IMPACTS OF BRIDGE DESIGN AND LAND COVER CHARACTERISTICS ON CLIFF SWALLOW NESTING

by

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ABSTRACT

The Texas Department of Transportation (TXDOT) and the Texas Commission on Environmental Quality (TCEQ) were concerned with the possible contamination of water resources resulting from animals roosting on bridges, particularly, from Cliff Swallows (The Texas Department of Transportation, 2012). Considering there are approximately fifty thousand bridges currently in Texas, these potential contamination sources could be an environmental problem. These bridges can offer thousands of potential nesting sites to Cliff Swallow colonies, which vary in size from 2 to 3700 nests (Brown & Brown, 2004). An assessment of 108 bridges was made to develop a model for predicting total Cliff Swallow nest density based on bridge characteristics and geographical information systems (GIS) land cover and soil data. Backwards step-wise regressions were run and then evaluated based on Akaike's Information Criteria adjusted for small sample sizes (AIC_c) to determine the best model for analysis. This model indicated the number of nest scars, twenty-five degree bridge skew, average sand and silt percentages within the bridge surroundings, the number of spans, span length, and the percentage of water within the bridge surroundings is positively correlated with Cliff Swallow nest density, while bridge length, bridge orientation, fifteen degree bridge skew, bridge design, percentage of developed open land within the bridge surroundings, and percentage of shrubs within the bridge surroundings have a negative correlation.

CHAPTER 1

Introduction

1.1 Background

There are eight different types of swallows that breed in North America. Prior to the introduction of man-made structures, the original nesting sites of Cliff Swallows consisted of primarily cliffs and canyon walls. However, as the quantity of man-made infrastructure has increased, so did the nesting sites of Cliff Swallows. Buildings, bridges, overpasses, irrigation channels, and canals are just a few of the man-made structures where Cliff Swallows have nested (Gorenzel & Salmon, 1982).

1.2 Research Motivations

Cliff Swallows cannot be disturbed during their breeding season due to being protected under the Migratory Bird Treaty Act of 1918. Because of this, construction, maintenance, and repairs become difficult on bridges where Cliff Swallows nest. (Coates, Delwiche, Gorenzel, & Salmon, 2012) As per request from the Texas Department of Transportation (TXDOT) and the Texas Commission on Environmental Quality (TCEQ), an initial assessment of at least sixty bridges was conducted to develop a model for determining the relationship between bridge design, surrounding land characteristics, and Cliff Swallow nesting. After the second nesting season, the total number of bridges sampled grew to one hundred and eight to increase the data set for the model. This information of the birds' nesting behavior was sought to predict the types of bridges and composition of surrounding areas that attract Cliff Swallows. Bridge designers could use this understanding to help reduce or promote Cliff Swallow nesting, whichever is preferred.

1.3 Objectives and Scope

The primary objective of this research was to develop a model that predicts the likelihood of Cliff Swallows nesting on a bridge by correlating the observed number of Cliff Swallow nests with structural characteristics, bridge orientation, soil type, and land cover around a bridge site. Cliff Swallows migrate throughout North America in areas where elevations range from sea level to about 3000 meters (Grinnell & Miller, 1944). The scope of this study, however, focused on seven counties in Central Texas. The studied counties were Hays, Comal, Guadalupe, Kendall, Blanco, Caldwell, and Travis County, encompassing a total area of 4,916 square kilometers (1898.07 square miles) as illustrated in Figure 1-1.

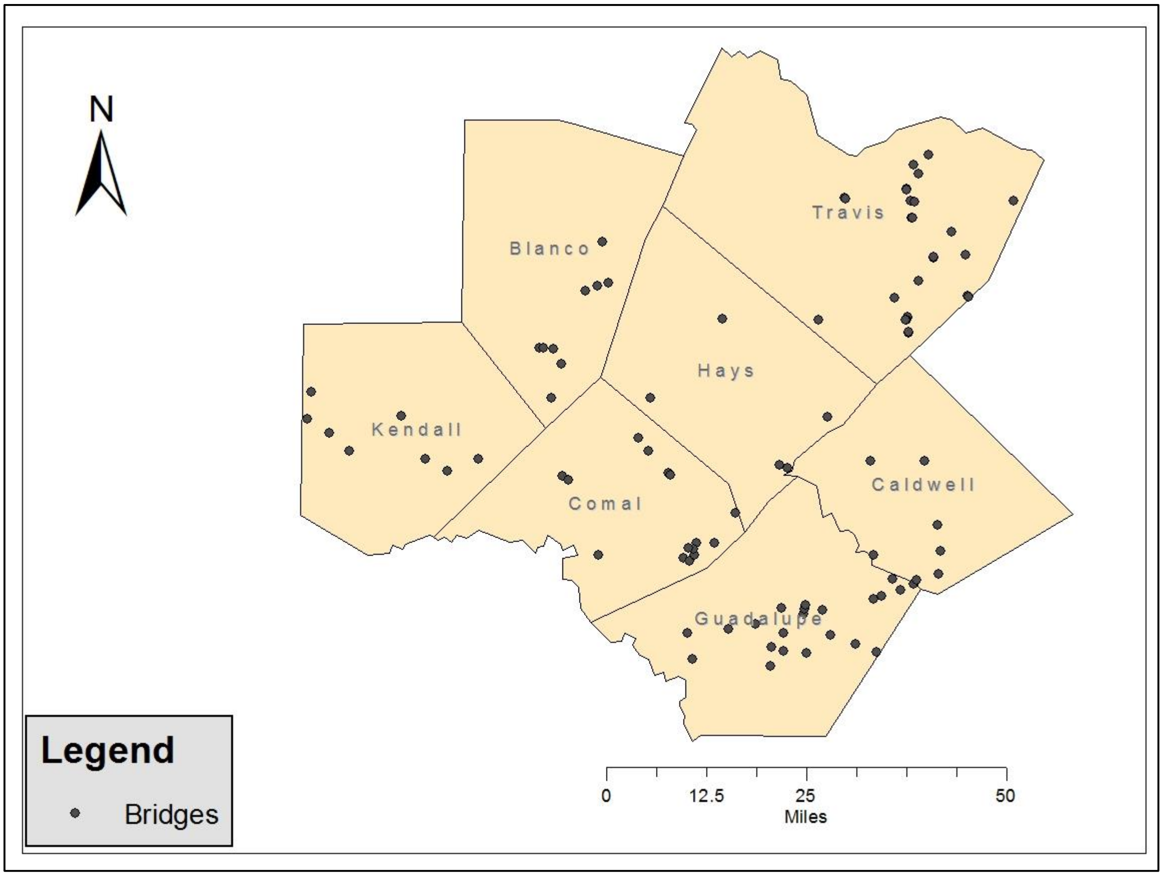

Figure 1-1: A map displaying the counties and location of bridges sampled in the study

1.4 Organization

After this introduction, which makes up chapter 1, chapter 2 will provide a detailed background on Cliff Swallows, a discussion of other bridge roosting animals, a bridge design guide, and a guide to geographical information systems (GIS) land cover and soil data. Chapter 3 entails the procedure, which covers bridge selection, data collection, GIS data pre-processing, and the analysis. Chapters 4 and 5 cover the discussion of results and conclusions, respectively.

CHAPTER 2

Detailed Background

2.1 The Cliff Swallow

2.1.1 Physical Appearance and Range

The only square tailed swallow in North America, the Cliff Swallow, about 13 to 15 centimeters in length, and weighing approximately 20 to 28 grams, is easily recognized by it's triangular white forehead patch, dark orange colored throat, orange-brown rump, and steel-blue crown and back. (Gorenzel & Salmon, 1982; Brown & Brown, 1996). The difference between males and females is the presence of a brood patch, as well as the large dark blue patch at the base of the males throat (Brown & Brown, 1995) A detailed illustration of a Cliff Swallow can be seen in Figure 2-1 (The Cornell Lab of Ornithology, 2014).

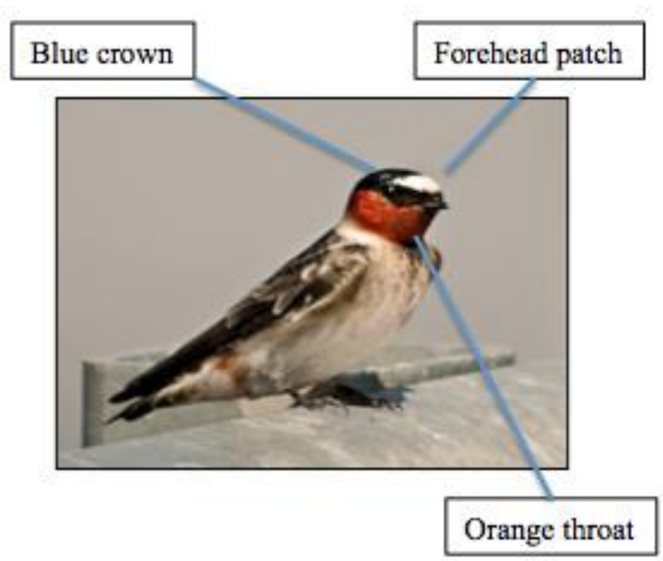

Figure 2-1: Illustration of a Cliff Swallow

The Cliff Swallow ranges from southern Alaska to Central Mexico as illustrated in Figure 2-2 (American Ornithologists' Union, 1983), during it's breeding season. This season begins as early as March in Central Texas, and typically ends late July or August (Brown & Brown, 1996; Brown & Brown, 2004).

Figure 2-2: Breeding range of the Cliff Swallow in North America

2.1.2 Nesting habits

In the past Cliff Swallows were more concentrated in the western mountains based on their nesting preferences for cliffs and canyon walls. The swallows have spread all across North America due to the almost endless potential nesting sites on man-made structures. Buildings, bridges, overpasses, and canal walls are just some of the artificial nesting sites created by man that are used by the Cliff Swallow (Erskine, 1979).

2.1.3 Nest Construction Materials

In a study conducted by Harrison (1975), a series of colonies were observed with an average of fifteen nests per colony, including one colony totaling over eight hundred nests. Although this colony seems to be a very large, Brown (1988) performed a sizeable study that showed a range of 2 to 3000 nests nesting colonies with a mean of 323.6 nests. Later, an even larger study that lasted over twenty years revealed a range of 2 to 3700 nests in the observed nesting colonies with an average of 326.6 nests (Brown & Brown, 2004), which is consistent with earlier findings. There are a number of determinants for the presence of a Cliff Swallow nesting colony, but Brown and Brown (2002) hypothesized that the two most likely factors are an area to build nests and the availability of food within the foraging range from the colony. Emlen (1954) proposed that an open space for foraging, a structure with an overhang to attach nests, and a supply of mud are the prime determinants of a Cliff Swallow colony.

A crucial feature for a Cliff Swallow habitat is a supply of mud that is suitable for building a nest. Cliff Swallows build gourd shaped nests with a tubular entrance tunnel out of mud and clay (Emlen, 1954). These nests contain an average of 900 to 1200 mud pellets (Harrison, 1975). Emlen (1954) states that nests are constructed at about two and a half centimeters per day; taking approximately one to two weeks to complete. Therefore, the nests are built close together, usually sharing walls (Brown & Brown, 2004), with the first nests built at the highest point possible of a structure, while succeeding ones are attached below other nests (Gorenzel & Salmon, 1982) as shown in Figure 2-3 (Cliff Swallow nests, 1972).

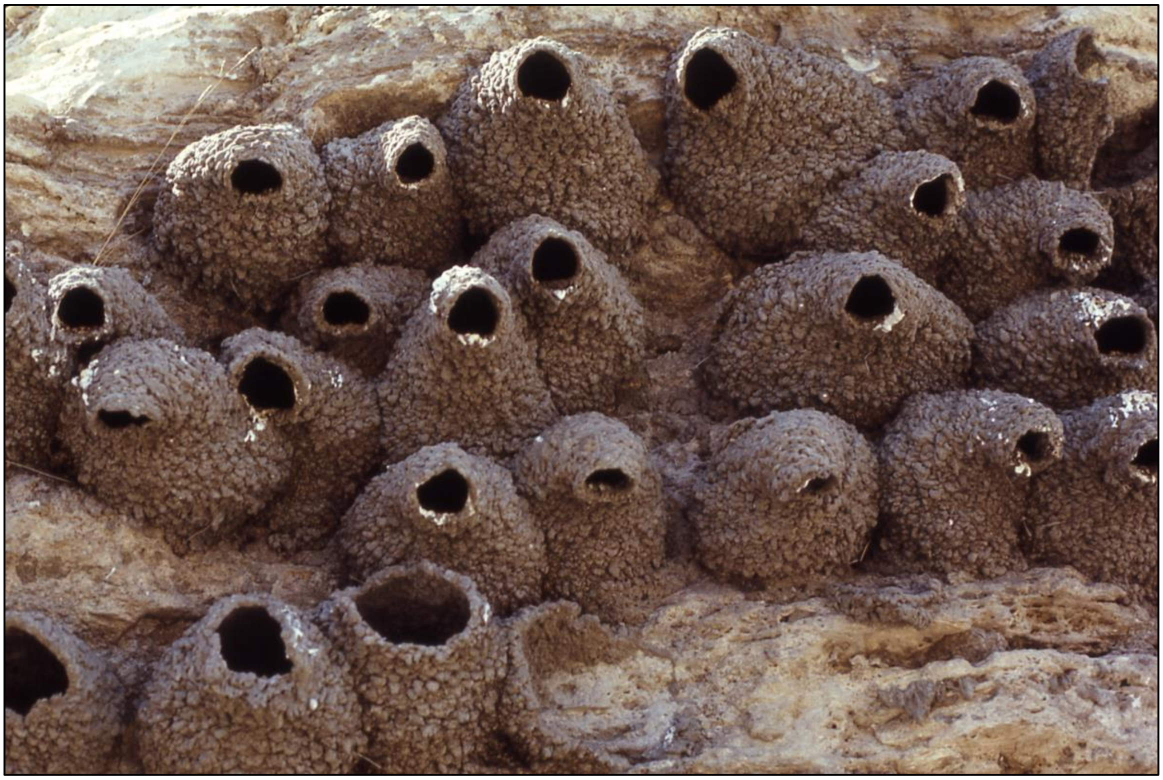
Figure 2-3: Illustration of multiple Cliff Swallow nests on a rock face

Various mud types exist throughout different nests within a single colony, and even throughout different colonies, meaning that multiple mud sources are used when constructing nests (Emlen, 1954). Kilgore and Knudsen (1977) performed an extensive breakdown on the textural components of the soil for mud nests of Cliff Swallows as shown in Table 2-1.

Table 2-1: Cliff Swallow nest soil texture distribution

Sand	Silt	Clay
61.4 % ± 0.8%	25.7 % ± 0.9 %	12.7 % ± 0.7 %

It is also believed that not only the type of the soil but also the moisture content could affect mud choice since too dry of a soil could cause a nest to crumble, and too wet of a soil could cause the mud not to stick to the structural surface (Winkler & Sheldon, 1993). The mud pellets for nest construction are carried in the Cliff Swallows beaks from a mud source that can range from 6 to 805 meters from the nesting site (Emlen, 1954). Brown and Rannala (1995) found that Cliff Swallows used a mud source within a half-kilometer radius while Brown and Brown (1996) found that the length traveled for mud increased with colony size. Cliff Swallows in the smallest colonies traveled only one meter to gather mud (Brown & Brown, 1996). With this information, Brown and Brown (1996) believed that the availability of mud could affect colony size. With soil being the prime component in nest construction, and also a possible reason for site selection, the physical aspects of the soils in the area of study were included as part of the analysis of the present study.

2.1.4 Foraging

A lack of food could make a nesting site unacceptable to the Cliff Swallow (Brown & Brown, 1996). Therefore, by knowing what Cliff Swallows eat and where that prey thrives, a prediction of where Cliff Swallows might roost based upon their food source could be made. The problem with measuring food availability for colonial animals is that their habitat size and prey diversity is so immense that it becomes impossible to quantify (Brown & Brown, 1996; Hunt & Schneider, 1987). A better method of calculating food availability could be to correlate the foraging habitats with colony size (Gibbs, Woodward, Hunter, & Hutchinson, 1987).

Brown and Brown (1996) observed in one of their studies that the longest distance traveled for foraging was 0.65 kilometers from the nesting site. They state that foraging range increases with colony size but Cliff Swallows are rarely seen foraging further than one kilometer from the nesting site, therefore, land use patterns affecting food availability within the one kilometer range of a nesting site could affect colony size. Brown and Brown (1996) found that large expanses of water reduce the suitable foraging area for a Cliff Swallow because these birds tend to only forage over water during severe weather conditions. When the weather is acceptable they prefer to forage over fields and grasslands, which emit high thermal levels that attract insects (Emlen, 1954). Emlen (1954) observed that wooded areas were typically avoided when foraging but low sage-covered hills were frequently crossed and used to forage. Emlen (1954) also saw that open water did not act as a barrier for Cliff Swallows and that they were seen foraging over lake shores. Other studies show that developed land reduced Cliff Swallow nesting (Coates et al., 2012) and that the abundance of agriculture in the Sacramento Valley increased nesting (Mayhew, 1958).

There are many different land use types, which vary amongst geographic location that can impact Cliff Swallow nesting in many different ways. Brown and Brown (2002) performed an extensive study on habitat type and land use diversity within the foraging ranges of Cliff Swallows. For their study they used the Simpsons Index, which measures the diversity of land use, and eight different habitat types. With these variables they performed a multiple linear regression, which showed that the only significant predictor of mean colony size was the amount of flowing and standing water, where flowing water pertained to rivers and streams, and standing water pertained to lakes and ponds. When performing univariate tests, or tests on one variable at a time, they found that crop land had a negative effect on colony size, while grassland, marsh, bare earth, or trees had no effect on colony size. The Simpson's Index showed that foraging ranges with lower Simpson's Indices, or greater land use diversity, had larger colony sizes and also greater nest site repeatability.

The surrounding habitat has also had an impact on other foraging animals. For instance, heron colony size varied based on the amount of wetlands within their foraging ranges (Gibbs et al., 1987) and rooks' colony size with the amount of meadow and pasture land (Griffin & Thomas, 2000). Based upon these previous studies, land cover type within half kilometer and one kilometer radii was analyzed in this study.

2.1.5 Bridge Characteristics

2.1.5.1 Overhang

Another factor that comes into play with Cliff Swallow nesting is the structure to which they are attaching their nests. Gorenzel and Salmon (1982) mention the importance of an overhang for Cliff Swallow nesting. They claim that overhangs with acute and right angles are potential nesting sites but overhangs that have obtuse angles, or are rounded and concave in shape are rarely used. Examples of angles can be seen in Figure 2-4. The critical point of overhang length is unknown but colonies are scarcely seen nesting on overhangs less than fifteen to twenty centimeters (six to eight inches) in length (Gorenzel & Salmon, 1982). This study therefore, will include overhang length as a variable.

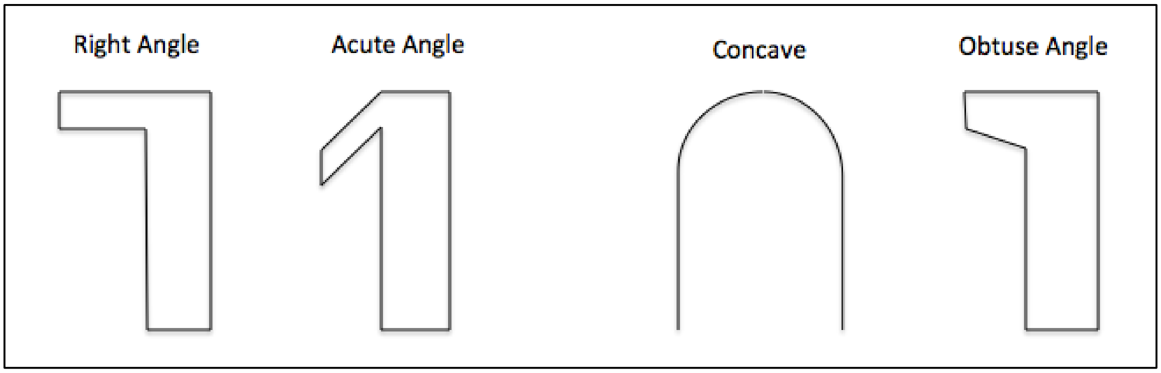

Figure 2-4: Illustration of potential nesting site angles and girder shapes

2.1.5.2 Material and Design

Another feature of the nesting site is the texture and material composition of the surface where nest construction takes place. In Texas, the primary material for bridge construction is concrete, with steel as the second most common material. Gorenzel and Salmon (1982) found that bridges constructed of steel are seldom used for nesting. Brown and Brown (1996) mention in their study that Cliff Swallows mostly use concrete bridges and very rarely use wooden bridges. As seen in Table 2-2, bridges with concrete drop caps or concrete girders had a larger percentage of nests than sites with flat slab and I-beam superstructure.

Table 2-2: Cliff Swallow occupancy from a study by Brown and Brown (1996) based on bridge superstructure

Design Type	Number of Bridges in Study	Percent Occupied
Flat Slab	137	22%
Concrete Drop Cap	25	52%
Concrete Girders	30	67%
Steel I-Beam	14	36%

2.1.5.3 Bridge length

When looking at a large dataset of bridges, some will be longer than others. While one might assume there would be more Cliff Swallows nesting on longer bridges than shorter ones as there are more nesting sites available, this scenario is not supported by literature. Brown and Brown (1996) observed that the three longest bridges in their study had small to medium colony sizes in comparison to the other colonies in the study. They reported that some long bridges had small colonies and some short bridges had large colonies. For each bridge in this study the length and width will be recorded to look for nesting trends and to determine nesting density.

2.1.5.4 Openness

Another characteristic of a nesting site is its openness. Cliff Swallows need enough open space that allows for flight in and out of the nesting area for the transportation of mud and food. For example, when Cliff Swallows nest in culverts the chosen sites are typically free of vegetation or trees (Brown & Brown, 1996). Part of the openness of a bridge relates to the height of the bridge, specifically how much space there is between the undersurface of a bridge and the ground. Brown and Brown (1996) reported that although most nesting sites are on bridges that span a waterway, there are also nesting sites over dry land, canyons, or highways and that the minimum height of culverts used by Cliff Swallows was two meters. Further, Emlen (1954) says that low sites without an overhang have no appeal to Cliff Swallows. This study, therefore, considers height and openness as variables.

2.1.5.5 Orientation

An additional factor in nesting choice for the Cliff Swallow is exposure to the sun. The amount of sunlight received at a bridge site relates to the orientation of the bridge. Selander and Baker (1957) reported that Cave Swallows tend to nest within the twilight zones of caves and sinkholes of the Edward's Plateau. An observed Cliff Swallow colony on a barn showed that the initial nests were built on the East wall and then the North. Eventually nests appeared on the West side, but none were ever built on the South side of the barn. This pattern was believed to be due to the warmness felt in the morning from the sunrise and the coolness in the evening after the sun began to set (Myres, 1957). Each bridge's orientation will be measured in degrees from North in this study to consider orientation as a variable in the nesting model.

2.2 Bridge-Roosting Bats

Various man-made structures unintentionally serve as roosting sites for a number of species (Barbour & Davis, 1969; Davis & Cockrum, 1963; Sandel, Benatar, Burke, Walker, Lacher, & Honeycutt, 2001). Besides Cliff Swallows, one species in particular that takes advantage of man made structures for roosting are bats. Bats spend most of their lives in roosts (Kunz, 1982). Therefore, it is quite important for the roosts to meet the bats' expectations of an adequate living environment. As another bridge-roosting animal, bats were investigated through the literature to determine if there were any parallels or additional factors related to Cliff Swallows that could assist this research project.

2.2.1 Bridge Design Choice

Refinesque's Big-Eared bats choose artificial structures that resemble natural cave-like environments such as dark abandoned buildings, cisterns, wells, and highways

(Barbour & Davis, 1969; Clark, 1990; Lance, Hardcastle, Talley, & Leberg, 2001; Mirowsky, Horner, Maxky, Sinrrh, 2004; Trousdale & Beckett, 2002; Trousdale & Beckett, 2004; Ferrara & Leberg, 2005). Previous studies have shown that bats use bridges as day and night roosts (Hendricks, Lenard, Currier, & Johnson, 2005). Bat Conservation International surveyed 2241 highway structures over the southern and western United States and found over seventeen different bat species using bridges and culverts (Keeley & Tuttle, 1999). With so many various species of bats using bridges, it's no wonder that bridge construction is the most significant predictor of the Rafinesque's big-eared bat occupancy (Lance et al, 2001; McDonnel, 2001; Trousdale & Beckett, 2002). One study in particular showed that bats used concrete, steel, and wood bridges as night roosts and concrete and wood bridges as day roosts (Hendricks et al., 2005). This difference in roosting preference by time of day may be due to how hot a steel beam can get from the sun throughout the day. Numerous studies on bats nesting on bridges have shown that they typically prefer to nest on bridges with a supporting structure that contain beams and avoided flat slab bridges (Lance et al., 2001; Lewis, 1994; Hendricks et al., 2005; Bennet et al., 2008) because they provide fewer areas to attach and offer less protection from predators (Hendricks et al., 2005).

2.2.2 Roosting Location

Some factors that impact where a bat will roost are availability of food, level of predator threats, social factors, energetic limits, and roost availability (Kunz, 1982). These factors are similar to those of a Cliff Swallows' decision in nesting on a bridge. As previously mentioned, one important criterion for roost selection in bats is the level of predator threat. Predators can be avoided by roosting high enough above the ground (Hutchinson, J.T. & Lacki, M. J., 2001). Similarly to the cliff swallow, bats seem to have a minimum height to which they prefer to nest. Lewis (1994) found that bridge roosts ranged from 1.5 to 4 meters above the ground, while Geluso and Mink (2009) stated they observed bridge roosts as low as 1.1 meters from the ground. Various studies have documented different roost preferences for bats. Some show that bats prefer to roost in between girders underneath bridges but not in the tight expansion joints (Ferrara & Leberg, 2005; Bennet et al., 2008). In one study on bridge selection in Rafinesque's big-eared bats, it was documented that they preferred to nest over the dry banks on the ends of the bridges, near the abutments. Initially it was thought that the level of disturbance, length, width, and area of the bridge mostly influenced bat presence, but after a logistic regression, region, bridge type, and width were the best predictors of bat presence. Level of disturbance, which was measured on a scale of zero to three, was based on human activity, vandalism, footprints, and vehicle traffic, showed no significance in bat roost selection (Bennet, Loeb, Bunch, & Bowerman, 2008). In another study that observed steel I-beam, wooden, and cast in place concrete bridges, Adam and Hayes (2000) found that cast-in-place concrete bridges had the highest number of bats. They also observed that bridges with a greater surface area were used more frequently and assumed this was due to the increase in accessibility, protection from predators, and greater retention of the sun. Similarly to the cliff swallow, the bats in this study tended to roost at the joint where the girders meet the bridge’s undersurface. Bats usually roost in warmer areas of a bridge (Ferrara & Leberg, 2005). Lewis (1994) found that bats roosting on bridges selected open areas that allowed ease of flight around the roosting area but in a study in New Mexico, Geluso and Mink (2009) observed bats roosting between the beams of timber bridges with spacing between 1 and 150 mm, and rarely nested in open areas.

2.2.3 Land Cover Factors

In a study in south central Montana, land cover was observed in relation to highway bridge use by bats. The only significant land cover types were forest and open plains. No bats were observed on bridges in open plain areas but there was greater forest cover in roosted bridges. This pattern is believed to be due to a greater amount of prey for the bats and additional nesting choices throughout the woods (Hendricks et al., 2005)

2.2.4 Summary

As mentioned in the preceding sections, land cover, availability of food, bridge design, openness, and height affect bat roost site selection. These factors are also being considered as variables in this study.

2.3 Bridge Design Guide

The following section is a brief illustrated description of the various bridge design types included in this study. Each bridge description will include the most common locations for swallow nests for that bridge type.

2.3.1 Flat Slab

The bridge slab itself carries the loads to pier caps in lieu of bridge beams in a flat slab bridge. The pier caps distribute the collected loads to the bridge columns for vertical support. Cliff Swallows typically nest at the right angles that are formed where the pier caps meet the slab as seen in Figure 2-5 and Figure 2-6.

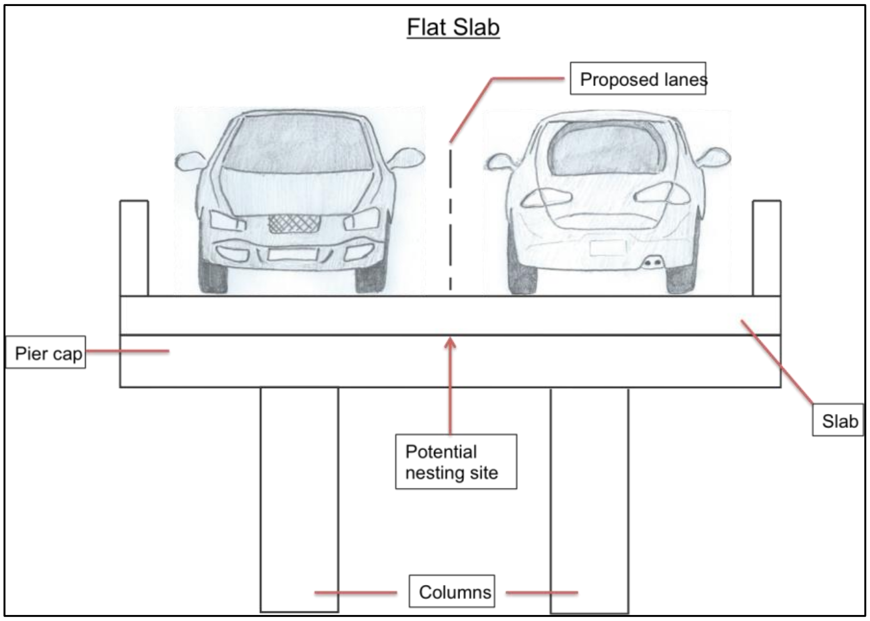

Figure 2-5: Cross-section view of a flat slab bridge design with potential nesting sites

Figure 2-6: Illustration of a concrete flat slab bridge design with Cliff Swallows nesting at the right angle formed where the pier meets the slab

2.3.2 Concrete Multi-Girder

A concrete multi-girder bridge is designed with a concrete deck on top of concrete I-girders that span between concrete pier caps. As was the case for the flat slab bridges, the pier caps distribute loads to the columns. A potential cliff swallow nesting site is where the girders create a right angle with the concrete deck as seen in Figure 2-7 and Figure 2-8.

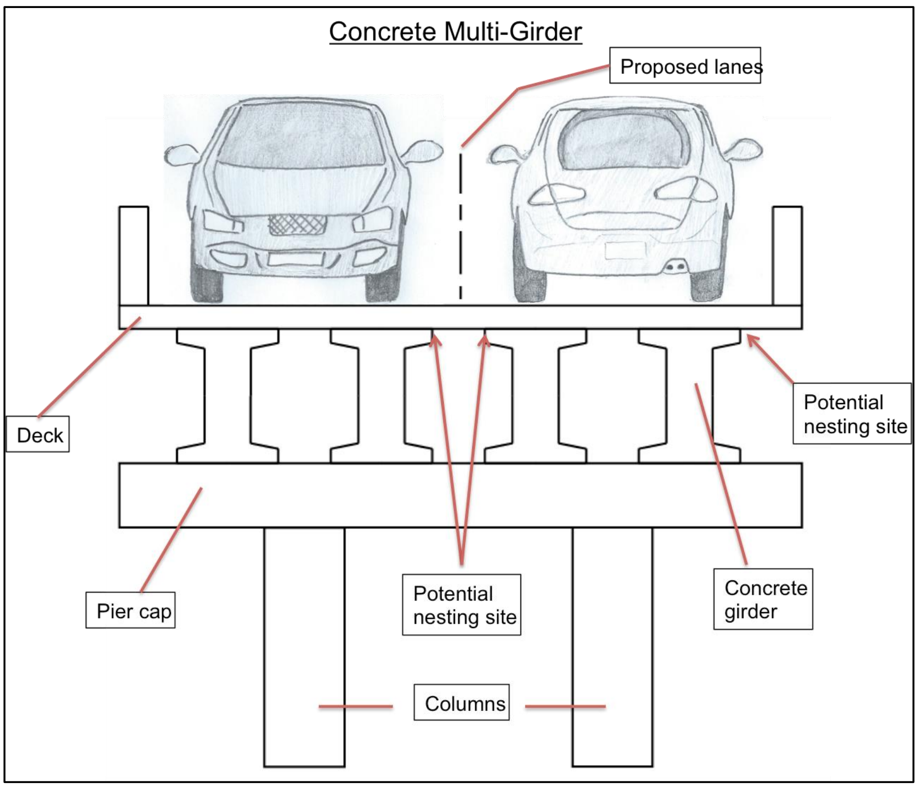

Figure 2-7: Cross-section view of a concrete multi-girder bridge with potential nesting sites

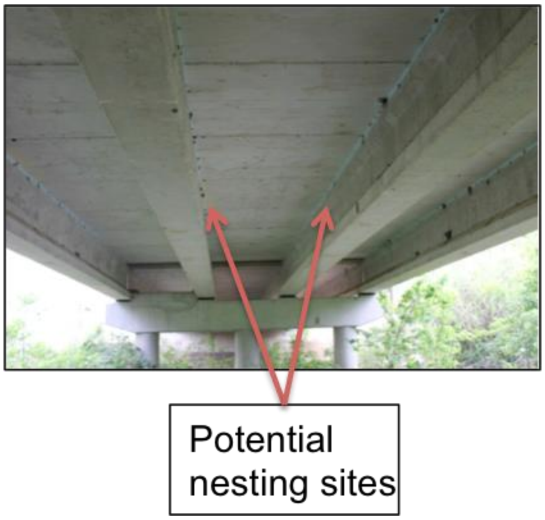

Figure 2-8: Illustration of a multi-girder concrete bridge design type

2.3.3 Pan Formed Girder

This bridge design consists of girders cast monolithically with the bridge deck. These girders span to pier caps that distribute bridge loads to the columns as shown in the cross section in Figure 2-9. The girder to deck joints in this bridge design are U-shaped. Therefore, the potential cliff swallow nesting site for this bridge type is where perpendicular walls abut the girders above the pier caps as shown in Figure 2-10. Figure 2-11 depicts an image of the underside of a pan formed girder bridge.

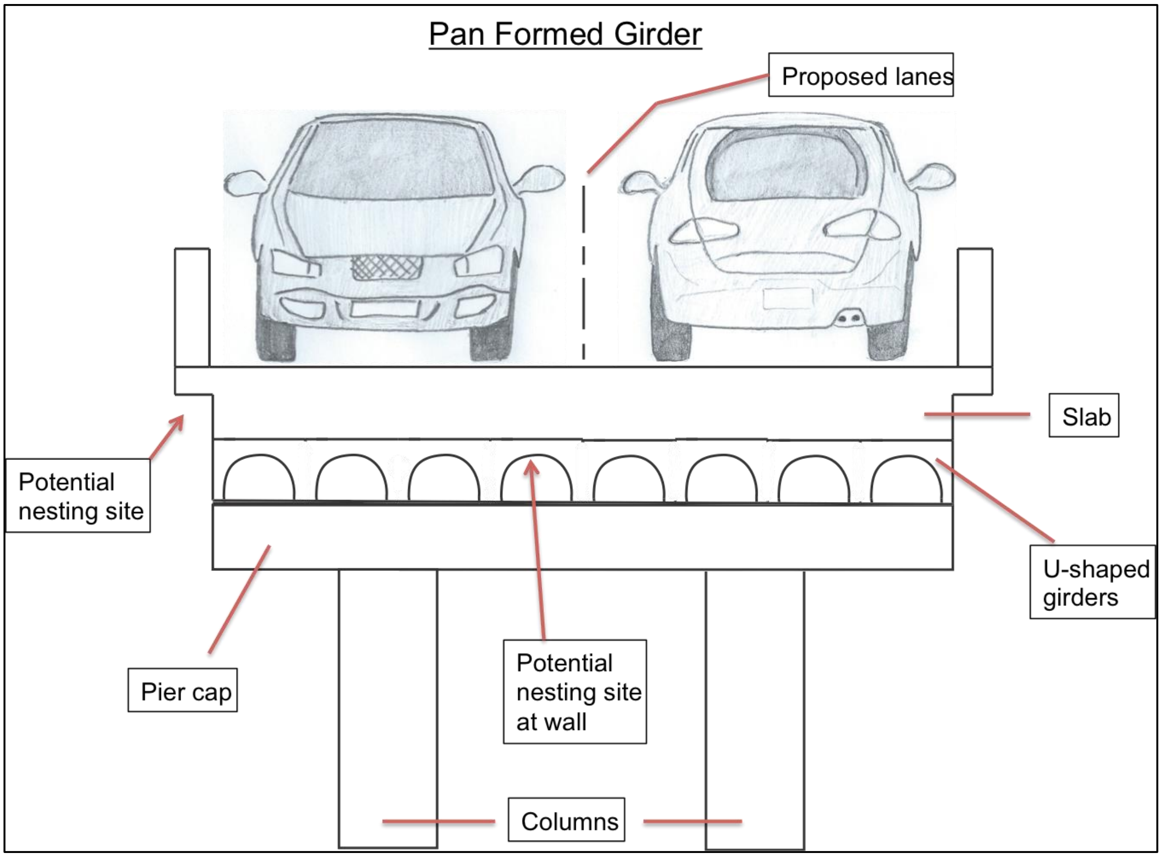

Figure 2-9: Cross-section view of a slab and girder pan formed bridge with potential nesting sites

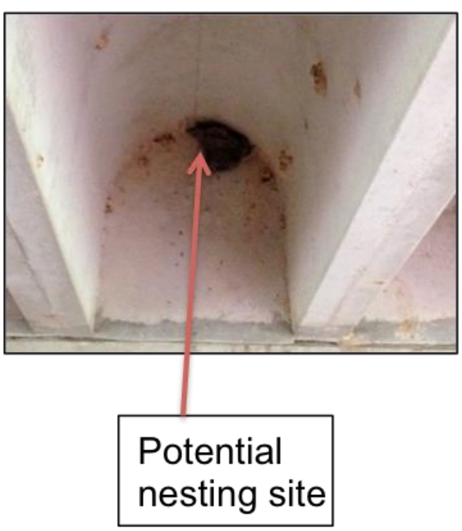

Figure 2-10: Close up illustration of a pan-formed girder abutting a wall

Figure 2-11: Illustration of a slab and girder pan-formed bridge design type

2.3.4 Girder T-beam

Girder T-beam bridges are constructed with a deck on top of a series of T-shaped beams that span between pier caps as shown in Figure 2-12. The pier caps, in turn, distribute the load to support columns. Potential nesting sites are where the T-beams form right angles with the bridge decking as seen in Figure 2-12 and Figure 2-13.

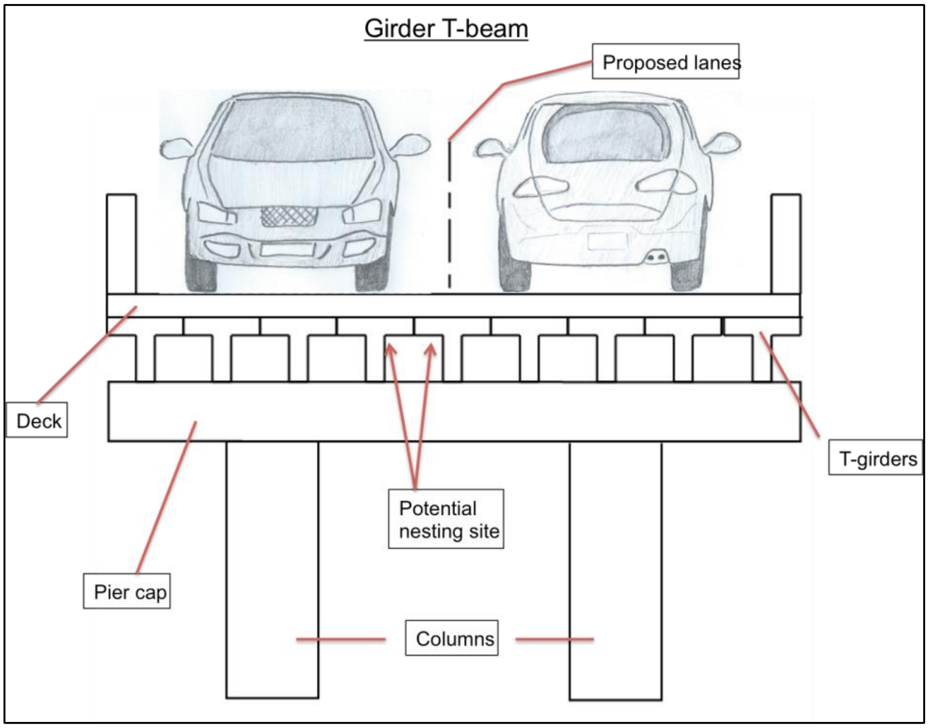

Figure 2-12: Cross-section of a girder T-beam bridge with potential nesting sites

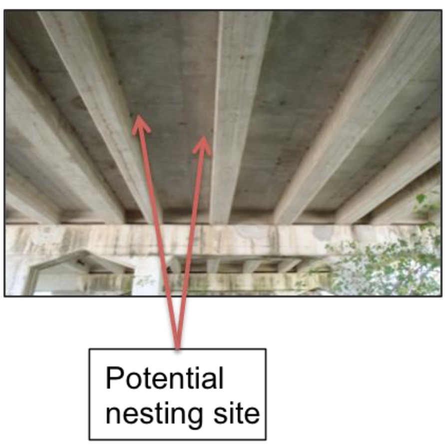

Figure 2-13: Illustration of a girder T-beam bridge design type with potential nesting sites

2.3.5 Concrete Box Beam Girder

Concrete box beam bridges are similar to all of the other girder-type bridges. The main difference is the shape of the girder is a relatively wide concrete rectangle. These girders have a small gap between each other that is too narrow for cliff swallow nesting as seen in Figure 2-14. Therefore, cliff swallow nesting is expected on the exterior of the girders when there is an overhang present or whenever the girders rest directly on a pier cap, forming a right angle. Figure 2-15 shows a cross section view of this bridge design type with potential cliff swallow nesting locations.

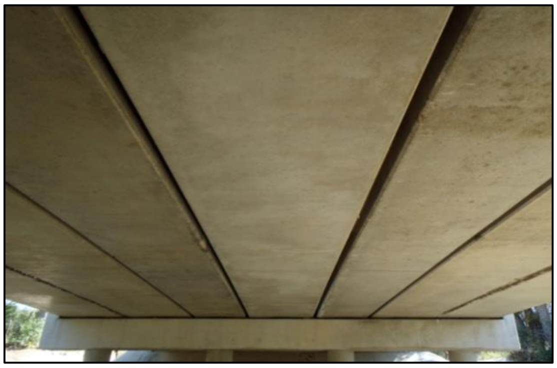

Figure 2-14: Illustration of the close spacing of the concrete box beam girders

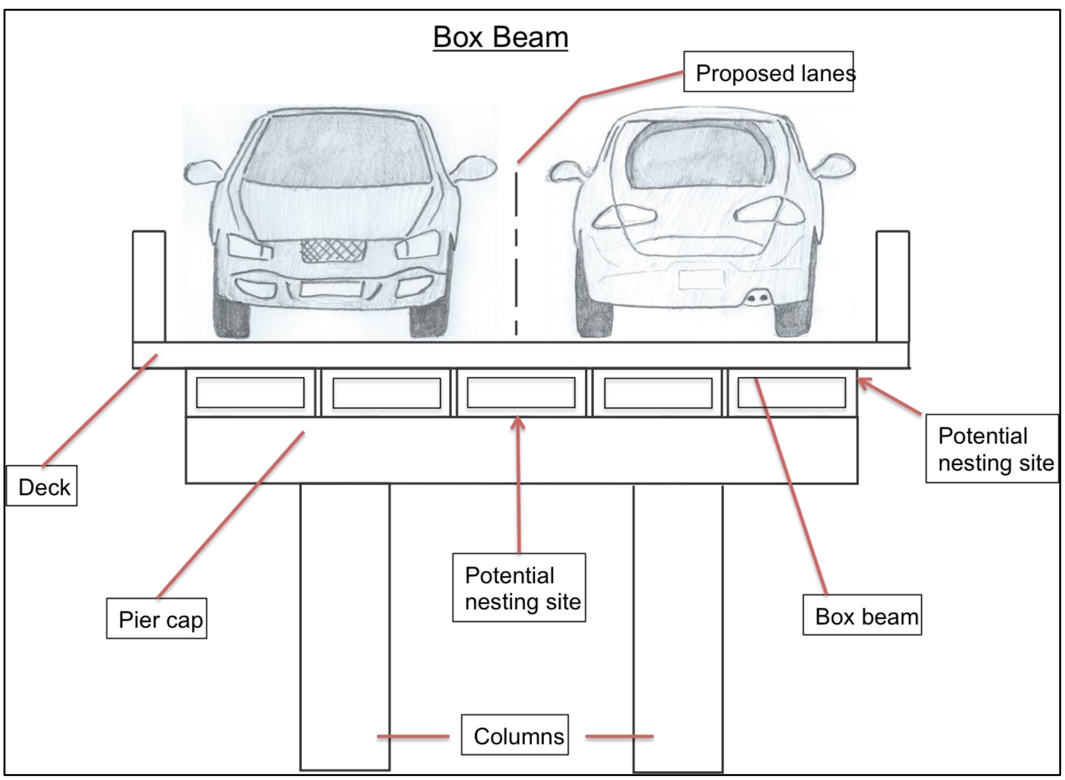

Figure 2-15: Cross-section of a concrete box beam bridge with potential nesting sites

2.3.6 Open Spandrel Arch

This bridge design is constructed of a deck slab resting on beams running perpendicular to the roadway. These beams are supported by columns that carry the load down to arches, which rest on the bridges foundation as shown in Figure 2-16. All of these members are constructed of concrete. Right angles are formed when the beams come into contact with the deck slab, as well as where the slab changes thickness at the bridges sidewalk. A cross section of this bridge can be seen in Figure 2-17.

Figure 2-16: Illustration of an open spandrel arch bridge design with potential nesting site

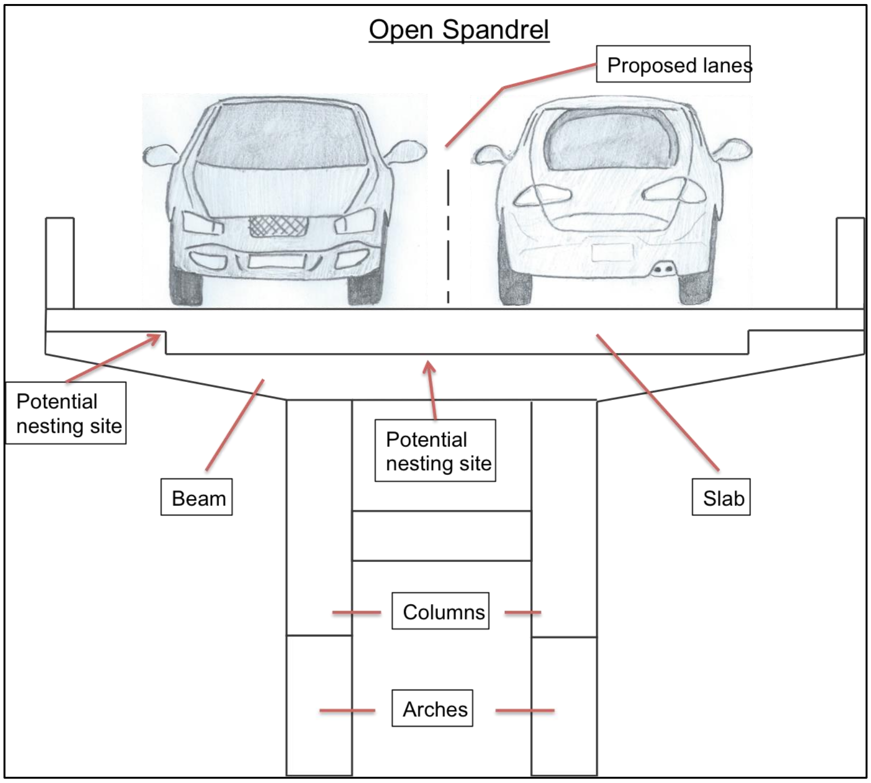

Figure 2-17: Cross-section of an open spandrel bridge with potential nesting sites

2.3.7 Steel Truss

This bridge design type is constructed of both concrete and steel and can be seen in Figure 2-18. The decking is composed of concrete and is supported by a steel truss. The steel truss, which is the primary load support, rest on top of concrete piers and vertical columns or column walls. Cliff Swallows could be expected to nest where there are right angles formed by the bridge members as seen in Figure 2-19.


Figure 2-18: Illustration of a steel truss bridge design type

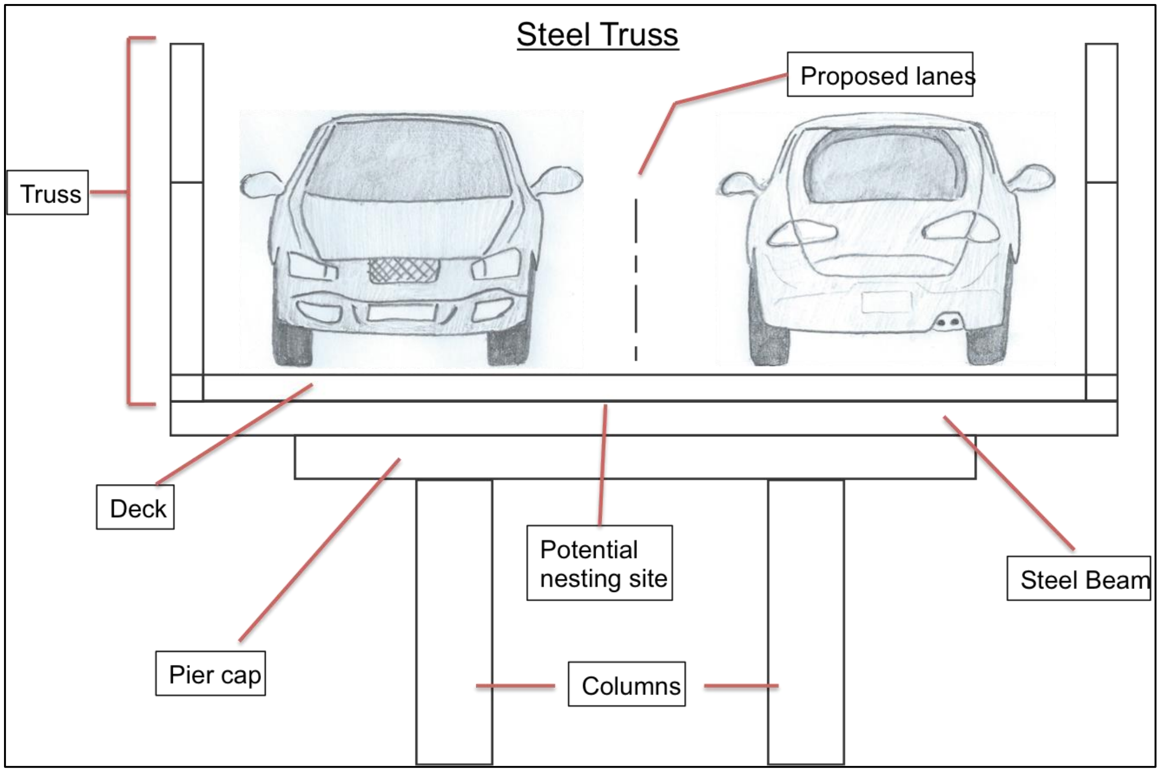

Figure 2-19: Cross-section of a warren truss bridge with potential nesting site

2.3.8 Steel I-Beam

This bridge design is composed of concrete and steel as seen in Figure 2-20. The steel portion of the bridge is the primary load support and consists of I-beams underneath a concrete deck. The steel I-beams span between concrete pier caps that distribute the loads to concrete columns. Where these steel I-beams meet the bridge deck as seen in the cross-section view shown in Figure 2-21 are potential cliff swallow nesting sites.

Figure 2-20: Illustration of a steel I-Beam bridge design type

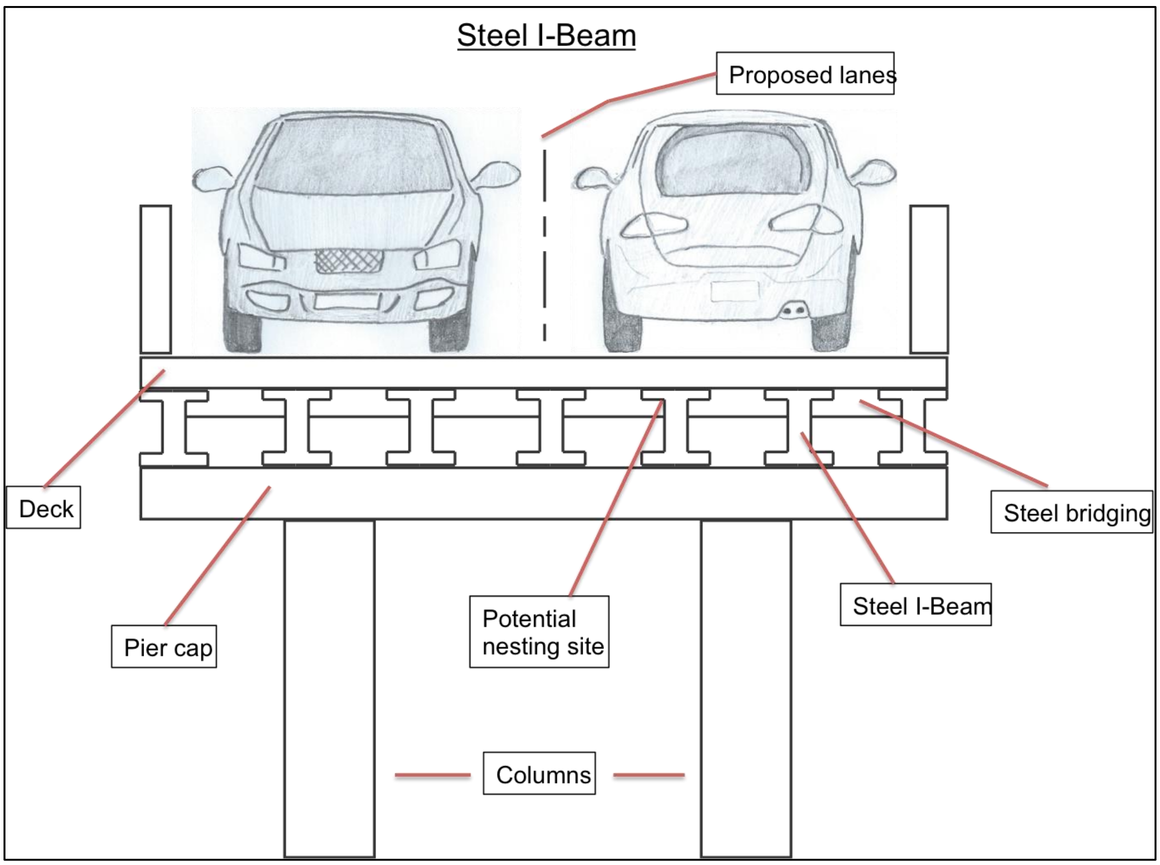

Figure 2-21: Cross-section of a steel I-beam bridge with potential nesting site

2.4 Guide to Land Cover and Soil

2.4.1 Land Cover Background

Land cover pertains to the type of land, such as forest, urban, or water, while land use pertains to the way a land cover is used, such as mining, logging, or farming. A commonly used land classification that is used in geographic information systems is the National Land Cover Database (NLCD). The most current NLCD edition is from 2006 and consists of twenty different land cover classes that cover the United States of America at a spatial resolution of thirty meters. Figure 2-22 (Fry, Xian, Jin, Dewitz, Homer, Yang, Barnes, Herold, & Wickham, 2011) presents these twenty land cover classes. The area of study however, consists of only fifteen land cover classes as shown in Figure 2-23. This land cover data is represented in ArcGIS as a raster layer that represents the data as a series of cells or pixels, which each represent the value of a particular type of land cover.

Figure 2-22: List of NLCD 2006's twenty different land cover classification's

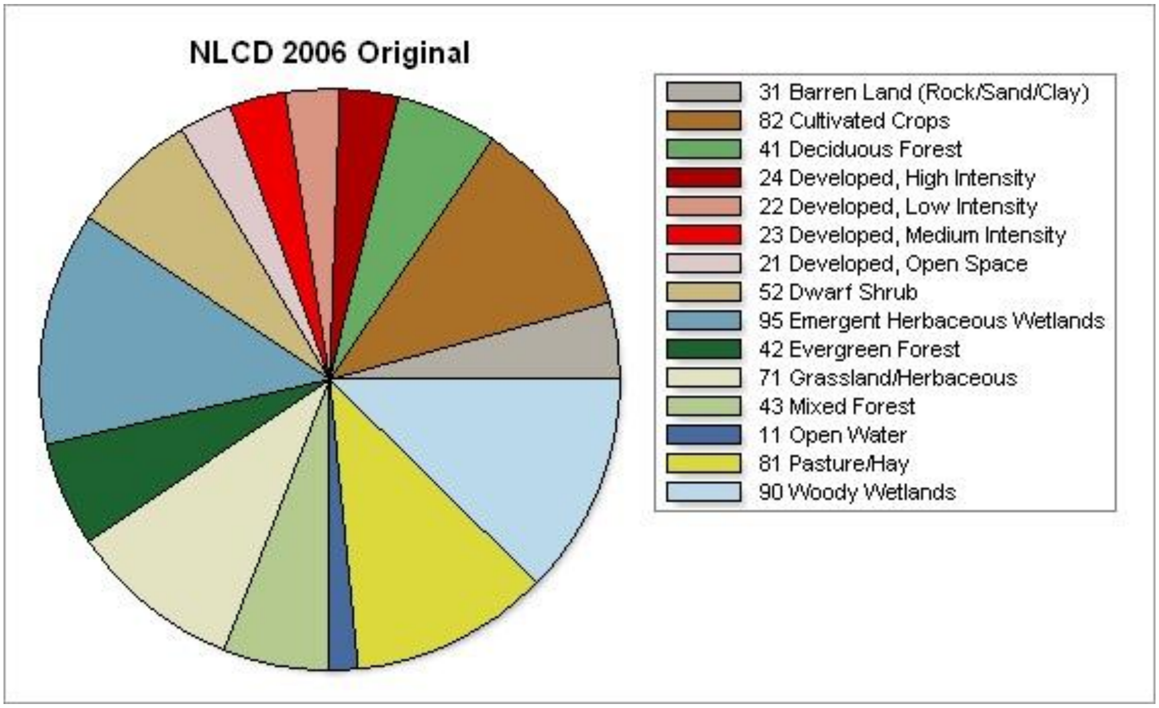

Figure 2-23: A breakdown by percentage of land area of the original land cover in the study area

2.4.2 Soil Background

The Soil Survey Staff (1999) defines soil as a combination of minerals, water, air, and organic matter. The minerals make up the majority of the soil. Besides large rocks, stones, or gravel, soil minerals consist of sand, silt, or clay and are what give soil its texture. Sand particles have diameters that range from .05 millimeters (mm) to 2 mm and have a gritty feel. Silt particles diameters range from .002 mm to .05 mm and have a texture similar to flour. Clay particles are the smallest and are anything less than .002 mm. Water and air flow through the open spaces within the soil permitting soil productivity, and plant growth. The final component of soil is organic matter, which consists of dead plant and animal materials. Figure 2-24 shows all of the soil textures in the study area.

Figure 2-24: Soil textures in the study area

CHAPTER 3

Procedure

3.1 Bridge Selection

For the first year of cliff swallow nest observations (2013) an initial list of 100 bridges was generated from the National Bridge Inventory Database based on their location over waterways and characteristics to make sure all major types of bridge designs were included. The list of bridges was then narrowed to sixty-six bridges based on the prerequisites listed in Table 3-1 while maintaining a variety of design types. Google Maps street view was used to preview the bridge sites and it was noted that most bridges less than forty meters were too low for cliff swallow nesting per the findings of Brown and Brown (1996). The length criteria had to be met to make sure that the bridges were large enough for Cliff Swallows to nest but not too large to maintain a safe work environment. Therefore bridges outside of the length threshold were not used in this study. No wooden bridges were used in this study due to the low number of bridges of this design type as well as the lack of use by Cliff Swallows from previous research. Only bridges over waterways and in the study area were selected to follow the instructions in the project proposal. This allowed for the requirement of sixty bridges suggested in the project proposal to be met while also keeping an additional six bridges as backup in case any bridges proved to be inaccessible. Geographical locations were then input into a Google Maps document to aid in planning trips to the bridges and to assure a geographical representation for all of Central Texas.

Table 3-1: Bridge selection prerequisites.

Length	Construction Material	Over a waterway	Location

40 – 250 meters 130 – 820 feet	Concrete or steel	Yes	Within the study area

Due to a lower number of bridges occupied by Cliff Swallows than expected in the first season of nesting, an additional set of bridges was selected for the second season (2014). For season two, eighty-six potential bridges were selected from the national bridge inventory database. With the aid of TXDOT Bridge Inspection Reports, which provide detailed information and pictures for each bridge, the eighty-six bridges were narrowed down using the same prerequisites in Table 3-1 to forty-two that deemed most suitable for cliff swallow nesting. Geographical locations were input into the previous Google Maps document to represent the locations of all bridges incorporated into the study as shown in Figure 3-1. Season one bridges are represented by blue markers while season two bridges are represented by yellow markers.

Figure 3-1: Map showing the location of Central Texas for all bridges included in the study

3.2 Data Collection

With information gathered from TXDOT Bridge Inspection Reports, an initial spreadsheet was created that detailed categories such as length, material, and average daily traffic for each bridge in this study. To facilitate the collection of data in the field, pictures from the bridge inspection reports were used to develop simplified sketches of the bridges, such as the one shown in Figure 3-2. The top figure is a sketch of the underside of the bridge superstructure, featuring the locations of girders and pier caps. The figure in the lower-left hand corner shows an elevation of the bridge cross-section, and there is space reserved for notes in the lower right-hand corner.

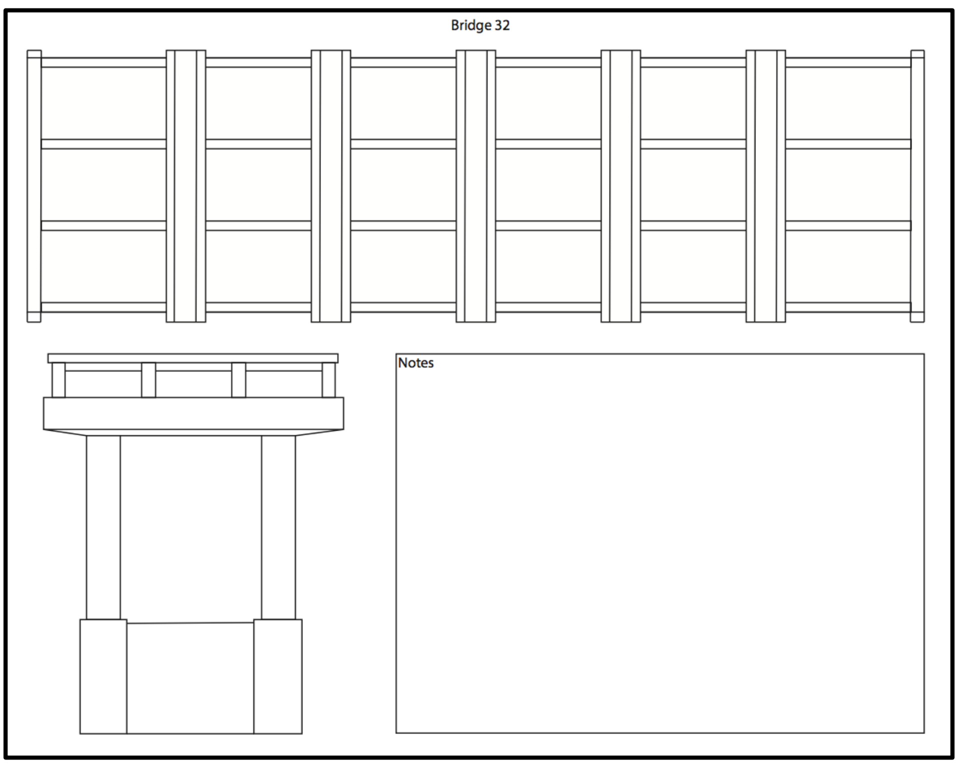

Figure 3-2: Example of a bridge sketch used to collect data in the field

Bridges were visited June 10, 2013 to June 25, 2013 the first year of study and May 20, 2014 to May 27, 2014 the second year of study. At each bridge the following data was recorded: number of mud-built nests, number of mud-built nest scars, bridge orientation, bridge height from the waterway, overhang length, girder spacing, waterway width, and water amount. The number of mud-built nests is the total number of cliff swallow nests for the entire bridge and the number of mud-built scars is the total number of cliff swallow scars on the bridge. Bridge orientation is measured as the degrees from North using a compass while at the bridge location. Bridge height from the waterway is the height measured using a laser range finder from the waterway bank to the bridge superstructure. As demonstrated in Figure 3-3, overhang width was measured from the junction of the bridge deck and side of the girder to the outside of the bridge deck, and girder spacing was measured from the left edge of one girder to the left edge of another. As the girders were of equal width and symmetrical, the centerline-to-centerline spacing was able to be measured from this method.

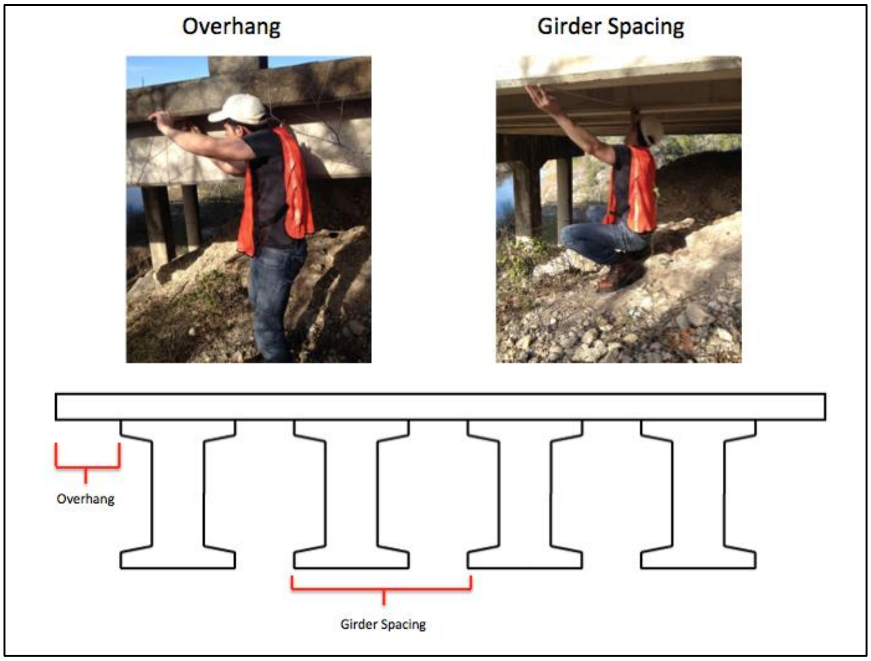

Figure 3-3: Illustration of overhang and girder spacing measurements

Waterway width was measured as the distance of the waterway from shore to shore. The amount of water was evaluated using a scale of 0 to 3: 0 pertaining to bridges with no water underneath them; 1 representing bridges with some water present but less than approximately two inches; 2 for bridges with water approximately greater than two inches but less than knee deep; and 3 for bridges with a water source approximately knee deep or greater. Examples of the water amounts can be seen in Figure 3-4.

Figure 3-4: An illustration of water amount examples

The immediate surroundings at each bridge were divided into four quadrants using the waterway and bridge centerline as the quadrant dividers. Each quadrant was given a level of openness on a scale of 0 to 3: 0 having an area with the most open space, i.e. with no brush; 1 for an area with a little vegetation but mostly open; 2 for areas with some vegetation and some openness; and 3 having an area with large amounts of brush and no openness. After this, the openness for each quadrant was summed and divided by four to get the average openness for the bridge site. To document the quadrants and the levels of openness, pictures were also taken of each quadrant. Figure 14 shows an example of each level of openness.

Figure 3-5: Example of each level of openness

The mud nests and mud nest scars typical of Cliff Swallows were counted separately at each bridge by visual inspection. Other swallows species such as the barn swallow also build mud nests but there was no attempt to distinguish between the various swallow species mud-built nests in this study since the primary focus was mud nests and not swallow species'. The data was collected and recorded one span at a time and the nests and nest scars were counted separately for all bridges. For bridges constructed with girders, the counts were kept separate for each side of each girder. This approach helped maintain accuracy while also documenting the locations of the nests and scars, which can be used for further analysis on nest location. The same method was followed for counting nests and scars on flat slab bridges, except instead of counting nests on girders, which are not part of flat slab construction, the sides of the supporting piers were the focus for counting nests.

After finishing the nest and scar counts, additional field observations were made. A compass was used to record the orientation of the bridge, overhang length and girder spacing were measured to the nearest quarter inch with a tape measure, and a laser range finder aided in the measurement of bridge height and waterway width. The height of the bridge was measured from the ground closest to the waterway, up to the underside of the bridge deck. The waterway width was measured from shore to shore at the bridge crossing. These steps were repeated for all 108 bridges. These additional observations were recorded in the "Notes" section of each completed sheet. Figure 3-6 is an example of one of the completed bridge sheets. The nest and scar numbers were recorded using the notation nests/scars, and these numbers are highlighted in Figure 3-6 to assist the reader.

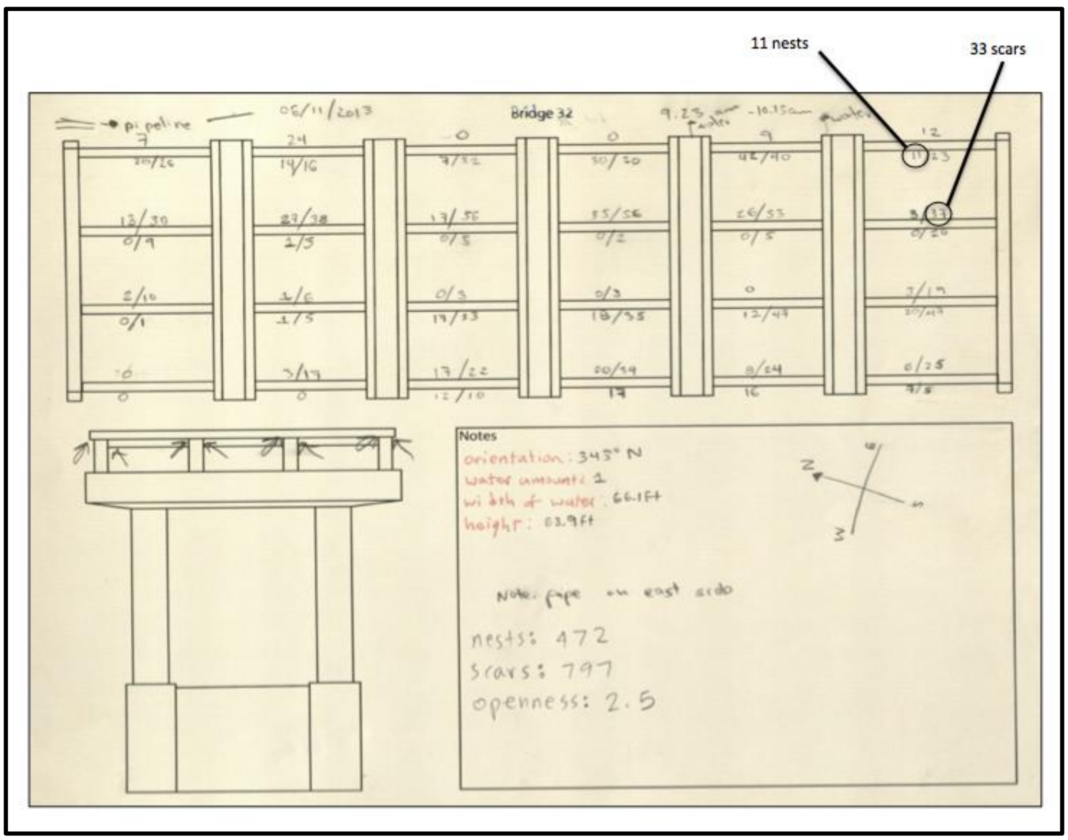

Figure 3-6: An example of a completed bridge sheet

After all data was gathered, additional categories were calculated from the collected information: total density of nests per length, density of nests per length over water, density of nests per length exterior, and density of nests per length interior. The various densities were calculated by dividing the number of nests by the total potential length for nesting on the bridge. These calculations were done to ensure that certain bridges didn't have more nests strictly due to size.

3.3 Land Cover Characteristics

Each bridge was imported using latitude and longitude coordinates with Geographic Information System (GIS) software (ArcMap 10, ESRI, Redlands, CA). Land cover and soil data were clipped to fit the area of study, which includes Blanco, Caldwell, Comal, Guadalupe, Hays, Kendall, and Travis counties. Land cover and soil data were taken from the Multi-Resolution Land Characteristics Consortium (MRLC) and The United States Department of Agriculture's Natural Resources Conservation Service (NRCS) respectively. Two buffers, or areas around the bridges were created around all bridge sites, one at half a kilometer and one at one kilometer. These buffers represent the Cliff Swallows typical range for mud gathering and foraging as reported in the literature. The areas within these buffers were the focus of the land cover and soil aspects of the study.

The land cover data consists of fifteen different classes as previously discussed in section 2.4.1. These categories were condensed into a group of nine categories to simplify analysis. The land cover classes of moss, lichens, sedge/herbaceous, and dwarf scrub only appear in Alaska, and therefore, they were not used in this study. The developed land categories of low intensity, medium intensity, and high intensity were all reclassified into one type of land cover named “developed”, leaving the “developed open” category by itself. The three forest classifications were reclassified into one classification named forest. Land cover classes of pasture/hay and cultivated crops were combined into one class labeled as “agriculture”. The two-wetland classifications were combined into one classification called “wetlands”. Figure 3-7 presents the quantity of each land cover type by percentage in the study area before and after the category reclassification and Figure 3-8 shows a map of the reclassified land cover.

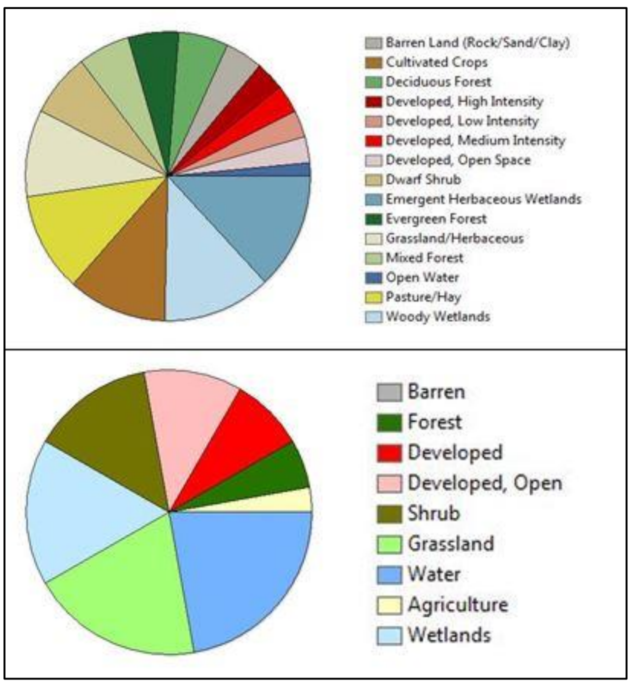

Figure 3-7: Pie charts showing the land cover before and after reclassification

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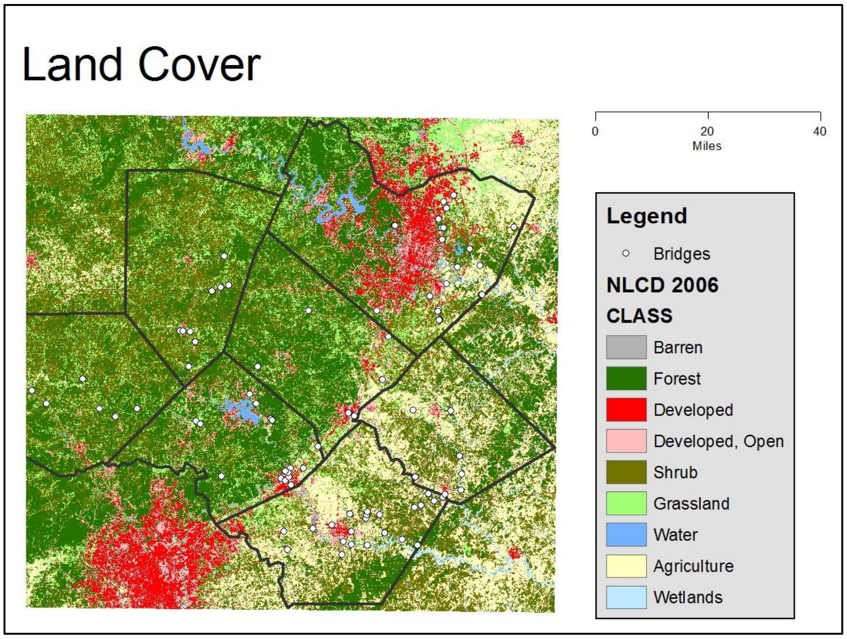

Figure 3-8: A map displaying the NLCD 2006 reclassified data for the study area

The number of pixels for each land cover type was tallied for both the half-kilometer and one kilometer buffers for each bridge. After the pixels were summed for each land cover category, this sum was divided by the total number of pixels within the buffer to calculate the percentage of each land cover type. These percentages were used in the analysis to determine if there were any correlations of land cover with cliff swallow nest densities on bridges.

3.4 Soil Characteristics

The soil data consist of 140 different soil types which all vary in percentages of clay, silt, and sand. For map-making purposes, the soil data was classified by texture based on The United States Department of Agriculture's (USDA) soil classification scheme as shown in Figure 3-9. This data was originally in a shapefile format, which stores geometric location and attribute information about features and represents the data in the form of points, lines, or polygons. This data was changed to raster format to match the land cover data using the polygon to raster tool in ArcMap. This conversion made it easier to calculate the percentages of each soil type within a buffer.

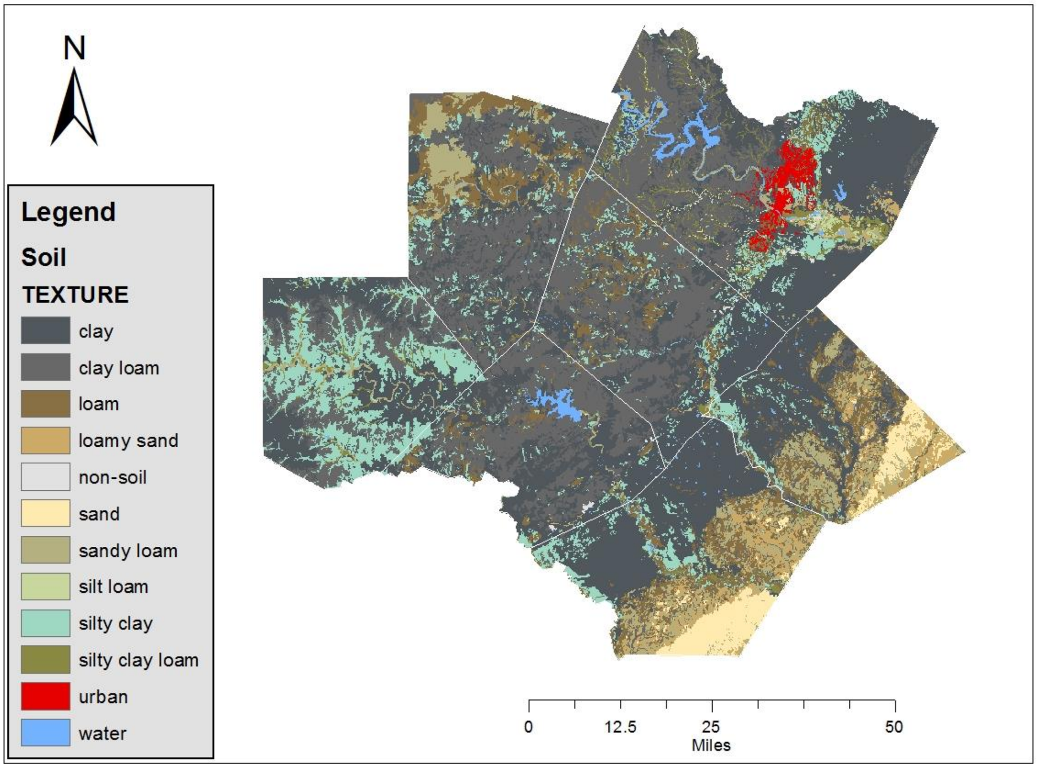

Figure 3-9 : A map displaying the various soil textures in the study area

The same procedure used to find the percentages of each land cover type was followed for calculating the percentages of each soil type. A focus for this study was the texture of the soil. Therefore, the relative amount of each soil within the buffers was multiplied by its composition of clay, silt, and sand by percentage to determine the weighted average clay, silt, and sand content for each buffer. These average clay, silt, and sand percentages were used in the analysis to look for correlations between soil composition and cliff swallow nest densities on bridges.

3.5 Analytical Procedure

The analytical procedure of this study is broken down into two main divisions: the study of bridge factors and the study of the surrounding environment. The bridge portion of the study consists of information pertaining to bridge design, shape, and environmental elements within the area of the bridge site. The bridge setting aspect of the study covers the various classes of land cover and the types of soil in the half kilometer and one kilometer buffers around each bridge site. These variables were analyzed to try and predict the density of cliff swallow nests at a given bridge site.

Two groups of backwards step-wise regressions were run using all variables in the study. One group used all bridge variables and the land cover and soil variables in the half kilometer buffer, the other group used all bridge variables and the land cover and soil variables in the one-kilometer buffer. The backwards step-wise regression began with all variables in the analysis and ran a linear regression. After each regression was run, the least significant variable was deleted to improve the model, and this process was repeated until the model could not be improved any further. After the backwards step-wise regression was run the top five models with the highest adjusted R-squared value for both buffer ranges were selected to determine the overall best model using Akaike's Information Criteria adjusted for small sample sizes (AIC_c). AIC_c can be calculated using the formulas in Figure 3-10.

$$AIC = 2k - 2\ln(L)$$

$$AICc = AIC + \frac{2k(k+1)}{n-k-1}$$

Figure 3-10: AIC and AIC_c formulas

CHAPTER 4

Results and Discussion

4.1 Bridges with Nests

Only bridges with nests were analyzed since the prime focus of this study was to determine what factors influence cliff swallow nesting. Out of the 108 bridges that were observed, 72 had nests on them, ranging from 1 to 890 nests, which was analogous with previous literature.

4.1.1 Best Model With Half-Kilometer Buffer

After the backwards step-wise regression, the top five models were selected to run through an AIC_c analysis to determine the overall best model using the bridge variables and half-kilometer buffer variables. The AIC_c analysis as seen in Table 4-1 shows that model 1 far surpasses all other models from the backwards stepwise regression due to the significant difference in ΔAIC_c and weight values for the subsequent models.

Table 4-1: Ranking of models assessing total nest density for Cliff Swallows with log-likelihood values, number of estimable parameters (k), AIC_c values, delta AIC_c values, and Akaike weights (Wi) for each model

	Model	-2logL	k	AIC_c	ΔAIC_c	W_i
1	scars+length+spacing+factor(skew)+design+north+ waterwidth+silthalf+sandhalf+devopenhalf+shrubhalf+ grasshalf	69.425	14	-74.2	0.00	0.804
2	scars+length+spacing+factor(skew)+design+north+ waterwidth+silthalf+sandhalf+devopenhalf+foresthalf+ shrubhalf+grasshalf	70.023	15	-71.0	3.15	0.166
3	scars+length+spacing+factor(skew)+design+north+ waterwidth+silthalf+sandhalf+devopenhalf+foresthalf+ shrubhalf+grasshalf+agrhalf	70.304	16	-67.1	7.12	0.023
4	scars+length+spacing+factor(skew)+design+north+ waterwidth+silthalf+sandhalf+devopenhalf+devhalf+ foresthalf+shrubhalf+grasshalf+agrhalf	71.227	17	-64.2	10.00	0.005
5	scars+length+spacing+factor(skew)+design+north+ openness+waterwidth+silthalf+sandhalf+devopenhalf+ devhalf+foresthalf+shrubhalf+grasshalf+agrhalf	71.943	18	-60.7	13.51	0.001

Model 1 gives the best explanation on total nest density and includes number of scars, bridge length, spacing, skew, design, north, water width, percentage of silt within the half-kilometer buffer, percentage of sand within the half-kilometer buffer, percentage of developed open land within the half-kilometer buffer, percentage of shrub within the half-kilometer buffer, and percentage of grass within the half-kilometer buffer as independent variables. The coefficients for model one can be seen in Table 4-2 and shows the significance of each variable and how they affect total nest density.

Table 4-2: Coefficients for model 1

variable	estimate	std. error	t-value	sig.
(intercept)	0.235	0.141	1.669	0.101
scars	0.001	0.000	7.642	0.000
length	-0.002	0.000	-4.782	0.000
girder spacing	0.056	0.041	1.364	0.178
(skew)15	-0.117	0.084	-1.389	0.171
(skew)25	0.228	0.092	2.473	0.016
(skew)30	-0.058	0.040	-1.427	0.159
(skew)40	0.19	0.091	2.095	0.041
(skew)45	0.063	0.072	0.874	0.386
(skew)55	-0.121	0.138	-0.872	0.387
girder-multiple	-0.188	0.104	-1.797	0.078
girder t-beam	-0.232	0.098	-2.355	0.022
open spandrel	-0.049	0.151	-0.324	0.747
pan formed	-0.198	0.076	-2.587	0.012
north	-0.001	0.000	-2.813	0.006
waterwidth	0.002	0.001	1.892	0.064
silthalf	0.679	0.303	2.236	0.029
sandhalf	0.413	0.168	2.444	0.018
devopenhalf	-0.597	0.154	-3.86	0.000
shrubhalf	-0.546	0.139	-3.909	0.000
grasshalf	-0.209	0.173	-1.211	0.231

Bridge length, girder T-beam bridge design, pan-formed bridge design, degrees from north, percentage of developed open land within the half-kilometer buffer, and percentage of shrub within the half-kilometer buffer are the factors in this model that had a negative correlation with total cliff swallow nest density. Bridge length may not directly impact the number of cliff swallow nests, but instead reflect the fact that there is more available nesting space on longer bridges, which would lower nesting density. The two bridge types with negative correlations probably result from different aspects of their characteristics. The girder T-beam bridge design type may have a negative effect on cliff swallow density due to the small girder spacing for this design type. For the pan-formed girders, the lower density may be a result of the low number of favored nesting sites versus the total bridge length. As previously stated in the literature review, Cliff Swallows prefer nesting at right angles. Therefore, the concave shape of the beams in pan-formed bridge design types restricts the favored nesting sites to the girders' joints with perpendicular walls over the pier caps. This restriction of favored sites versus the total length of girders likely causes the negative correlation of bridge type with nesting density seen from the regression.

North-to-South oriented bridges receive more sunlight on the bridge girders as the sun rises and sets. Therefore, the resulting lack of sun exposure on the exterior girders as orientation from North increases may be the reason for the negative correlation with degrees from North and nest density. Land cover factors that negatively affected cliff swallow nest density were percentages of developed open space and shrubs within the half-kilometer buffer. Although percentage of grassland within the half-kilometer buffer was not significant in this model, Emlen (1954) stated that Cliff Swallows prefer to forage over grassland because insects are attracted to the warm thermals that are emitted from this land cover type. Shrubs and Developed open space could have a negative correlation with cliff swallow nest density due to the lack of insects within these land cover types.

The number of nest scars, bridge skew of twenty-five degrees, bridge skew of forty degrees, percentage of silt within the half-kilometer buffer, and percentage of sand within the half-kilometer buffer positively impact total cliff swallow nest density. The number of scars that are present positively correlates to cliff swallow nest density most likely because the nest scars are an indication of previous colonies nesting at those specific locations. As such, they indicate that the bridge is already a favorable location for nesting. It is not certain why a skew of twenty-five degrees and a skew of forty degrees were significant and positively correlated with nest density while the other skews, including an intermediate skew of thirty degrees, were not significant. This data was run as categorical, therefore maybe if the data was run as quantitative data the skew may not have an impact at all. Two soil characteristics also had positive correlations with nest density. As discussed in the literature review, cliff swallow nests are primarily constructed of sand, then silt, and lastly clay, by percentage. Therefore, increasing percentages of silt and sand in the soil being positively correlated with cliff swallow nest density was expected.

Although included in the model, the variables of girder spacing, bridge skews of fifteen degrees, thirty degrees, forty-five degrees, fifty-five degrees, girder-multiple bridge design, open spandrel bridge design, water width, and percentage of grass within the half-kilometer buffer were statistically insignificant. Therefore these variables cannot confidently predict total nest density. Model 1 has an adjusted R^2 value of 0.601 and is statistically significant, which indicates that when using the significant variables in the model the total cliff swallow nest density can be calculated with a confidence level of 60.1 %.

4.1.2 Best Model With One-Kilometer Buffer

Similarly to the half-kilometer buffer case, after the backwards step-wise regression was completed, the top five models were selected to run through an AIC_c analysis to determine the overall best model using the bridge variables and one-kilometer buffer variables. The AIC_c analysis as presented in Table 4-3 shows that the top ranked model far surpasses all other models identified by the backwards stepwise regression due to the significant difference in Δ AIC_c and as well as the higher weight values versus the subsequent models.

Table 4-3: Ranking of models assessing total nest density for Cliff Swallows with log-likelihood values, number of estimable parameters (k), AIC_c values, delta AIC_c values, and Akaike weights (Wi) for each model

	Model	-2logL	k	AIC_c	Δ AIC_c	W_i
1	scars+length+overhang+factor(skew)+spantype+spans+spanlength+north+sand+waterkm+devopen+dev+barren+shrub+grass+agr	74.017	18	-74.5	0.00	0.849
2	girderct+scars+length+overhang+factor(skew)+spantype+spans+spanlength+north+sand+waterkm+devopen+dev+barren+shrub+grass+agr	74.537	19	-70.8	3.69	0.134
3	girderct+scars+length+overhang+factor(skew)+spantype+spans+spanlength+north+openness+sand+waterkm+devopen+dev+barren+shrub+grass+agr	74.815	20	-66.4	8.07	0.015
4	girderct+scars+length+overhang+height+factor(skew)+spantype+spans+spanlength+north+openness+sand+waterkm+devopen+dev+barren+shrub+grass+agr	75.095	21	-61.8	12.68	0.002
5	girderct+scars+length+overhang+height+factor(skew)+spantype+spans+spanlength+north+openness+clay+sand+waterkm+devopen+dev+barren+shrub+grass+agr	75.286	22	-56.8	17.70	0.000

Model 1 gives the best explanation of total nest density and includes number of nest scars, bridge length, overhang, bridge skew, span type, the number of spans, span length, degrees from north, percentage of sand within the one-kilometer buffer, percentage of water within the one-kilometer buffer, percentage of developed open land within the one-kilometer buffer, percentage of developed land within the one-kilometer buffer, percentage of barren land within the one-kilometer buffer, percentage of shrub within the one-kilometer buffer, percentage of grass within the one-kilometer buffer, and percentage of agriculture within the one-kilometer buffer as independent variables. The coefficients for model 1 can be seen in Table 4-4 and shows the significance of each variable and how it affects total nest density.

Table 4-4: Coefficients for model 1

Variable	estimate	std. error	t value	sig.
(Intercept)	0.000	0.000	3.028	0.003
scars	0.000	0.000	7.166	0.000
length	-0.000	0.000	-4.289	0.000
overhang	0.000	0.000	1.715	0.092
factor(skew)15	-0.000	0.000	-2.206	0.032
factor(skew)25	0.000	0.000	3.453	0.001
factor(skew)30	-0.000	0.000	-0.514	0.609
factor(skew)40	0.000	0.000	1.091	0.281
factor(skew)45	0.000	0.000	0.819	0.416
factor(skew)55	0.000	0.000	0.924	0.359
spantypeContinuous	-0.000	0.000	-1.334	0.188
spantypeSimpleSpan	-0.000	0.000	-1.783	0.081
spans	0.000	0.000	2.215	0.031
spanlength	0.000	0.000	2.331	0.023
north	-0.000	0.000	-2.732	0.008
sand	0.000	0.000	3.061	0.003
waterkm	0.000	0.000	2.205	0.032
devopen	-0.000	0.000	-3.265	0.002
dev	-0.000	0.000	-2.059	0.044
barren	0.000	0.000	1.561	0.124
shrub	-0.000	0.000	-4.586	0.000
grass	-0.000	0.000	-1.609	0.114
agr	-0.000	0.000	-2.238	0.029

Similar to the model using half-kilometer buffers, bridge length, bridge alignment in degrees from North, the percentage of open developed land, and the percentage of shrub-covered land all negatively correlated with total cliff swallow nesting density. This model with one-kilometer buffers, however contained a few additional variables with a negative correlations to total cliff swallow nest density: a skew of fifteen degrees, the percentage of non-open developed land, and the percentage of agriculture. Similar to developed open space, developed land most likely negatively influences total cliff swallow nest density due to the increase in human activity, building obstructions, and the subsequent decrease in available food source that is likely impacted by human development. Mayhew (1958) believed that cliff swallow nesting increased in the Sacramento Valley region of California due to agriculture. However, a possible increase in pesticide use over the past fifty years may be reason for the negative correlation with agriculture in this study.

The number of nest scars, a skew of twenty-five degrees, and the percentage of sand in the soil are all factors that positively correlate with increasing cliff swallow nest density, just as they did with the regression run with the half-kilometer buffer. Some additional positively correlating variables include the number of bridge spans, span length, and the percent of water in the buffer area. The number of spans and span length were expected to be another way of viewing bridge length. However, if the number of spans and span length are considered to be another way of viewing bridge length, this would contradict with bridge length negatively correlating with nest density. The amount of water likely increases nest density due to the use of water for mud and an increase in food availability. These results conquer with previous mentioned literature.

Overhang, bridge skew of thirty, bridge skew of forty, bridge skew of forty-five, bridge skew of fifty-five, span type, percentage of barren land, and percentage of grass land were included in the model but were all deemed to be insignificant variables. Therefore, these variables cannot be used to predict cliff swallow nest density.

This model had an adjusted R^2 value of 0.635 and was statistically significant. As such, when using the significant variables in the model, the total cliff swallow nest density can be calculated with a confidence level of 63.5%.

4.2 Bridges With Nests Versus Bridges Without Nests

To determine if there was a significant difference between the variables for bridges with nests and the variables for bridges without nests, and not just due to random chance, log likelihood tests were run on categorical data and t-tests were run on quantitative data. The results from these tests can be seen in Table 4-5 and Table 4-6.

After running these tests, the bridge factors that made a significant difference in bridges with nests and bridges without nests were the number of scars, bridge skew, number of spans over water, average daily traffic, overhang width, girder spacing, height, design type, and material type. The number of scars is most likely significant due to the indication of past nesting at a location. It is unsure why skew is significant because all skew types had nests at least once. The number of spans over water is most likely significant because of the importance of water for foraging and nest building. The more of a bridge that is over water is probably better for nesting. Average daily traffic may be a significant factor because of the noise or activity from vehicles. Overhang, girder spacing, and height may not continuously affect cliff swallow nesting but there may be a cutoff with these variables the aren't suitable for nesting. Design and material type are both significant meaning that certain designs and material types influence if a bridge is occupied. No Cliff Swallows were seen nesting on steel design types therefore this may be why design and material proved to be significant. The only variable in the immediate surrounding area that had a significant value was the level of openness. Therefore, there may be a particular optimal openness for Cliff Swallows, but this has yet to be discovered. Average clay and sand percentage proved to be significant for both buffer zones but not average silt percentage. This may be because sand and clay are the most and least used soil texture used in nest building respectively and silt falls in the middle. No land cover variables in either buffer zone proved to have a significant impact on bridges with nests versus bridges without nest. This may be due to the sparsely occupied percentages of particular land cover types.

Table 4-5: Likelihood Ratio's for categorical data

Likelihood Ratio			
Variable	Value	df	Sig.
design	35.623	7	0.000
spantype	1.44	2	0.487
Water amount	7.318	3	0.062
skew	16.343	8	0.038
material	13.904	1	0.000

Table 4-6: T-Tests results for quantitative data

T-Test			
Variable	t	df	sig. (2-tailed)
scars	-4.056	106	0.000
spans	0.527	61.611	0.600
spanlength	-1.376	75.232	0.173
spanswater	-3.198	75.573	0.002
age	-0.713	106	0.477
adt	-2.048	100.602	0.043
length	-1.226	83.021	0.224
deckwidth	0.248	106	0.805
overhang	-3.348	66.924	0.001
spacing	-3.734	67.148	0.000
height	-3.313	74.01	0.001
north	0.951	71.356	0.345
openness	-3.05	71.744	0.003
waterwidth	-1.965	97.042	0.052
clayhalf	3.869	90.462	0.000
silthalf	0.932	77.949	0.354
sandhalf	-3.246	106	0.002
claykm	3.607	89.4	0.001
siltkm	0.793	82.963	0.430
sandkm	-3.196	106	0.002
waterhalf	-0.853	100.135	0.396
devopenhalf	0.953	106	0.343
devhalf	1.163	65.966	0.249
barrenhalf	-1.074	106	0.285
foresthalf	-0.739	61.273	0.463
shrubhalf	-0.516	54.271	0.608
grasshalf	-0.43	73.835	0.669
agrhalf	-0.078	64.101	0.938
wethalf	0.751	57.493	0.456
waterkm	-1.088	79.31	0.280
devopenkm	1.415	60.215	0.162
devkm	1.948	62.189	0.056
barrenkm	-1.146	84.408	0.255
forestkm	-1.196	57.268	0.237
shrubkm	-1.327	58.886	0.190
grasskm	0.31	66.022	0.757
agrkm	-0.212	66.965	0.833
wetkm	0.328	69.338	0.744

4.3 Summary of Results

For regressions with both the half-kilometer and one-kilometer buffers, nest scars, a skew of twenty-five degrees, and average sand percentage within the buffers were all statistically significant and positively correlated with total cliff swallow nest density. Additional factors that may increase cliff swallow nest density are the number of spans and span lengths, the amount of water within the buffers, and the average silt percentages within the buffers. These variables were found to have a positive impact on cliff swallow nest density and statistically significant with regressions of one buffer range but not both.

For both buffer ranges, regressions showed that length, degrees from north, percentage of developed open land, and percentage of shrub had a negative impact on total cliff swallow nest density. Although a skew of fifteen degrees, percentage of developed land, percentage of agriculture, girder T-beam bridge design, and pan-formed bridge design were only significant for one buffer zone or the other, these variables are assumed to have a negative impact on total cliff swallow nest density as well. For the bridge design category, no bridges designs that were significant had a positive correlation with total cliff swallow nest density. However the pan-formed bridge design had the most negative affect, therefore it is assumed that this bridge design is the least likely for a cliff swallow to nest.

Height never showed significance in this study but it is to be noted that Cliff Swallows were not observed nesting on any bridges lower than 3.5 meters (approximately 12 feet). No cliff swallow nests were observed on steel bridges, but one cave swallow nest was. Due to the lack of cliff swallow nests on steel bridges, only concrete bridges were used in the regression.

CHAPTER 5

Conclusion

5.1 Summary of Research

As per request from TXDOT and TCEQ, an initial assessment of at least sixty bridges was conducted to develop a model to determine the relationship between bridge design, surrounding land characteristics, and cliff swallow nesting. In the end, 108 bridges were analyzed to create a model that would predict cliff swallow nest density at a given bridge with certain characteristics.

5.2 Summary of Conclusions and Implications

A complete list of all variables that were included in this study is presented in the appendix. Out of forty-five variables, fifteen had an impact on total cliff swallow nesting density: nest scars, bridge skew, average sand percentage within the buffer zones, number of spans, span length, water percentage within the buffer zones, average silt percentage within the buffer zones, bridge length, bridge orientation from North, developed open land percentage within the buffer zones, developed land percentage within the buffer zones, shrub percentage within the buffer zones, agriculture percentages within the buffer zones, girder T-beam bridge designs, and pan-formed bridge designs. Of these significant variables, two can be used to aid bridge designers in promoting or discouraging Cliff Swallows from nesting. According to the results from the best models in this study, by constructing bridges of the pan-formed or the girder T-beam design type, cliff swallow nesting can be reduced. Although not statistically significant, no Cliff Swallow nests were seen on steel bridge designs therefore building bridges with steel could also lower Cliff Swallow nest density. It also may be vital for bridge designers to know that when building bridges in areas with high levels of developed land, shrubs, or agriculture, Cliff Swallow nest density will be lower than areas without these land cover types. On the contrary, to increase cliff swallow nesting, bridge designers should avoid the pan-formed, girder T-beam, and steel bridge design types. Bridge designers should also be prepared to account for an increase in Cliff Swallow nesting density in areas with high levels of sand and silt in the soil and areas with large amounts of water.

One limitation of the study was the low number of some of the bridge design types available in the study area. Most bridges in the area were girder-multiple and flat slab bridge designs. If more bridges of the other design categories were available to analyze a better understanding of the Cliff Swallows nesting choice based on bridge design could be better developed. Another qualification of the study resulted from analyzing only bridges over water. Many bridges were seen with Cliff Swallows nesting that overpassed roadways, but as the initial bridge selection required waterways, a conclusion about the need for bridges over roadways cannot be made with this dataset.

5.3 Recommendations for Future Research

From the analysis of this project, five main recommendations for future research are proposed. One of the recommendations would be to increase the sample size of the other bridge design types beyond girder-multiple and flat slab bridges. Cliff swallow nests and nest scars were only counted once at each bridge site, therefore I would recommend future researchers to count nests multiple times to increase accuracy in nest and scar counts. Another recommendation would be to increase the pool of available building stock by looking into bridges that overpass roadways and not limiting to only bridges over waterways. Since some bridge skews had positive affects and one had a negative affect, an additional recommendation would be to analyze the skew variables as quantitative data rather than categorical data to determine if there really is an impact on cliff swallow nest density. Many land cover types in the area of study were very sparse, with zero or very low percentages of occupancy within the buffers at many bridge sites. Therefore, a final recommendation would be to further condense the land cover data. This additional reclassification could be done be combining the water and wetland data into one category, combining the forest, and shrub into one category, and combining barren with the developed category. This would solve the problem of having many land cover types be insignificant in the study due to scarcity.

APPENDIX

Table 5-1: Variables used in the study of cliff swallow nest density on bridges in Central Texas

Variable	Code	Description
Bridge Characteristics		
Cliff Swallow Nest Scars	scars	The number of cliff swallow nest scars counted at a bridge
Age of Bridge	age	How old a bridge is. Year of study minus year of bridge construction
Average Daily Traffic	adt	Average number of vehicles that use the bridge in a day
Length	length	The length of the bridge
Deck Width	deckwidth	The width of the bridge deck
Overhang Width	overhang	The measurement from the girders to the end of the bridge deck
Girder Spacing	spacing	The distance from one girder to the next
Height	height	The height of a bridge measured from the edge of the waterway to the bridge deck
Skew	skew	The angle that the bridge is oriented. Skew factors include 15, 25, 30, 40, 45, and 55 degrees for this study
Material	Material	What material the bridge is constructed out of. The material types are concrete and steel.
Number of Spans	Spans	How many spans there are or spaces from one vertical support to the next.
Span Type	spantype	The type of spans, either being simple or continuous
Spans Over Water	spanswater	The number of spans that are over a waterway
Span Length	spanlength	The length of the spans measured between the vertical supports of a bridge
Design Construction	design	Includes seven bridge design types: Girder-multiple, flat slab, girder T-beam, pan formed girder, box beam, open spandrel and steel I-beam
Degrees from North	north	Degrees from North that the bridge is oriented
Immediate Surroundings		
Average Openness	openness	A measurement of how open the bridge area is on a scale of 0 to 3 with 0 being completely open and 3 being completely obstructed
Water Amount	water	A measurement of how much water is under a bridge site on a scale of 0 to 3 with 0 being dry and 3 having a large amount of water
Water Width	waterwidth	How wide the waterway is measured from shore to shore
Land Cover and Soil		
Average Clay Half	clayhalf	The average clay percentage within the half kilometer buffer of a bridge site
Average Silt Half	silthalf	The average silt percentage within the half kilometer buffer of a bridge site
Average Sand Half	sandhalf	The average sand percentage within the half kilometer buffer of a bridge site

Table 5-1 Continued		
Average Clay Km	claykm	The average clay percentage within the one kilometer buffer of a bridge site
Average Silt Km	siltkm	The average silt percentage within the one kilometer buffer of a bridge site
Average Sand Km	sandkm	The average sand percentage within the one kilometer buffer of a bridge site
Water Half	waterhalf	The percent of land that is classified as water in the half kilometer buffer of a bridge site
Developed Open Half	devopenhalf	The percent of land that is classified as developed open space in the half kilometer buffer of a bridge site
Developed Half	devhalf	The percent of land that is classified as developed space in the half kilometer buffer of a bridge site
Barren Half	barrenhalf	The percent of land that is classified as barren in the half kilometer buffer of a bridge site
Forest Half	foresthalf	The percent of land that is classified as forest in the half kilometer buffer of a bridge site
Shrub Half	shrubhalf	The percent of land that is classified as shrub in the half kilometer buffer of a bridge site
Grass Half	grasshalf	The percent of land that is classified as grass in the half kilometer buffer of a bridge site
Agriculture Half	agrhalf	The percent of land that is classified as agriculture in the half kilometer buffer of a bridge site
Wetland Half	wethalf	The percent of land that is classified as wetlands in the half kilometer buffer of a bridge site
Water Km	waterkm	The percent of land that is classified as water in the one kilometer buffer of a bridge site
Developed Open Km	devopenkm	The percent of land that is classified as developed open space in the one kilometer buffer of a bridge site
Developed Km	devkm	The percent of land that is classified as developed space in the one kilometer buffer of a bridge site
Barren Km	barrenkm	The percent of land that is classified as barren in the one kilometer buffer of a bridge site
Forest Km	forestkm	The percent of land that is classified as forest in the one kilometer buffer of a bridge site
Shrub Km	shrubkm	The percent of land that is classified as shrub in the one kilometer buffer of a bridge site
Grass Km	grasskm	The percent of land that is classified as grass in the one kilometer buffer of a bridge site
Agriculture Km	agrkm	The percent of land that is classified as agriculture in the one kilometer buffer of a bridge site
Wetland Km	wetkm	The percent of land that is classified as wetlands in the one kilometer buffer of a bridge site

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