at risk of damage from changes in terrain. Results revealed that photogrammetric modeling of historic aerial imagery, with limitations, can be a useful decision making tool for cultural resources managers to prioritize conservation and monitoring efforts. An attempt to identify key environmental factors that would be indicative of future topographic changes did not reveal conclusive results. However, the methodology proposed has the potential to add an affordable temporal dimension to future digital terrain modeling and land management. Furthermore, the methods have global applicability because they can be utilized in any region with an arid environment.
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CHAPTER 1

INTRODUCTION

1.1 A Need For New Management Tools

Numerous modeling projects pertaining to the prediction of archaeological resource presence have been performed in recent decades using geographic information systems (GIS) (see Judge & Sebastian, 1988; Kamermans et al., 2010). The field survey initiatives that frequently accompany the production of these models have resulted in large databases and collections of site records. Across the United States, cultural resources managers are assigned the daunting task of managing these collections of archaeological sites across expansive properties with limited budgets and personnel. Site databases often span decades with records varying in format, accuracy, detail, and completeness. Between the expansive government-held lands and the growing complexity of resource databases, it is imperative that GIS be implemented in new ways to help resource managers prioritize their efforts to identify and monitor areas of critical need. This research project proposes and investigates the utility of a new methodology that uses both historic and modern remote sensing data, aerial photogrammetry, and change-detection techniques in GIS to identify resource zones that are vulnerable to topographic changes in the landscape. Vulnerable resources could be experiencing damage from erosion, receiving deposition of nearby eroded sediments, or otherwise changing in ways that may no longer be suitable for the preservation of archaeological sites. Identifying these vulnerable resource zones would be useful in prioritizing conservation, investigation, and monitoring efforts.
1.2 Historic Aerial Photogrammetry and Terrain Modeling

Using photogrammetric techniques, historic aerial imagery collections were processed to create historic digital terrain models (hDTMs). Each hDTM was georeferenced and compared to modern light detection and ranging (LiDAR) data in GIS to identify regions in the landscape that have experienced significant changes over time; whether they were the result of erosion, deposition, or other natural and artificial impacts. Rasters measuring elevation change rate were produced to identify topographic dynamics that may have increased the vulnerability of nearby resources.

1.3 Future Vulnerability

In addition to measuring landscape changes that have occurred in the historic past and present, the data were statistically explored in order to better understand what environmental variables could be contributing to changes in the landscape. Quantifiable environmental variables such as slope, aspect, curvature, flow accumulation, and solar radiation were examined for correlations with elevation change rates to identify which attributes have the greatest influence on the project area's unique topographic morphology. The results of the analysis could assist in identifying what variables are indicative of certain hydrological processes across the terrain. Understanding these processes could reveal how they are impacting nearby cultural resources and thus provide insight on the risk of site damage or destruction. The application of these tools could assist resource managers in targeting areas that would most benefit from monitoring and mitigation activities.
1.4 Further Significance

While this project primarily focuses on the identification of cultural resources that are vulnerable to landscape changes, the research and methodology have a number of other practical uses. For example, the model could be used to develop time- and cost-efficient CRM survey strategies. Project archaeologists will be able to distinguish between areas that only require surface or shallow field testing and areas that may require deeper subsurface testing such as shovel testing or backhoe trenching. Information derived from the vulnerability model could also contribute to the determination of site integrity, an important component in National Register of Historic Places (NRHP) eligibility evaluations of cultural resources sites. Encountered archaeological sites generally need to be intact to be considered NRHP eligible. Therefore, if it can be shown that particular regions have experienced drastic changes in topography, the NRHP eligibility of sites located in these areas may be significantly reduced.
CHAPTER 2

BACKGROUND

2.1 The Project Area

There has been a renewed flurry of archaeological interest in the Lower Pecos Cultural Region in recent years (SHUMLA Archeological Research & Education Center, 2014; Texas Archeological Society, 2013). This southwestern nook of Texas (Figure 1) is best known for its collection of rock shelters with vivid ancient pictographs. Many of these recorded sites were initially discovered during pedestrian field surveys that were conducted prior to the filling of the Amistad Lake in 1969 (“Amistad Reservoir,” 2013). The reservoir Amistad Lake is now part of the National Parks Service Amistad National Recreation Area (NPS) (“Amistad National Recreation Area,” 2013). In addition to rock shelters, open air campsites are highly visible on the eroding upland surface and can most easily be identified by their burned rock middens and stone hearths. Most of these upland sites were discovered during pedestrian surveys of the Seminole Canyon State park and Historic Site (SCSP) in the 1980s (“Seminole Canyon State Park & Historic Site,” 2013). These early site reports provided a glimpse of the rich prehistoric culture of the Lower Pecos.

Figure 1. Location of the Lower Pecos Cultural Region in southwestern Texas.
The selected project area is a 6,430 hectare (15,889 acre) region in southwestern Val Verde County, Texas along the Rio Grand River, south of the Pecos River, and encompasses the SCSP and a portion of the NPS (Figure 2). This region was selected due to its higher volume of recorded sites and also its direct association with some of the more iconic pictograph rock shelters in the region such as Panther Cave and White Shaman (SHUMLA Archeological Research & Education Center, 2014). This project area is favorable for the use of photogrammetry because it is located in an arid part of the United States with minimal vegetation cover. Regions with dense vegetation do not model well using photogrammetric methods because vegetation canopies obscure the true ground elevation. The sparse vegetation across the project area will

Figure 2. Location of the project area and government held lands within the Lower Pecos Cultural Region.
maximize the capabilities of historic aerial photogrammetry to model the bare earth's surface. There are also other state protected lands in the project area's vicinity; the Devil's River North and South Units. Therefore, the methods and results documented by this project could have broader management applications.

2.2 GIS Modeling in Cultural Resources Management

GIS has been utilized in federal and state resource management for over 30 years (Sipes, 2006). Despite the vast GIS modeling capabilities for archaeological research, predictive models are the most common use in cultural resources management (CRM) to calculate or minimize field survey costs (Verhagen & Whitley, 2011). While it has been demonstrated that such predictive models can produce accurate results, they are merely correlative and fail to explore how or why such settlement patterns exist (Altschul, 1990). This practice of non-explanatory modeling has resulted in a lack of academic interest and restricted application of modeling in GIS research fields. Some have even warned that "the use of predictive modeling within the compliance framework...actually perpetuates stagnation in our understanding of past human land use" (Dore & Wandsnider, 2005, p. 68).

As an alternative approach, it has been proposed that predictive modeling would be a more valuable tool if its focus shifted away from site discovery and instead towards site management (Dore & Wandsnider, 2005). As stated by Sipes (2006, p. 58),"...resource managers are in a constant struggle to do more with less. Budgets are getting smaller, while at the same time the issues they deal with are more complicated than ever." With resource databases growing larger with each field survey, it is becoming less important to resource managers to
know where sites are, and more important to know how to identify priority areas or “red-flags.” (Altschul, 1990, p. 227). Altschul calls for models that will help resource managers prioritize their efforts and “bring some order and direction to the huge databases that have been, and are continuing to be, amassed” (p. 227). Although Altschul was discussing NRHP eligibility as grounds for “flagging” a resource, a similar system could be implemented to call attention to other useful attributes such as vulnerability to erosion or other dynamic changes in topography that could threaten site integrity.

2.3 LiDAR: History and Use in Archaeology

Light detection and ranging (LiDAR) is defined by the National Oceanic and Atmospheric Administration (NOAA) as a remote sensing method that uses pulsed lasers to measure the distance between the instrument and the Earth’s surface (National Oceanic and Atmospheric Administration, 2015). The pulsed light from the laser is reflected from the ground surface and is recaptured by a sensor, measuring the time delay between the emitted and returned signal. The measurements combined with global positioning systems (GPS) create dense point clouds that can be post-processed into high-resolution terrain models. LiDAR was first used to collect data about the earth’s surface in the 1980s, but the technology has seen significant improvements in accuracy and detail over the last few decades (Campbell & Wynne, 2011).

LiDAR has demonstrated to be a useful tool in archaeological research. Digital terrain models (DTMs) derived from LiDAR are commonly used in archaeological site predictive modeling. There have also been recent advancements in local relief modeling where LiDAR can be analyzed in a more precise manner for direct archaeological site prospecting (Hesse, 2010).
However, due to the high cost of LiDAR equipment and the fact that the technology is quite recent, there is a considerable lack of temporal resolution in available datasets. If temporal scale could be added to digital terrain modeling, LiDAR could be utilized in new ways that would extend beyond archaeological site prediction.

2.4 Photogrammetry: History and Use in Archaeology

Photogrammetry is becoming a reliable and affordable technique in three-dimensional modeling. The term *photogrammetry* was first used in 1867 (Kucukkaya, 2004) and is currently understood as “the science of making reliable measurements from aerial photographs or remotely sensed imagery” (James et al., 2012, p. 185). The modeling power of photogrammetry already has a well documented history in archaeological circles. Stereoscopic photographs of artifacts and monuments have been captured for decades, and photogrammetry has also been used in the past to swiftly document salvage excavations facing tight deadlines (Fussell, 1982).

Another advantage to photogrammetry is that it can be done in-house using commercial software and inexpensive camera equipment. This is more cost-effective than other remote sensing techniques such as LiDAR because users and researchers can produce their own models rather than paying third-party service providers to collect the data and produce the final product (Baltsavias, 1999).

2.5 Historic Terrain Modeling and Landscape Change Detection

This project used low-altitude aerial photogrammetric techniques to produce hDTMs in order to detect historic changes in the landscape when compared to LiDAR-derived modern
digital terrain models (mDTMs). Previous attempts have been made to produce hDTMs from historic aerial collections with varying degrees of success. The most common problem encountered was with regards to camera lens calibration (James et al., 2012). In the past, correcting for lens distortion was done by manually inputting calibration values prior to processing. Manual calibration required detailed camera lens information, which was especially problematic for historic aerials because metadata for historic frames are not always available. Fortunately, modern commercial photogrammetry software suites now utilize automated tie-point processes and image correlation techniques (Casana & Cothren, 2008). The development of self-calibrating pixel matching algorithms has significantly improved the accuracy of derived models and has decreased the dependency on camera calibration data.

To test the feasibility and affordability of modern aerial photogrammetry techniques, a project was conducted by Altmaier & Kany (2002) to produce hDTMs from declassified CORONA satellite imagery for a project area in Morocco. Their goal was to achieve a “large area coverage” with “the least financial and temporal efforts as possible” (p. 228). The project was able to produce an hDTM for a 100 km² area; the region's sparse vegetation made bare-earth terrain production an efficient process with minimal need for manual correction. Due to the arid nature of the Lower Pecos, similar efficiency is achievable for the project area in this study.

Historic aerial photogrammetry has also been reported to be a successful technique in modeling geomorphological processes. Along the Coast of Huelva in Spain, ortho-rectified historic aerial images from three decades (1979, 1989, 1994, 1996) were used to produce a series of hDTMs (Ojeda Zújar, Borgniet, Pérez Romero, & Loder, 2002). An analysis of the hDTMs showed considerable changes along the coast between 1979 and 1996. The authors also
noted that photogrammetry produced the best results of several modeling methods attempted.

The photogrammetrically derived models were capable of estimating sediment redistribution by surface area and volume to produce quantifiable results for the time intervals between the sequential historic aerials.
3.1 Data Acquisition

A large collection of aerial imagery is available free to download from the USGS EarthExplorer website (U.S. Geological Survey, 2015). Imagery was used from two different years: 1950 and 1971. It is important to note that model accuracy and detail will be directly related to the quality and resolution of the available data (Challis, Priestnall, Gardner, Henderson, & O’Hara, 2004, p. 142). While high-resolution low-altitude aerial imagery is preferred, the data available for downloaded at EarthExplorer varies in these qualities considerably. In order to effectively detect change over time across the landscape, the produced historic digital terrain models (hDTMs) will need to be compared to others of similar detail and resolution. Higher quality models need to be aggregated to match the lower quality ones. The metadata for the downloaded aerals contain focal length information which will improve the accuracy of the resultant hDTMs. For the project's mDTM, a light detection and ranging (LiDAR)-derived bare-earth digital elevation model was purchased from the Texas National Resources Information System (TNRIS) at one meter resolution. The International Boundary & Water Commission (IBWC) acquired the LiDAR data in 2011 that covers 100% of the project area (IBWC, 2011).

3.2 Aerial Imagery Pre-Processing

To ensure the best accuracy when producing hDTMs, the downloaded historic imagery was preprocessed. The imagery available on EarthExplorer are digital scans of microfilm
archives. Between the transition from original film, to microfilm, to digital scan, varying degrees of data loss is expected. To minimize error and create the highest quality hDTMs possible, the imagery needed to be rotated, cropped, masked, and color corrected (Figure 3). Rotation was necessary because the microfilm scanning process did not always keep the image squared to the frame’s intended orientation. Cropping was necessary because the downloaded images included USGS watermarked borders and extended into the adjoining film frames. Masking is a different process than cropping in that the dimensions of the cropped frame remain the same while parts of the image are erased so that they are ignored by the photogrammetry tie-point process. Examples of masked items include date stamps and fiducial marks. Lastly, the greyscale balance was enhanced by applying a histogram stretch to the images. Applying a histogram stretch enhances contrast between image features so that they are easily identifiable during tie-point photogrammetric calculations.

![Figure 3](image)

**Figure 3.** Pre-processing steps of historic aerial imagery. (a) depicts the original scan, (b) depicts a rotate and crop, and (c) depicts the masking of fiducials and text.

### 3.3 hDTM Production and Alignment

Once the historic aerial frames were preprocessed, they were imported to Agisoft PhotoScan for photogrammetric alignment and modeling. PhotoScan utilizes a new approach to
photogrammetric modeling called structure-from-motion (SfM). While conventional photogrammetry requires predetermined three-dimensional coordinates of either the camera locations or image targets, SfM estimates the camera and target positions relative to each other. As described by Westoby et al. (2012), “unlike traditional photogrammetry, the camera positions derived from SfM lack the scale and orientation provided by ground-control coordinates. Consequently, the 3-D point clouds are generated in a relative ‘image-space’ coordinate system, which must be aligned to a real-world, ‘object-space’ co-ordinate system” (p. 301).

There are a number of sources for error that should be taken into consideration when aligning photogrammetric models derived from SfM. One of the biggest vulnerabilities of photogrammetric modeling is the residual horizontal offset from georeferencing the 'image-space' to 'object-space' (James et al., 2012). Even a minor offset could cause large discrepancies along steep banks and ridges. Unfortunately, these regions are also precisely where topographic changes are most likely to occur, so model accuracy is crucial. Furthermore, since image frames had to be cropped manually in the pre-processing stage, it is possible that the digital representation of the frame extent differed slightly from the original film's frame. Inaccuracies in the cropping extent would cause the focal length value to be applied to the frame incorrectly and could result in unusual curvatures and undulations in the model. To minimize the effects of horizontal offset and curvature undulations it was important to fit each produced hDTM to the mDTM as closely as possible. Fifty (50) ground control points (GCPs) were selected across the project area to ensure accurate alignments (Figure 4). The GCPs were also used by PhotoScan to optimize the model curvature. This is achieved by running a secondary set of alignment
calculations that fine-tune the initial camera calibration estimates. Once each model was optimized in PhotoScan, they were exported as hDTM rasters for post-processing and analysis within the GIS framework.

3.4 hDTM Post-Processing

As a final processing measure, the hDTMs were corrected for any residual undulations in elevation. The need for this step was apparent when the hDTMs were subtracted from the mDTM. As can be seen in Figure 5, there are unusual ripple effects across the project area, especially where flight paths overlap. To correct for this, the undulations needed to be isolated and removed from the model while still preserving the higher-detailed terrain features. The
Figure 5. Maps depicting (a) all residual values in the 1950 hDTM, (b) isolated undulations, and (c) the adjusted 1950 hDTM residuals values. Residuals were calculated against the 2011 mDTM.
procedure to remove the ripple effect in the HDTMs is a multi-step process. First, each hDTM was subtracted from the mDTM producing rasters of residuals. These residual rasters were then aggregated to 200-meter resolution and converted to point feature classes. A high-pass filter was calculated from the aggregated residual raster and the values were also extracted to the point feature class. Point features with high-pass filter values that exceeded two standard deviations from the mean, or those that were located in the Amistad Reservoir, were removed. The remaining points were spline interpolated back to a five-meter resolution raster, capturing only the broad undulations from the residual rasters. The interpolated rasters were then added to the original hDTMs to normalize the rippling effects.

The final post-processing step was to clip each hDTM. The clipping extent was not only determined by the project area but also by the extent of the modern reservoir and reconstruction of US Highway 90. These additional regions were removed because they are well understood artificial impacts to the topography that overshadow the more subtle changes that this analysis is trying to observe.

3.5 hDTM Overviews

The hDTM production process described above is depicted as a flow chart in Figure 6. However, because of the varying flight altitudes and scan qualities between historic aerial sets, each hDTM posed its own unique set of challenges when creating the most accurate models. The unique obstacles for creating each hDTM will be described here separately.

The 1950 aerial imagery was flown on April 24th at an altitude of 23,000 feet and covers 100% of the project area. According to the USGS EarthExplorer metadata, the 229 millimeter...
Figure 6. Flow chart depicting the general process followed to create each Historic Digital Terrain Model.
(mm) microfilmed frames were digitally scanned at “high” resolution, resulting in 9275*9275 pixel digital images after pre-processing. Unfortunately, the imagery from the southernmost flight path showed evidence of microfilm scratch damage. Horizontal lines can be seen running across the frames causing holes and inaccuracies in the produced model. However, a medium-resolution collection of the same imagery that was digitally scanned prior to the microfilm damage is also available for download. The medium-resolution scans were included in the model processing to fill holes and minimize the inaccuracies that were apparent when processing the high-resolution images on their own. The model was aligned to the mDTM with forty-eight (48) ground control points; two points were excluded because they were located in poorly modeled areas. The hDTM was exported from PhotoScan at a five-meter resolution raster and post-processed as previously described. When compared to the mDTM, the post-processed model had a root mean squared error (RMSE) of 1.4 meters. It was visually apparent that certain regions of the model had considerably more erroneous noise than other regions. High-noise areas coincided with portions of the model that were derived from only two photo frames. When more images overlap, terrain noise is significantly reduced and the elevation is more accurately represented (Figure 7). Further analyses will focus on the most accurate regions of the model. When high-noise regions were excluded, the RMSE was reduced to 1.33 meters.

The 1971 aerial imagery was flown on March 23rd at an altitude of 15,000 feet and covers 100% of the project area. According to the USGS EarthExplorer metadata, the 229 mm microfilmed frames were digitally scanned at “high” resolution, resulting in 8964*8964 pixel and 9160*9160 pixel digital images after pre-processing. It appears that one leg of the flight
Figure 7. Maps depicting areas of low photo overlap from the 1950 (a) and 1971 (b) hDTMs. The final map (c) shows the high photo overlap areas spanning both hDTMs. Squared residual values were calculated against the 2011 mDTM.
path was scanned from microfilm at a slightly different resolution than the rest, resulting in the two different post-processed frame resolutions. The model was aligned to the mDTM with forty-eight (48) ground control points; two points were excluded because they were located in poorly modeled areas. The hDTM was exported from PhotoScan at a five-meter resolution and post-processed as previously described. When compared to the mDTM, the post-processed model had a RMSE of 1.19 meters. Similarly to the 1950 imagery, it was visually apparent that there was more erroneous noise in areas where only two photo frames overlapped. When high-noise regions were excluded, the RMSE was reduced to 0.99 meters.

3.6 Elevation Change Rate

Once the hDTM models were produced, elevation change rate rasters were created. This was achieved by subtracting an earlier DTM from a later DTM, then dividing by the number of years between the two DTM’s dates. The result is a new raster with positive and negative cell values. The cell values are approximate annual elevation changes that may have occurred during the time interval between DTMs. Values close to zero indicate little change, while extreme positive or negative values indicate that erosional or depositional processes are likely occurring and could be impacting nearby archaeological sites. Three elevation change rate rasters were created and evaluated: 1950 to 1971, 1971 to 2011, and an overall 1950 to 2011. See Figures 8-10 for the final change rate models.
Figure 8. Elevation change rate model for the time period of 1950 to 1971.
Figure 9. Elevation change rate model for the time period of 1971 to 2011.
Figure 10. Elevation change rate model for the time period of 1950 to 2011.

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community, NHD

Project Area

Low Photo Overlap Area

Highway

Water

Elevation Change Rate (cm/yr)

> 5

Soil Accumulation

2.5 to 5

1 to 2.5

< 1

-1 to -1

-2.5 to -1

-5 to -2.5

< -5

Soil Removal

2.5 to 4

1 to 2.5

< 1
CHAPTER 4
RESULTS AND VERIFICATION

4.1 Site Reviews for Verification

Once elevation change rate models were created, it was important to determine how closely the models represent the true terrain history of the project area. In order to do this, archaeological site records from the Texas Historical Commission were reviewed to determine if reported site conditions match what the models depict. A sample of sites were selected across the project area using a purposive-based sampling strategy. Sites needed to be open-air (e.g. no rock shelters), be located in an area with high photo overlap for both 1950 and 1971 historic digital terrain models (hDTMs), and have reports that contain sufficient descriptions of the site's condition and environmental impacts. A total of 22 sites met the sample criteria and were compared against the elevation change rate models. Six sites that were representative of the overall results were selected for further discussion below.

4.2 41VV370

41VV370 is a prehistoric site that is located on the lower slopes of the southwestern bank of Presa Canyon within SCSP (Figure 11). The THC had three records available for this site from 1980; the University of Texas at Austin Site Survey Form, the Amistad National Park Service Site Form, and the State of Texas Archaeological Site Data Form. The site was also deemed eligible for SHPO site designation in 1983. The site is comprised of multiple burned rock middens and a lithic scatter. Lithic material included quartzite and chert, and diagnostic projectile point fragments suggest that the site dates to the Archaic period. The site is described
Figure 11. Time series of aerial imagery (a-c), elevation (d-f), and modeled terrain changes (g-i) within the vicinity of archaeological site 41VV370.
as having relatively deep soils and is estimated to be 90% intact with some natural downslope dispersion. The two models from 1950 to 2011 and 1971 to 2011 both clearly portray an accumulation of dispersed soil along the southwestern bank, indicated by a rise in elevation. The rate-of-change model that is most difficult to interpret is for the date range of 1950 to 1971. This model has a substantial amount of noise, yet still depicts an accumulation of dispersed soil along the bank where the site is located. Therefore, a review of 41VV370 records suggest that the rate-of-change models have reliably captured the topographic changes that have occurred within the site's vicinity.

4.3 41VV394

41VV394 is a prehistoric site with a historic component that is located approximately 200 meters south of US Hwy 90 and 150 meters northwest of a confluence of West canyon and Infierno Canyon (Figure 12). The THC had four records for the site from 1980; the University of Texas at Austin Site Survey Form, the Amistad National Park Service Site Form, and two State of Texas Archaeological Site Data Forms. The site is described as a cluster of three burned rock middens that have had their cultural material dispersed along the downslope of a nearby mesa. The northern end of the site was reported to have an eroding gully channeling between two middens. This site was found surrounded with sotol and overgrown with heavy brush, suggesting that the region has received and/or retained a significant amount of topsoil. When comparing the site description to the elevation change rate models, some time-intervals appear to be more accurately represented than others. First, the 1950 to 1971 model portrays the site area as experiencing significant soil accumulation, with a few small pockets of significant
Figure 12. Time series of aerial imagery (a-c), elevation (d-f), and modeled terrain changes (g-i) within the vicinity of archaeological site 41VV394.
erosion. While some topographic changes were reported in the site records, the extreme range of rate-of-change values suggest that the model's reliability may have been compromised by the cumulative error from the two hDTMs it derived from. The 1970 to 2011 rate-of-change model depicts a more stable terrain with what appears to be gullies starting to erode across the northern half of the site. Minor soil accumulation is also depicted downslope to the southeast, which is consistent with reports of cultural material showing signs of dispersal. The overall elevation change rate model from 1950 to 2011 shows less evidence of gullying, but downslope soil accumulation is still apparent. Due to the significant differences between the three models, it is difficult to determine if they are depicting different historical terrain events, or if model inaccuracies are obscuring the terrain's true history. However, it is important to note that the northern region of the site area is consistently depicted with eroding regions, possibly gullies, towards the canyon.

4.4 41VV450

41VV450 is a prehistoric site with a historic component located on a flat bench on the northern edge of a minor tributary on the east side of Seminole Canyon (Figure 13). The THC had two records for the site from 1983; the Amistad National Park Service Site Form, and the State of Texas Archaeological Site Data Form. The site is described as three stone cairns surrounded by scatters of burned rock and other lithic material. Only fifty percent of the site was estimated to be intact due to animal traffic and sheetwash erosion dumping sediment and cultural material across the rising interfluvial benches. The 1950 to 1971 rate-of-change model continues to provide inconsistent results with very extreme positive and negative values that do
Figure 13. Time series of aerial imagery (a-c), elevation (d-f), and modeled terrain changes (g-i) within the vicinity of archaeological site 41VV450.
not appear to relate to the region's topography. Fortunately, both the 1971 to 2011 and 1950 to 2011 models show similar terrain dynamics that closely correlate to the descriptions provided in 41VV450's site records. The rising interfluvial benches are easy to distinguish along the Seminole Canyon tributary.

4.5 41VV541

41VV541 is a multicomponent site located on relatively flat terrain west of Seminole Canyon (Figure 14). The THC had two records for the site from 1978; the Amistad National Park Service Site Form, and the State of Texas Archaeological Site Data Form. The site consists of a burned rock and lithic scatter with cultural material exposed within the banks of an old railroad grade. The southeast portion of the site was not disturbed by the railroad line and both historic and prehistoric artifacts were noted on the surface from slight erosion. This site is located in a region that demonstrates a significant amount of error at particular stratigraphic layers of the canyon uplands. For example, the surface depicted in the 1971 hDTM was so noisy that the 1950 to 1971 and 1971 to 2011 rate-of-change models appear to be extreme inverts of each other. For a site with such flat terrain and minimal reported erosion, it seems very unlikely that the topography has been as dynamic as these two models suggest. Therefore, it can be concluded that the 1971 hDTM and derived rate-of-change models will be unreliable for this region. The 1950 to 2011 model shows that the topography around the site has remained stable with a few areas experiencing minor erosion. Despite the problems with models related to the 1971 hDTM, it appears that the 1950 to 2011 elevation change rate model is accurately depicting the topographic history of the area surrounding 41VV541.
Figure 14. Time series of aerial imagery (a-c), elevation (d-f), and modeled terrain changes (g-i) within the vicinity of archaeological site 41VV541.
4.6 41VV602

41VV602 is a prehistoric site located south of a minor tributary on the east rim edge of Seminole Canyon (Figure 15). The THC had two records for the site from 1983; the Amistad National Park Service Site Form, and the State of Texas Archaeological Site Data Form. The site is described as three stone hearths with no other associated artifacts. The ground surface is mostly exposed bedrock with a maximum of five centimeters of trapped sediment. Approximately 20% of the site has been damaged from animal traffic, erosion, and rock decay. The rate-of-change models show some agreement with each other, yet disagreement with the site description records. First, all three rate-of-change models depict an increase in elevation along the east bank where the site is located. Although it is possible that rock decay and erosion could have accumulated downhill from the higher ground to the east, this is an unlikely explanation because the site was reported to be on exposed bedrock with minimal soil present. Another possible explanation for the contradictions between the models and site records could be horizontal offset between the hDTMs and the mDTM. As previously discussed, elevation error from horizontal offset will be highest in regions with a lot of topography, such as in this case along the steep canyon edge. Despite one's best efforts to align the models to each other accurately, even the slightest shift along the x (east-west) or y (north-south) axis could have significant consequences to the alignment of z (elevation) values. It appears that horizontal offset might have impacted the reliability of the rate-of-change models along the steep slopes of the canyon rim.
Figure 15. Time series of aerial imagery (a-c), elevation (d-f), and modeled terrain changes (g-i) within the vicinity of archaeological site 41VV602.
4.7 41VV754

41VV754 is a prehistoric site on a flat surface south of a Buda limestone hill and north of a minor drainage that leads to the Rio Grande River (Figure 16). The THC had two records for the site from 1985; the Amistad National Park Service Site Form, and the State of Texas Archaeological Site Data Form. The site is described as an erosion-exposed hearth field with burned rock and lithic scatters. The site has also been disturbed by a road cut through its center. There is quite a bit of agreement between the rate-of-change models and the terrain descriptions from the site records. For instance, the 1950 to 2011 and 1971 to 2011 models both show some erosion around the site along the road and north of the drainage. However, the cumulative error between the 1950 and 1971 hDTMs still obscure the results in the 1950 to 1971 rate-of-change model. Overall, despite the erroneous depictions in the 1950 to 1971 model, the other two models show consistent elevation trends that match the descriptions in the site's records.

4.8 Discussion

An evaluation of hDTM accuracy brings to attention to some important shortcomings of photogrammetric modeling with historic aerial imagery. First, model accuracy is severely compromised when only two images contribute to terrain geometry. When three or more photos overlap, the terrain quality is dramatically improved. Unfortunately, most aerial imagery available from USGS follow stereoscopic photo standards of 60% overlap across each flight path. Therefore, most historic aerial collections will contain large areas with overlap of only two frames. However, even with significant overlap from multiple images, the terrain is still
Figure 16. Time series of aerial imagery (a-c), elevation (d-f), and modeled terrain changes (g-i) within the vicinity of archaeological site 41VV754.
susceptible to undulations and rippling effects that must be corrected for. The undulations are most likely caused by a combination of factors. First, the quality of the aerial imagery was compromised when it was archived to microfilm and then later digitally scanned. Also, the necessary step of image pre-processing could have caused the focal length value to be applied to the image frame slightly incorrectly. These image quality issues described above materialize as parallel rippling effects because linear flight paths capture imagery in a consistent and parallel manner. Awareness of these potential modeling issues is important when one is trying to use digital copies of historic aerial imagery for photogrammetric modeling. Depending on the intended use of the derived data, low photo overlap or rippling effects could compromise the integrity of the model beyond its utility. Such being the case with this project, only areas with more than two overlapping photos produced useable terrain models—and only after post-processing was able to remove the rippling effects.

After producing the elevation change rate models and comparing them to the six representative sites described above, it is clear that the use of photogrammetry to evaluate historic terrain change is a complicated matter. While many of the site descriptions matched what the elevation change rate models portrayed, two sites revealed scenarios where the models produced unreliable results. First, horizontal offset is suspected to have caused inaccuracies along the steep canyon rims, as could be seen at site 41VV602. Second, the 1971 hDTM contained a considerable amount of noise and produced some extreme elevation change rate values. Noise was most notable across specific stratigraphic zones that have lighter colored ground surfaces. The selective way that the 1971 hDTM misrepresented lighter colored ground surface was especially apparent at site 41VV541 and two possible causes are proposed. First,
the digital images could have undergone overzealous histogram grayscale enhancement that diminished the visibility of surface features. A second possibility is that the mineral composition of lighter stratigraphic layers, predominantly limestone, resulted in overwhelming light reflectivity that was captured by the aerial camera in an overexposed manner. Atmospheric conditions, the sun's position on the horizon, or even camera settings could have caused poor capture of exposed limestone surfaces during the collection of 1971 imagery.

Despite the shortcomings of historic aerial collections, it is encouraging to see that many of the site records from across the project area described terrain characteristics that were also observed in the elevation change rate models. With careful consideration of data quality vulnerabilities, it is plausible that historic terrain modeling using photogrammetry could be a valuable tool in cultural resources management. The creation and comparison of hDTMs can contribute to a temporal understanding of terrain dynamics that could be impacting the integrity of archaeological sites.
5.1 Sample Selection

Although this research’s primary focus was to model elevation changes that have occurred in the past, statistical exploration of terrain characteristics might reveal topographic dynamics that may occur in the future. Due to the inconsistent levels of error and noise between the historic digital terrain models (hDTMs), the objective of statistical exploration was not to measure or predict exact elevation changes but rather to gain a general understanding of environmental factors that might be indicative of dynamic topography in this particular area. If certain environmental factors could be identified as strong indicators of significant terrain change, GIS modeling of these factors could be incredibly useful in locating zones that are at high risk for disturbance or destruction of archaeological sites.

The statistical sample was selected using the following criteria. First, a grid of fifty-meter evenly spaced points were created across the project area. Second, the grid of sample points were clipped to the area of reduced noise for both hDTMs (refer to Figure 7). Third, points were removed that had conflicting results between the 1950 to 2011 and 1971 to 2011 elevation change rate models. To identify sample points with conflicting change rate values, the models were reclassified into three categories. Erosion areas were classified by values below -1 centimeters (cm) a year, static areas were classified by values between -1 and 1 cm a year, and depositional areas were classified by values greater than 1 cm a year. If the classifications matched between 1950 to 2011 and 1970 to 2011 models, the point was retained for sample use. If classifications conflicted, the point was removed from the sample. Finally, to reduce the
effects of horizontal offset from the statistical results, points that were within fifty meters of the canyon embankment crest were removed. The canyon embankment crest was calculated from the mDTM’s elevation value of 351.2 meters, which is the official threshold published by NPS (National Park Service, 2014). The final sample size was n=4341 and a variety of environmental variables were collected at these sample locations from both 1950 and 1971 hDTMs for statistical exploration. Environmental variables were also calculated from the 2011 mDTM to compare against the elevation change rate models. The statistical exploration included mDTM derived values because some of the environmental variables are very susceptible to noise that is known to be present in the hDTMs. By comparing the elevation change rate values against both hDTM and mDTM variables, it will be easier to evaluate if noise obscured any results.

5.2 Environmental Variables

A variety of ground surface characteristics can be computed from a DTM through GIS geoprocessing tools. The following variables were calculated and evaluated for their correlation to topographic change:

- **Elevation**: The basic value of any DTM, measured in meters above mean sea level (amsl)
- **Slope**: measured in degrees
- **Aspect**: categorized by cardinal directions including intermediate intervals (North, Northeast, East, Southeast, etc.)
- **Solar Radiation**: measured in watt hours per square meter (WH/m²) per year.
- **Flow Accumulation**: calculation of accumulated flow to each cell in a downhill direction. Values are relative to the project area and resolution of the DTM, where each cell contributes a value of one (1).
- **Curvature**: expressed in one hundredth (1/100) of the DTM’s z-unit, which equates to
centimeters. Positive values indicate a convex upward curve, negative values indicate a concave upward curve.

- **Profile Curvature:** measured along the direction of the maximum slope and expressed in centimeters. Negative values indicate a convex upward curve, positive values indicate a concave upward curve.

- **Plan Curvature:** measured perpendicular to the direction of the maximum slope and expressed in centimeters. Positive values indicate a convex upward curve, negative values indicate a concave upward curve.

5.3 Results

The variables were evaluated individually for their correlation with elevation change rate. Elevation (Figure 17) appears to have a slightly positive linear correlation with elevation change rate. This would suggest that higher elevations are more likely to accumulate sediment while lower elevations are more likely to be experiencing erosion. This is counter intuitive, since sediments would fall downhill away from higher elevations. If a second-order polynomial trendline is fitted to the data instead of a linear one, the model appears to make more sense; sediment accumulation at high elevation values is no longer indicated. The polynomial trendline suggests that the terrain was most stable above 390 meters above mean sea level and becomes more susceptible to erosion as elevation decreases below this threshold.

A scatter plot of slope against elevation rate change (Figure 18) demonstrated a very weak relationship for both hDTM and mDTM values, suggesting that one is not indicative of the other. A similar conclusion can be made when reviewing the boxplots for aspect (Figure 19). All boxes from hDTM and mDTM values broadly straddle the elevation change rate of zero and there is an overwhelming number of outliers, rendering interpretation of the results
Figure 17. Comparative scatter plots modeling elevation against elevation change rates. Note that despite the very weak correlation, the general trend between the noisy hDTM and accurate mDTM values are very similar.
Figure 18. Comparative scatter plots modeling slope against elevation change rates. Note the negligible correlation strength between these variables that only slightly improves with the mDTM values.
Figure 19. Box plots modeling aspect against elevation change rates. The median elevation change rate is slightly lower for south-facing directions and higher for north-facing directions. However, the long whisker length and high number of outliers suggests that aspect is not a reliable indicator of elevation change.
inconclusive. Solar radiation was perhaps the most unreliable variable in determining elevation rate change (Figure 20). When compared to values derived from the hDTM, the scatter plot shows a very slight, almost negligible negative correlation. In fact, the correlation is so weak that it reverses from negative to positive when compared to mDTM values. Flow accumulation shows a more promising, albeit still weak, relationship with elevation change rate (Figure 21). As flow accumulation increased, the risk for erosion also increased. However, it should be noted that flow accumulation values were not indicative of sediment accumulation, only sediment removal. The scatterplot trendlines never reach an elevation change rate above zero centimeters per year.

The most promising environmental variables with the strongest correlations to terrain change were related to curvature (Figures 22–24). While elevation change rate did not appear to have a discernible relationship with values from the hDTM, the correlation strength dramatically improved when compared to values from the mDTM. This is not surprising because curvature values would have been distorted by the inherent noise in the hDTMs. Therefore, it is understandable that correlation strength would improve when the more accurate terrain model was the source for curvature values.

After a review of the data, it is clear that the statistical exploration was only able to partially reveal the environmental factors contributing to dynamic terrain. These findings are consistent with those observed by Jetten et al. (2003) who noted that modeling erosion is extremely difficult—especially small erosion events. The authors also note that severe or localized precipitation events can have dramatic impacts on erosion patterns, many of which cannot be reliably modeled. To summarize, additional environmental parameters that were not
Figure 20. Comparative scatter plots modeling solar radiation against elevation change rates. Note that the negligible correlation reverses between the hDTM and mDTM solar radiation values.
Figure 21. Comparative scatter plots modeling flow accumulation against elevation change rates. Note that despite the weak correlation, the general trend between the noisy hDTM and accurate mDTM calculations are very similar.
Figure 22. Comparative scatter plots modeling overall curvature against elevation change rates. Note that the correlation strength improves significantly against the curvature values from the mDTM.
Figure 23. Comparative scatter plots modeling profile curvature against elevation change rates. Note that the negative correlation increases in strength and severity when curvature is compared to the mDTM instead of the hDTMs.
Figure 24. Comparative scatter plots modeling plan curvature against elevation change rates. Note that both the trend and correlation strength increase when curvature is compared to the mDTM instead of the hDTMs.
considered in this study are likely at play. Also, it is possible that the level of error within the hDTMs may have resulted in an underestimation of the explanatory power of the factors that were examined.

5.4 Discussion

A review of the data has found that the terrain characteristics derived from the hDTMs are not very strong indicators of dynamic topography. Curvature—overall, plan, and profile—proved to be the strongest indicator, but only when compared with mDTM variables. The environmental factor with the second strongest correlation was elevation. While it is hard to conceive how elevation could be an indicator of terrain change, the relationship with this variable could be suggestive of another factor that was not included in this study.

Aerial imagery of the project area reveals that there are a series of different stratigraphic layers exposed across the ground surface. It is very likely that these stratigraphic layers will react to environmental variables in different ways, such as the ability to erode or trap sediments at different rates. The U.S. Geological Survey publishes geology data at a state-level scale and soils data at a county-level scale (National Resources Conservation Service, 2013; Stoeser et al., 2007). Unfortunately, the stratigraphy of the project area is not captured in sufficient detail in either dataset. Before geology or soil data could be included in future analyses, a detailed large-scale feature class of the local formations would first have to be mapped. Unfortunately, such a feat is beyond the scope of this project. However, it is important to note that certain geologic features and soil properties could be more abundant in particular elevation zones, potentially influencing the correlation between elevation and its change rate.
The third most indicative variable of erosion was flow accumulation. The negative correlation between flow accumulation and elevation change rate increased in strength and severity with the values derived from the mDTM. However, the overall trend was similar and generally weak across all samples. The remaining environmental variables proved to have little or no correlation with elevation change rate. An overall review of the results shows that while some environmental variables such as curvature have proven to be a possible indicator of dynamic topography, it appears that a number of other contributing factors have alluded this study.
CHAPTER 6
CONCLUSIONS

6.1 Implications

Hydrological processes combined with historic land use have been responsible for a variety of changes across the project area’s landscape. A review of the archaeological site records reveal that the most destructive process contributing to the loss and damage of archaeological sites is erosion. In contrast, archaeological sites in depositional zones were usually found more intact than those found on exposed surfaces. It is important to note that most archaeological surveys conducted within the project area were pedestrian surveys. Even sites that were found in depositional zones were only located because portions of the buried sites were exposed from partial erosion or isolated gulleys. While it is common sense that pedestrian surveys will only be able to locate sites that are visible on the surface, site records revealed that such a survey method will also be biased towards sites that have been damaged by erosion. Sites that remained buried were usually described as intact or mostly intact. Therefore, for cultural resources managers who are most concerned with prioritizing conservation efforts, it could be argued that pedestrian surveys would be a sufficient survey method for locating sites at high risk for damage. On the contrary, if one wants to find intact archaeological sites with high research potential, subsurface testing in static or depositional zones would be a more appropriate, albeit a more expensive, survey strategy.

Despite the challenges that were faced while producing historic digital terrain models (hDTMs) from historic aerial imagery, a lot can be said about the feasibility of using photography as an affordable means of modeling terrain in high detail. The use of modern digital
photography would resolve most of the data quality issues that arose in this project. First, detailed lens specifications are available for most modern cameras. Photogrammetry software using SfM techniques will have very precise measurements to generate a scene's relative geometry. Second, the images will be natively digital—error will not be introduced by digital scanning or manual frame adjustments. Lastly, advancements in technology have developed a variety of low cost ways to acquire low-altitude aerial imagery. Small cameras mounted on poles, kites, and even unmanned aircraft systems (UAS) can collect large amounts of imagery data in short time frames. These new techniques of remote photo capture can be customized to meet particular project needs. Photo overlap can be increased and pictures can be taken from a variety of scales and angles for more complete terrain coverage. Even steep canyons with limited line-of-sight visibility could be fully captured in high detail. In recent years, the Federal Aviation Administration (FAA) has been revising the laws and regulations for the use of UAS in commercial and public sectors (Federal Aviation Administration, 2015). As long as current FAA mandated rules are followed and the correct permits are acquired, UAS could prove to be a promising new tool in monitoring resources that are located across vast and remote government-held lands. If low-altitude aerial images were captured at regular time intervals, terrain changes from either hydrological processes or modern disturbances could be modeled and monitored at high temporal and spatial resolutions at a relatively low cost. Such detailed modeling could then be utilized in a number of ways—whether it be for conservation, research, education, or even tourism.
6.2 Closing Remarks

It is the responsibility of cultural resources managers to preserve the material evidence of our common human heritage. Unfortunately, limited budgets, ever-growing databases, and vast expanses of rugged wilderness make their tasks difficult to achieve. The purpose of this project was to develop and assess a new methodology that could assist resource managers in prioritizing archaeological sites that are in most critical need for monitoring or conservation. The new methodology consisted of using historic aerial imagery collections to produce a series of hDTMs. The hDTMs provided a temporal dimension to terrain modeling and were used in a GIS framework to identify dynamic topography that was putting the integrity of archaeological sites at risk. Archaeological site records from the THC were reviewed to verify if the hDTMs and elevation change rate models accurately depicted what was observed in the field. Although the historic imagery posed some unique challenges that impacted the accuracy of the models, the methodology was able to overcome many data quality hurdles through GIS post-processing. The elevation change rate models derived from the hDTMs were still able to provide usable insight about the history of Lower Pecos terrain dynamics. Lastly, statistical exploration revealed that environmental variables derived from the DTMs were poor indicators of the effects of hydrological processes. Despite the difficulty in predicting how the terrain will fluctuate in the future, advancements in photographic technologies and low-altitude remote sensing techniques will allow for more affordable and precise data collection. As new data is collected in the future, the methodology developed by this project will improve in accuracy, be highly versatile, and will be applicable to other arid parts of the world with resource management needs.
REFERENCES


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