A QUANTITATIVE ANALYSIS OF THE GEOMORPHIC AGENCY OF THE MUD-NESTING SWALLOWS IN CENTRAL TEXAS

DISSERTATION

Presented to the Graduate Council of
Texas State University-San Marcos
in Partial Fulfillment
of the Requirements

for the Degree

Doctor of PHILOSOPHY

by

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San Marcos, Texas
August 2012

A QUANTITATIVE ANALYSIS OF THE GEOMORPHIC AGENCY OF THE MUD-

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DEDICATION

This dissertation is dedicated to my father, George Michael Tsikalas. I have followed in his footsteps into education and strive to be as good a person as he was. Everyone who knew him loved him for his personality, compassion, generosity, and overall good-hearted nature. Thank you Dad, you are my greatest role model, and I will continue to do my best to make you proud.

ACKNOWLEDGEMENTS

I would first like to thank the committee members for their time and dedication to this research. Dr. Dixon, your knowledge of statistics has been of tremendous help in this process, and your personality and ability to communicate have inspired me to learn more about research statistics. Dr. Earl, among your many great qualities, your passions for the environment and for geography education have made you a wonderful asset to this committee. Dr. Huffman, your knowledge of ornithology has been crucial to this dissertation. I have learned much from our discussions and greatly appreciate your perspective as a biologist and ornithologist. Dr. Butler, what can I say but I would not have started, followed through, or completed this dissertation if it was not for your guidance as my academic advisor. You play many vital roles in Texas State's Geography Department and are a well-known scholar and Regents' Professor. How you are able to manage your time and still provide the great amount of attention to all of your students is baffling to me, and highly respectable. You have been a true role model for me, and I wish to express my sincerest gratitude to you.

I would also like to extend my thanks to the faculty, staff, and students in the Geography Department at Texas State University-San Marcos. Thank you to Dr. Suckling for your support and guidance as the Department Chair. Also, a special thank you goes to Allison Glass-Smith for being extremely helpful through this process and for always being an amazing person. Thank you to my colleagues who are always helpful, friendly, and encouraging. I would like to extend special thank yous to my office mate and close friend, Clayton Whitesides, and to my great friends Melanie and Annie Stine.

I must thank my family for their patience, love, and support. My love and thank you goes to my mother, Barbara, sister, Jessica, and stepfather, David. You have believed in me from the start and have supplied me with the encouragement and motivation to see this through. Mom, I would not have had the confidence to make it this far without your dedication to my success in education. I will never forget the countless hours you spent with me through grade school helping me study, put together projects, and enjoy my schoolwork. Jessica, your hard-work ethic and passion for humanity have made you into a very successful medical doctor. You are a great inspiration to me, and I am very proud of you. Dave, I am truly thankful to have you in our family. You are an amazing person, full of support and encouragement that you generously share with my mom, sister, and me. We are very fortunate to have you in our lives, thank you.

Lastly, I wish to thank Najéda, my wife, soul mate, best friend, and the most wonderful person in the world. Your fiery passion to do good and make a positive difference in the world, your selfless and committed work ethic, and your overall positive energy have motivated me to do my best in this doctoral program. Your unrequited love and support have been my saving grace for these past four years. I have no idea where I would be without you, love.

This manuscript was submitted on June 29, 2012.

TABLE OF CONTENTS

Page

LIST OF TABLES

Table **Page**

LIST OF FIGURES

Figure **Page**

ABSTRACT

A QUANTITATIVE ANALYSIS OF THE GEOMORPHIC AGENCY OF THE MUD-NESTING SWALLOWS IN CENTRAL TEXAS

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August 2012

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This dissertation provides a quantitative analysis of sediment erosion, transportation, and deposition conducted by the three mud-nesting swallows of Central Texas, namely the barn swallow (*Hirundo rustica*), the cave swallow (*Petrochelidon fulva*), and the cliff swallow (*Petrochelidon pyrrhonota*). The study area for this research is within the city limits of San Marcos, Texas, which straddles the Balcones Escarpment separating the Edwards Plateau from the Blackland Prairies. Swallows were investigated for their geomorphic role on the landscape, specifically, how much sediment is existing at the colonies positioned under fifteen bridges and one parking garage, what is the annual sediment transport per site, and is there a significant difference between cup-shaped and gourd-shaped swallow mud-nests. This dissertation is a contribution to the growing

subdiscipline of *zoogeomorphology*, the study of animals as geomorphic agents. Little research has directly investigated any form of avian zoogeomorphology. Swallows, although commonly found in academic literature, have yet to be analyzed for their role in mud and clast transport for use in nesting. This dissertation aims at quantifying this geomorphic process.

CHAPTER 1

INTRODUCTION

The term *zoogeomorphology* was defined by Butler (1992) as the study of the geomorphic effects of animals. The study of animals as geomorphic agents is not widespread. Zoogeomorphology is not a common topic of earth-science texts and classes in K-12 and higher education, but may be discussed in some advanced university classes in biogeography (Butler 1995). Therefore, the sub-discipline leaves much to be explored by both geomorphologists and biogeographers. Since the turn of the millennia, geomorphic research has centered on scientific theory; issues of scale; use of remote sensing and Geographic Information Systems (GIS); fluvial, eolian, coastal, and weathering processes; mass wasting, periglacial and glacial geomorphology; Quaternary geomorphology; environmental geomorphology; geoarcheology; and biogeomorphology (Butler 2003). Within the latter category, most work has focused on plants rather than animals; however, since the early 1990s, a growing body of research has addressed animal biogeomorphology. Zoogeomorphic studies have focused on a variety of animal species: beavers (Butler 1989, 1991a, 1991b, and 2006; Butler et al. 1992; and Butler and Malanson 1994 and 2005), grizzly bears (Butler 1992; Baer and Butler 2000), mountain goats and sheep (Butler 1993; Govers and Poesen 1998), cows

(Trimble and Mendel 1995), bison (Fritz et al. 1999), warthogs (Naiman and Rogers 1997), horses (Beever et al. 2008), muskrats (Connors et al. 2000), salamanders (Davic and Walsh 2004), crayfish (Statzner et al. 2000), alkali bees (Cane 2003), and many burrowing species (Godfrey and Crowcroft 1960; Ross et al. 1968; Meilke 1977; Hickman and Brown 1973; Anderson and McMahon 1981; Hall et al. 1999; Eldridge 2004).

Butler (1995) summarized the work in avian zoogeomorphology along with other vertebrates and invertebrates. Although many studies involve the geomorphic agency of birds, none had zoogeomorphology as their focus. The underrepresentation in avian zoogeomorphology may be attributed to the following:

> "[t]he transient nature of most midlatitude birds and the isolation of major seabird colonies from population centers have combined to lull most North American geomorphologists into believing in avian geomorphic insignificance" (Butler 1995, 59).

This research investigates the geomorphic role of the mud-nesting swallows of Central Texas. Specifically, the barn swallow (*Hirundo rustica*), cliff swallow (*Petrochelidon pyrrhonota*), and cave swallow (*Petrochelidon fulva*) were examined to further our understanding of the extent to which sediment is being transported for mud-nest construction.

Research Perspective

The purpose of this research is to determine the geomorphic agency of swallow species in Central Texas. The approach is that of a physical geographer focusing in biogeography and geomorphology. Geography is often difficult to distinguish from other disciplines, but can be identified by three well-defined perspectives: 1) the perspective of place, space, and scale, 2) domains of synthesis, and 3) spatial representation (National Research Council 1997).

The integration in place, interdependencies between places, and interdependencies among scales make up the first in the list of perspectives. A place, or as in this research, an environmental system, requires the analysis of complex interactions. When considering environmental systems theory, it should be clear that systems are not linear, but a constitution of complex relationships (Malanson 1999). Despite the isolation of swallows' role within the environmental system, it is important to acknowledge complexity exists (Malanson 1999). Zoogeomorphology at the landscape scale can provide insight into these complexities of the Earth-shaping system. Interdependencies between swallow nesting colonies were analyzed with respect to total and annual mud transport. Scale is a quintessential element in geography. This research will examine the interdependencies among site-specific nesting sites and the overall impact on the regional scale. Since two of the three mud-nesting swallow species (barn swallow and cliff swallow) are commonly found throughout the world, a global scale of geomorphic agency can be generalized; after all, "[t]he focus on scale enables geographers to analyze […] the impact of local events on global changes" (National Research Council 1997, 31).

Geography research can fall into three domains of synthesis: 1) Environmental-Societal Dynamics, 2) Environmental Dynamics, and 3) Human-Societal Dynamics (National Research Council 1997). The agency of mud-nesting swallows is primarily in the domain of Environmental Dynamics; however, the swallow colonies in this study are entirely located on human-made structures, implying a degree of environmental-societal dynamics. The focus here is not on the artificial structural influence on the nesting habits, but rather the agency of mud transport as a geomorphic process.

Spatial representation is the third core perspective in geography. Despite having the freedom of interdisciplinarity, geographic work of all sub-disciplines examines phenomena distributed over Earth-space and seeks to "produce a unified approach to spatial representation [devising] practical tools for representing the complexities of the world […]" (National Research Council 1997, 39). A single swallow may not transport significant quantities of sediment; however, when distributed in clusters, or colonies, in great numbers, do mud-nesting swallows play a significant role in sediment transport on the landscape? The objectives of this research address this question.

Objectives and Research Questions

Specific objectives of the proposed research are:

1. To determine the total existing mass of mud transported to the nesting sites by swallow species.
2. To determine the total mass of mud transported by swallows in a nesting season (April 2011 to October 2011).

3. To compare the geomorphic agency involved in the construction of a gourd-shaped mud-nest common to the cliff swallow and the cup-shaped mud-nest of the barn and cave swallows.

The research objectives were addressed by asking the following questions:

1. What is the total mass of sediment transported to the study sites by mud-nesting swallows (namely, *Hirundo rustica, Petrochelidon pyrrhonota, and Petrochelidon fulva*)?
2. What is the annual mass of sediment transported by swallows? How does this vary between preexisting colonies and the colonization of a location without nests?
3. Is there a significant difference in the mass of sediment used to construct a gourd-shaped mud-nest and the mass of sediment used to construct a cup-shape mud-nest?

Significance

This dissertation contributes to the limited zoogeomorphologic body of knowledge. Zoogeomorphology is a growing focus in geomorphology. The 2011 42nd Annual Binghamton Geomorphology Symposium theme was *Zoogeomorphology and Ecosystem Engineering*, a testament to the attention given to this emerging sub-discipline. A keystone to the physical geographic perspective, separating it from biology and geology, is the holistic approach to environmental or landscape study. A physical geographer believes “[t]he systematic analysis of […] environmental processes operating in a place provides an integrated understanding of its distinctiveness or character” (National Research Council 1997, 30). To fully understand the Earth-shaping processes at work in a particular landscape, it is important to not rule out any potential variables at work. This study was set forth to determine the function of swallow species on a particular landscape as a specific and unique role in a complex environmental system.

CHAPTER 2

THEORETICAL FRAMEWORK

Biogeomorphology and Zoogeomorphology

Throughout the history of geomorphology, the significance of living organisms, both fauna and flora, have been greatly neglected (Viles 1988 and Butler 1995). Biogeomorphology can be described as "the concept of an approach to geomorphology which explicitly considers the role of organisms" (Viles 1988, 1). There are two approaches that can be made in biogeomorphology:

> "1) the influence of landforms/geomorphology on the distributions and development of plants, animals, and microorganisms; 2) the influence of plants, animals and microorganisms on earth surface processes and the development of landforms" (Viles 1988, 5).

In a comprehensive review of geomorphology textbooks dating from 1939 to 2007, Stine and Butler (2011) found that only a small amount of attention was given to biogeomorphic process. In general, more attention has been given to the role of vegetation influences on surface processes and landform development, particularly in riparian environments (Gregory 1976; Johnson et al. 1976; Mosley 1981; Marston 1982; Yanosky 1982; Murgatroyd and Ternan 1983; Osterkamp and Hupp 1984; Hupp and

Osterkamp 1985; Hupp 1986; Hupp and Simon 1991; Lane et al. 1995; Abrahams et al. 1996; Friedman et al. 1996; Scatena and Lugo 1996; Hulscher and Brink 2001; Baptist and Mosselman 2002; Baptist et al. 2004).

Prior to the late 20th Century, the study of animal-related geomorphic processes was not the primary focus of research; however, quantification of said processes were more commonly reported as supporting data. Charles Darwin can be considered the first publicized zoogeomorphologist with his work done on earthworms and bioturbation (Darwin 1838; Darwin 1881). Mitchell (1988) provides a comprehensive table of calculated rates of soil bioturbation by invertebrates (i.e., earthworms, ants, termites, cicadas, crustaceans, and scarabs) reported in the literature. Some of the earliest zoogeomorphic studies involving mammals were on moles (Godfrey and Crowcroft 1960), mima mounds (Ross et al. 1968; Meilke 1977), and gophers (Hickman and Brown 1973; Anderson and McMahon 1981).

Avian Zoogeomorphology

Zoogeomorphic processes may either be direct (i.e., digging for and caching of food, burrowing and nest-building, mound-building, wallowing, geophagy and lithophagy, and dam-building) or indirect, resulting from animal trampling, tunneling, burrowing, or vegetation removal on a surface, which may lead to subsurface infiltration, soil creep, surface wash, or rainsplash detachment (Butler 2000). Although it is true that the majority of bird species spend the bulk of their time in the air, or off of the ground surface (i.e., at their nests, perched in trees or other artificial posts), their role as geomorphic agents is not to be dismissed. Birds interact with the landscape during a variety of activities (e.g., mating rituals, nest construction and excavation, and digging for food). Avian species can impact Earth's surface via several geomorphic processes, which have been categorized as follows: internal clast transport as gastroliths, geophagy, clast transport for use as tools, clast and mud transport for use in nests, mound building and surface scraping, vegetative removal, and burrowing and nest-cavity excavation (Butler 1995).

Lithophagy, Geophagy, and Clast transport for Use as Tools

Through the processes of geophagy and lithophagy, soil and stones, respectively, are ingested by birds to be later returned to Earth's surface in different locations. Since birds lack teeth to masticate their food, they ingest stones or sediments that stay in their gizzards to grind the food in a similar fashion. These stones, or gastroliths, are transported in the gizzards of birds from their original location to the location where the bird either regurgitates the stones or dies. Research on this process reveals some data about the size and shape of the gastroliths (Milton et al. 1994; Johnson 1993), but not as a geomorphic process.

Birds that practice soil ingestion, or geophagy, include geese, parrots, cockatoos, pigeons, cracids, passeriforms, hornbills, and cassuaries (Emmons and Stark 1979; Wink et al. 1993; Diamond et al. 1999; Burger and Gotchfeld 2003). Percentages of soil ingestion in the diets of sandpipers (*Calidris* spp.), 7 – 30%; Canadian geese (*Branton Canadensis*), 8%; and wild turkey (*Meleagris gallopavo*), 9%, have been reported (Beyer et al. 1994). The Psittacidae family of birds (i.e., parrots, macaws, and parakeet species) will flock in the thousands along clay-rich riverbank in the Peruvian Amazon to ingest the nutrient-rich clay (Munn 1994 and Brightsmith and Munoz-Najar 2004). Up to 28 species have been identified ingesting clay at the same time on the same river bank in Peru (Brightsmith 2004) and up to 1,700 parrots of 17 species have been documented along a riverbank in a single day (Powell et al. 2009). Unfortunately, research has not yet addressed erosion rates along riverbank geophagy sites.

For some species of birds, clast material is used as a tool to obtain food sources. Ostrich eggs, for example, are too difficult to crack open without the use of tools by their predators. Egyptian vultures will pick up clast material and transport it 50 m (Van Lawick-Goodall 1968) or up to 200 m (Thouless et al. 1989) to either be dropped onto an ostrich egg (Van Lawick-Goodall 1968; Andersson 1989; Thouless et al. 1989) or used to hammer them open (Bertram 1992). Fan-tailed ravens (*Corvus rhipidurus*) are another species that use clast material to crack open ostrich eggs (Andersson 1989). In either process, the stones or clast materials are being transported from their original location in an unknown quantity, which may or may not have a geomorphic significance. Further research is needed to determine the significance.

Mound Building, Surface Scraping, and Vegetative Removal

A bird's individual surface scraping or mound construction may have an inconsequential effect on a region's geomorphology, but the investigation of such processes could reveal that the totality of avian scrapping and mound construction may play significant roles at the local or regional scale. Unfortunately, little of this geomorphic process is revealed in the literature.

Research on Australian birds has shown that eleven species rake forest litter, forty-four species nest in shallow scrapes in the soil, and three species build large incubating mounds of soil and litter (Mitchell 1988). The actions by this magnitude of species have potential for a significant geomorphic impact, but without quantification, one can only speculate.

Male lyrebirds (*Menura novaehollandiae*) will make eighty or more display mounds to attract potential mates prior to the breeding season (Mitchell 1988). They will clear vegetation in a 1 m diameter circle and rake soil to create mounds 10 to 15 cm high, the average area disturbed being 1.03 m^2. The average mass of soil used by the lyrebirds was 24 kg, and the soil surrounding the mounds was typically scraped to a depth of 9 cm. Mitchell (1988) also calculated the soil turnover rate as 0.4 MT ha^{-1} yr^{-1}, meaning the top 10 cm of soil is up-turned in 1,000 years.

Troy and Elgar (1991) estimated that a male Australian brush turkey (*Alectura lathami*) would displace 2,500 kg of soil as they construct their incubation mounds. The process takes approximately thirty-six days, working five to seven hours per day raking and moving soil and litter to build the mound. After the completion of the mound, the male will continue scraping and raking the soil each day for the following three to five months.

In a study in the French Pyrenees, Verbeek and Boasson (1984) measured the soil pH in avian nesting mounds and determined that the presence of guano caused the soils to be more acidic than surrounding soils. The increase in growth of vegetation at these sites may be attributed to the nutrient-rich guano. In addition, Verbeek and Boasson (1984) measured the height of these mounds, which ranged from 10 to 28 cm, with an average of 20.7 cm.

Scraping and denudation of vegetation can be associated with avian breeding, feeding, or trampling (Butler 1995). Ground clearing for courtship, breeding, and egg laying purposes by the African ostrich (*Struthio camelus*) has been documented by Bertram (1992). The male ostriches will scrape and grind the soil to attract a mate; however, it is not clear whether the collective scrapping of ostriches has geomorphic significance. The activity of colonial seabird nesting often results in the denudation of the surface (Mitchell 1988). High density populations for penguin species have been reported as 2.3 to 4.5 pairs per cubic meter (Hall and Williams 1981). The result of such densities has been known to completely denude the surfaces of areas 82,000 and 110,000 m^2 on the sub-Antarctic Marion Island (Hall and Williams 1981).

Although a majority of birds spend little time traveling on the ground, there are several species that impact the surface by trampling. Vegetation removal results from the prolonged nesting and trampling of various albatross species (*Diomedea exulans*) (Hall and Williams 1981; Joly et al. 1987). Hall and Williams (1981) reported 0.01 m^3 slopes resulting from the presence of surface-breeding albatrosses (*Diomedea and Phoebetria* spp.), but did not list how many existed to run calculations of overall impact on the region. Rockhopper penguins (*Eudyptes crestatus*) have trampled paths 2 to 5 cm deep on vertical rock faces along the New Island, Falklands Islands, shoreline (Splettstoesser 1985).

The impact of lyrebird feeding on slopes in southeastern Australia disturbed soil at a rate of 63 MT ha^{-1}. At this rate, the overturning of soil to a depth of 8 cm on 1 ha would take place in thirteen years (Mitchell 1988).

Lesser snow geese (*Anser caerulescens*) were found to do tremendous damage to the coastal vegetation along the Hudson Bay in Manitoba, Canada (Jefferies et al. 1979; Jefferies 1988). An individual goose was able to strip an area of 1 m^2 of turf fringe in approximately one hour. The lesser snow geese were also responsible for creating a series of terraces as they stripped vegetation back into supporting mounds of willows. Areas of denudation were recorded up to 300 by 300 m.

Dionne (1985) analyzed greater snow geese (*Anser caerulescens atlanticus*) in the St. Lawrence River estuary in Quebec, Canada. In addition to trampling damage to the vegetation, the greater snow geese were observed digging thousands of holes measuring 6 to 12 cm deep and 10 to 25 cm in diameter while searching for roots to eat. This digging occurs every low tide during the months when the greater snow geese are present (i.e., May, September, and October). The net effect of this zoogeomorphic process, combined with the washing of the tide water, was estimated to lower the tidal-marsh surface 8 to 10 cm annually (Dionne 1985).

Cadée (1989) examined the bioturbational impact of shorebirds in the tidal flat region of the Dutch Wadden Sea. Gulls (*Larus ridibundus*) had dug feeding troughs approximately 3 m long, 15 cm wide, and 3 cm deep along the tidal flat region. Additionally, shelducks (*Tadorna tadorna*) had created feeding craters 10 cm deep and 60 cm in diameter. Cadée (1989) estimated that 30% of the region had been re-worked by gulls and 15% of the area had been re-worked by the shelducks. The calculations suggested that annual sediment reworking by both avian species for this area was 2.5 cm thick.

Burrowing and Nest-cavity Excavation

The act of burrowing results in the displacement of soil from under the surface to above ground. Among avian species, burrowing, or nest cavity excavating, is uncommon (Terres 1980); however, it is more common in colonial seabirds, such as petrels, shearwaters, storm petrels, diving petrels, and some auks and penguins (Furness 1991). Individual burrowing by a pair of breeding birds may not significantly alter the landscape, but a variety of avian species breed in great densities, which collectively will affect the geomorphology of the region.

Terrestrial burrowing birds include: bee eaters (*Merops* spp.), kingfishers (*Megaceryle alcyon*), and bank swallows (*Riparia riparia*). Bank swallows excavate their burrows by lateral slashing with their beaks rather than pecking or digging with their toes (Gaunt 1965). They need at least a 3 m vertical face of a stream bank to excavate their nests (John 1991). The preferred soil content is high in sand, low in organic matter, and the constitution of the stream bank needs to be stable enough to prevent the nest from caving in (John 1991). Bank swallow nests, in one study, ranged in depth from 38 to 138 cm and averaged 70 cm (Gaunt 1965).

Colonial seabirds nest in extremely high numbers along coastal regions and on islands. At Heron and Masthead islands, approximately 35,000 wedge-tailed shearwater

(*Puffinus pacificus*) breeding burrows existed with burrow densities approximately 0.12 m^{-2} (Hill and Barnes 1989). Burrow depth has been measured averaging 2 m in length (Dyer and Hill 1991). In another study, Dyer and Hill (1992) reported an average burrow length of 0.91 m ranging from 0.10 to 2.35 m. Manx shearwater (*Puffinus puffinus*) burrows averaged 7 cm in diameter and approximately 1 m long at Rhum National Nature Research in west Scotland (Furness 1991). A rough calculation suggests roughly 4,000 cm^3 of soil displacement per burrow.

Hall and Williams (1981) studied petrel and prion burrows at subarctic Marion Island. The estimated population was between hundreds of thousands to millions of birds. Individual burrows removed up to 1 m^3 of material, but using a conservative 0.2 m^3 and a range of 0.6 to 1 million burrowing birds, approximately 1.2 by 10^5 m^3 of material would be impacted by the bird nesting excavations (Hall and Williams 1981).

Atlantic puffins (*Fratercula arctica*) have been recorded to do severe damage to coastal regions and islands where they gather in great numbers to breed. A quarter million breeding pairs have been estimated at the coast of Newfoundland and 87,000 pairs nesting on the island of Labrador (Snyder 1993). Atlantic puffin burrow densities have been reported as three per square meter (Harris and Birkhead 1985). In an extreme example of puffin zoogeomorphology, Furness (1991) describes how the Atlantic puffin was responsible for the destruction of an entire island off the coast of Wales. In 1890, approximately half a million puffins gathered on the island of Grassholm. The burrow density on the 8.9 ha island was two to three per square meter. By 1928, most of the island had been worn away and the puffin population was reduced to two hundred.

Penguins are another example of significant burrowing colonial seabirds. Müller-Schwarze (1984) noted that blackfooted penguins (*Spheniscus demersus*), which burrow to avoid the high subtropical insolation, numbered approximately 176,000. In southern Argentina, Magellanic penguin (*S. magellanicus*) burrows measured greater than 1 m long and 1 to 2 m deep (Stokes and Boersma 1991). In fifteen samples, the average dimensions were: 59.3 cm in length, 56.3 cm in width at the entrance, 37.3 cm in width at the neck, and 21.1 cm in height for an overall total calculation of 0.05 m^3 removal of soil. Breeding pairs were listed between 200,000 and 446,000, meaning that 10,000 to 22,000 m^3 of sediment was excavated at one rookery (Stokes and Boersma 1991).

Clast and Mud Transport for Use in Nests

The category pertinent to this research is that of clast and mud transport for use in nests. Swallows are not the only avian species to use clast and mud in their nesting. Hobson (1989) analyzed the pebble content in the nests of the double crested cormorant (*Phalacrocorax auitus*), ranging from 0.1% to 6.2%. The average pebble size was reported as 4 cm and ranged from 0.5 to 10 cm. In addition, several species of penguin and Atlantic Alcidae utilize pebbles in above ground nesting. Razorbills (*Alca torda*) use small stones to lay their eggs on, and the dovekie auk (*Alle alle*) pebble piles have been measured ranging from 1 to 4 cm in diameter (Harris and Birkhead 1985). A total estimate of nests was not provided to run calculations of overall impact for the nesting region; however, with hundreds to thousands of nesting auks, it is highly probable that these processes significantly alter the surface of the colonial seabirds' territory.

Multiple studies have addressed the amount of clast material transported for nest construction by colonial seabirds (Nettleship and Birkhead 1985; Cadée 1989; Heine and Speir 1989; Hobson 1989), but fewer studies have analyzed the impact of pure mud-nest construction. Brown and Root (1971) reported over 20,000 tons of soda mud used by the lesser flamingos (*Phoeniconias minor*) of Tanzania, and Gauthier and Thomas (1993) reported average nest sizes for the cliff swallow (*Petrochelidon pyrrhonota*) in their study in Sherbrooke, Quebec. The barn swallow (*Hirundo rustica*) and cave swallow (*Petrochelidon fulva*) are also mud-nesting birds in the Hirundindea family. Collectively, these three species of swallow are not clearly represented in the geomorphic literature.

Mud is a vital component of nest-building material to approximately 5% of bird species (Rowley 1970). Few of these species construct nests entirely from mud. The Hirundinidea family, swallows and martins, are among those that do. Swallows are the only birds to build elevated attached nests composed entirely of mud (Rowley 1970), though the nests of swallows are often lined with a mixture of feathers, hair, or straw (Soler et al. 1998). Swallows construct their nests in a molding fashion (Hansell 2000). Typically, over a thousand mud pellets are brought to the nesting site and fused together creating a solidified wall (Emlen 1954). The construction of their nests starts at the base, working upward and outward (Rowley 1970; Turner and Rose 1989; Keith et al. 1992). All members of the Hirundinidae mud-nesting clade build their nests in a similar way, suggesting mud-nesting arose from a single point in evolution (Winkler and Sheldon 1993). To reduce air space between the pellets, a vibrating motion is conducted by the head of the swallow, which acts to spread mud into the existing cracks by the process of thixotropy (Hansell 1984, 2000). In addition, swallows will load a mud pellet in their beak followed by a moister pellet of mud on top of their beak. When the new pellet is pressed against the existing nest, the moist mud on top of the beak seals the two (Emlin 1954). To keep the nest from distorting under the weight of the moist mud, swallows will interrupt their construction, traveling to new mud sources allowing the nest walls to dry. Color variations in the mud-nest walls support this behavior (Emlin 1954).

The Hirundinidea Family

The family Hirundinidae is within the order Passeriformes and consists of Swallows and Martins. The birds in this family are medium-sized songbirds with long, pointed wings, short, wide bills, discreet legs and feet, and long, forked or square tails. Swallows are all aerial insectivores with similar morphology and habits. The 89 species in this family are distributed across all continents except Antarctica and have the greatest diversity in Africa and South America. The 9 species in 6 genera found in North America are some of the best-studied wild birds in the world. In the state of Texas, there are nine species of birds that are in this family: the purple martin (*Progne subis*), gray-breasted martin (*Progne chalybea*), tree swallow (*Tachycineta bicolor*), violet-green swallow (*Tachycineta thalassina*), northern rough-winged swallow (*Stelgidopteryx serripennis*), bank swallow (*Riparia riparia*), cliff swallow (*Petrochelidon pyrrhonota*), cave swallow (*Petrochelidon fulva*), and barn swallow (*Hirundo rustica*) (Lockwood and Freeman 2004).

Nesting habits of this Family of Aves include: excavating tunnels in sandbanks, constructing nests in holes or crevices in trees, banks, or cliffs, and constructing cup-shaped or gourd-shaped mud nests. Many species nest near humans and take advantage of artificial structures. Cavity-nesting swallows include: tree swallows (*Tachycineta bicolor*), violet-green swallows (*T. thalassina*), purple martins (*Progne sbuis*), northern rough-winged swallows (*Stelgidopteryx serripennis*), and bahama swallows (*T. cyaneovirdis*). The geomorphic agency of these swallows is not relevant because of the adoption of existing holes or crevices for their nesting sites. The bank swallow (*Riparia riparia*), however, earns its British name "sand martin" by excavating tunnels in sandbanks. The geomorphic agency of this process is outside the scope of this research, but does make for an excellent future study in zoogeomorphology. The only species of swallow to construct nests entirely of mud are the barn, cliff, and cave swallows (*Hirundo rustica, Petrochelidon pyrrhonota, and P. fulva*). As the focus of this research, each species are discussed separately in the following sections.

The Barn Swallow (Hirundo rustica)

The barn swallow (*Hirundo rustica*) is a medium sized swallow weighing between 17 to 20 g (The Birds of North America On-line 2012). It is easily distinguished from other North American swallows by its long, forked tail, and extensive chestnut underparts. Adult plumages are similar throughout the year, steely-blue upperparts, and chestnut underparts and forehead. Males have longer outer tail-streamers and tend to have darker chestnut underparts when compared to females. In addition, the North American race of barn swallow has more chestnut on underparts, compared to the whiter underparts of most Eurasian birds. Juveniles have paler underparts and less forked tails than the adult plumage (The Birds of North America On-line 2012) (Figure 1).

Figure 1: The barn swallow (*Hirundo rustica).*

In flight, the barn swallow rarely glides (short periods of 1 or 2 seconds), and will have bursts of straight flight that last longer than other swallows (Blake 1948). Their speed averages around 8.0 m/s ± 2.0 SD (Brown and Brown 1999). Swallows are rarely found on the ground and will fly up to heights of 25 m (Brown and Brown 1999). The deeply forked tail allows for higher aerodynamic lift, sharper turns, and quicker dives than other swallows (Norberg 1994). Maneuverability is also attributed to the symmetry in length of the outer tail-streamers (Møller 1991).

The barn swallow is the most widely distributed and abundant species of swallow in the world (Brown and Brown 1999), indicating their potential as a geomorphic agent (Figure 2).

Figure 2: Distribution of the barn swallow in North America (Armstrong 1995).

They are small in size, averaging 15 cm in length (Robbins et al. 1966). They have a dark orange forehead and throat with either pale orange or dark iridescent underparts. The long, deeply forked tail of the barn swallow distinguishes it from other members of the Hirundinidae family. Barn swallows have a diverse habitat range and may be found in farmlands, rural areas, suburban areas, or villages. Colonial nesting sites are found in various structures such as barns or other farm outbuildings, bridges, wharves, boat houses, or culverts (Harrison 1975). The colonies are relatively more abundant in human-built structures than in natural settings such as caverns and cliff sides. The site-specific requirements for their mud-nests include the presence of a ledge and vertical wall to support the nest and a protective roof (Robbins et al. 1966 and Link 2004). They have an open-cup shaped nest, and their nesting location is classified as mid-story/canopy nesting (Ehrlich et al. 1988). Both male and female barn swallows will travel up to 800 m to gather mud pellets in their beaks (Harrison 1975 and Link 2004). The process of nest construction takes between 6 to 80 days, but older nests will often be repaired for the next brood (Harrison 1975).

Barn swallows are neotropical migrants with an 18 to 23 day period to fledge and a 13 to 17 day incubation period. The common clutch size is 4 to 5, and average number of broods is 2 per season (Ehrlich et al. 1988). Surveys during the breeding period show that barn swallows are common throughout most of North America. By December, they are entirely absent from North America except for the southernmost parts of Florida and Texas (Gough and Sauer 1997) (Figure 3).

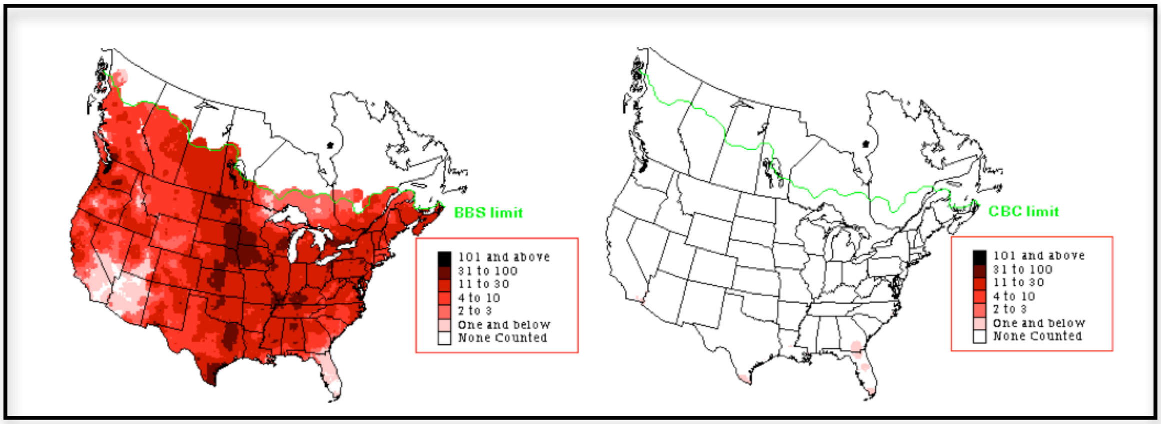


Figure 3: Barn swallow distribution in June (left) and mid-December (right). The BBS (on the left) represents a Breeding Bird Survey, which is performed in June by volunteers on over 4,000 bird counts (Gough and Sauer 1997). The CBC (on the right) represents a Christmas Bird Count, which is performed in one calendar day any time from mid-December to early January by volunteers (Gough and Sauer 1997).

Winkler and Sheldon (1993) analyzed the evolution of nest construction in seventeen species of swallows (*Hirundinidae*). Their investigation compared DNA-hybridization phylogeny with nest data to reveal the evolution in nest construction and composition (Figure 4). The results from this comparison indicated that the barn swallow's mud-nesting evolved in areas that lack the availability of natural cavities (for nesting) or substrates for burrowing (Winkler and Sheldon 1993).

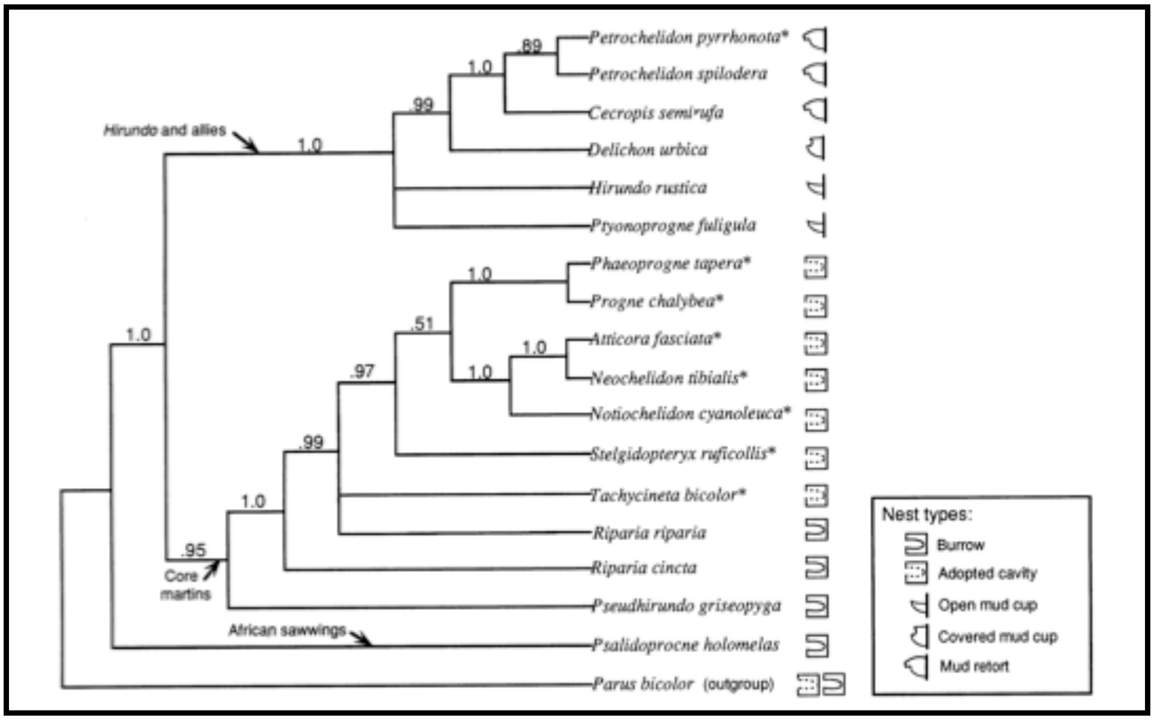


Figure 4: Nest types of seventeen swallow species (Winkler and Sheldon 1993). The barn swallow (*Hirundo rustica*) has an open mud cup type of nest.

Information concerning the geomorphic characteristics of barn swallow nests is limited. Harrison (1975) reported the following dimensions for an average barn swallow nest: the outside diameter is approximately 12.7 cm and the inside diameter approximately 7.6 cm. As many as 55 nests have been reported in one barn; however, the mean number of nests per site is 6 to 8 (Harrison 1975) (Figure 5).

Figure 5: This photograph of barn swallow nests along the beams within a barn (Fujita and Higuchi 2007) (left) reveals similar ceiling structure and nesting preference to that of the cave swallow nests in the Alkek Parking Garage joints in San Marcos, Texas (right).

Soler et al. (1998) conducted a study on the barn swallows of Badajoz, Spain, in which they analyzed different variables associated with nest building participation and gender. Their study revealed that male tail length, an attribute previously documented as an attractive characteristic of male barn swallows, was negatively correlated to their participation in gathering nest materials. They reported nest material volume for newly constructed nests as approximately 300 cm^3 (n = 14) (Soler et al. 1998). Møller (2006) calculated nest volume in a study that of 757 nests. This study presented the yearly averages of outer nest volume (370 cm^3), nest material (228 cm^3), and nest wall thickness (24 mm). Soler et al. (2007) analyzed the relationship between nest size and the inhabitants' immunity to specific parasites. The average nest volume reported in this study was 189 cm^3, although the methods for this calculation were not described.

These articles do not include nest mass in their calculations. In fact, no reference to barn swallow mass could be found within the existing literature. Ward (1996) analyzed the energy expenditure of female barn swallows during egg formation by placing scales under the nests and reporting the differences in female body mass, but did not report the mass of the nests sampled in the study. Kilgore and Knudsen (1977) removed two 50 g samples from seven barn swallow nests to compare the texture, sand size, organic matter, and water content with samples from five cliff swallow nests. The textural components of the barn swallow nests sampled were 56.4 ± 1.1% sand, 31.5 ± 0.9% silt, and 11.9 ± 0.6% clay. The variation of the sand-sized particles was 44.9 ± 2.5% fine, 23.8 ± 0.9% medium sized, 8.0 ± 0.6% coarse, and 21.7 ± 1.9% very coarse size. The organic matter included grass stems, horse hair, and feathers and accounted for an average 6.6 ± 0.5% of the barn swallow nest composition. The moisture content for the samples was low, averaging 1.8 ± 0.1%. A low moisture content seems logical, since humidity can cause the nests to decay (Winkler and Sheldon 1993).

The Cliff Swallow (Petrochelidon pyrrhonota)

The cliff swallow (*Petrochelidon pyrrhonota*) is 12 to 15 cm in length and is square-tailed, in contrast to the barn swallow's long, deeply forked tail (Salmon and Gorenzel 1981). The cliff swallow has a white forehead, dark rust-colored throat, and steel blue crown and back. Its rump is a pale, orange-brown color. Males and females can be distinguished only by the presence or absence of a brood patch or cloacal protuberance. In addition, males generally have a larger patch of dark blue at the base of throat. Juveniles exhibit variability in color and degree of white speckling on the throat and forehead (Brown and Brown 1995) (Figure 6).

Figure 6: The cliff swallow (Petrochelidon pyrrhonota).

Cliff swallows fly at various heights, from just above the Earth surface to 60 m. The average speed has been reported as 8.7 m/s (Withers 1977), although while commuting from mud holes to colony sites, cliff swallows have been clocked at 15.5 m/s (Brown and Brown 1995). Wing flapping rates range from 2.9 to 4.5 flaps/s, averaging 3.9 flaps/s (Blake 1948). Glides are short and frequent, lasting 2 to 3 seconds on average, but may last over 10 seconds. Of the North American swallows, the cliff swallow is unique in their gliding, slanting the wings downward (Blake 1948).

Cliff swallows are present throughout much of western North America (Figure 7).

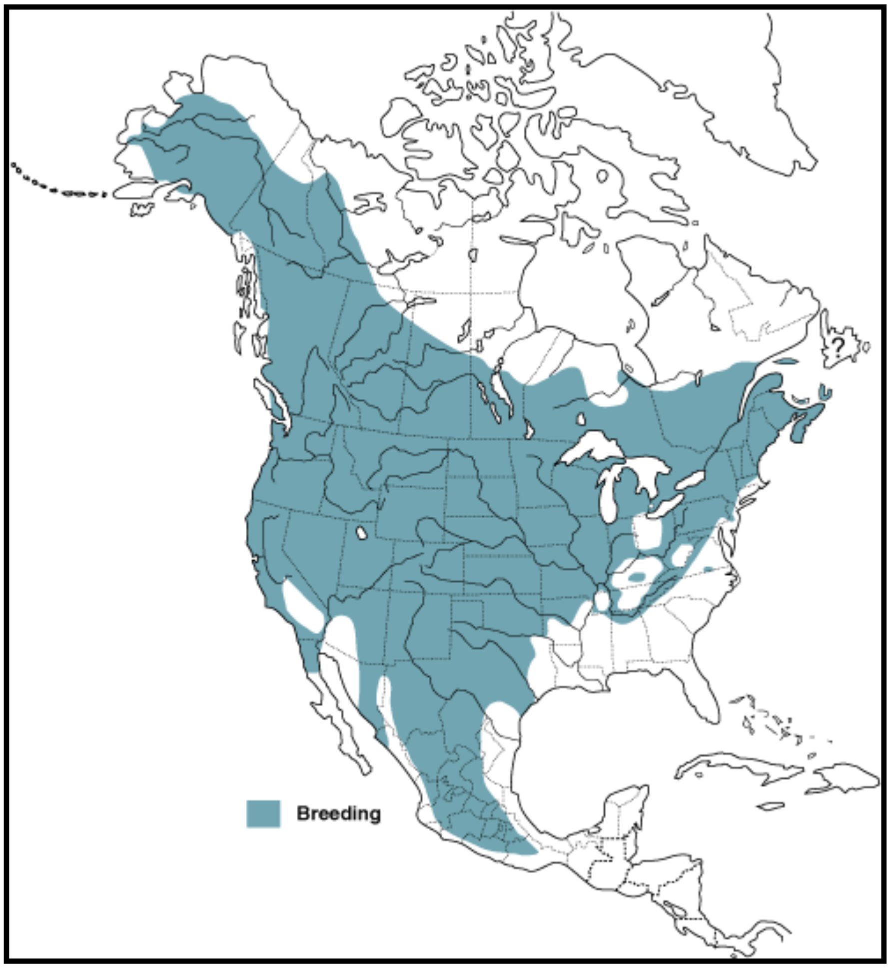


Figure 7: Distribution of the cliff swallow in North America (American Ornithologists' Union 1983).

Their elevation ranges from sea level to 3,000 m, and is rarely at higher elevations (Grinnell and Miller 1944). Their breeding period begins between March and early May and lasts until August or September. The winter range of cliff swallows is from Brazil to Argentina and Chile (A.O.U. 1983). This species of swallow resides in farmlands, villages, cliffs, and in fresh or saltwater areas (Harrison 1975) and tends to nest near open fields for feeding and bodies of water for use as a mud source required for nesting

(Brown 1988). Emlen (1954) published essential features of nesting habitat for cliff swallows as the following: an open foraging area, a vertical substrate with an overhang for nest attachment, and a supply of mud suitable for nest construction. Nesting locations are commonly inhabited in consecutive years, and old nests are often reused and refurbished. Upon arrival in the spring, cliff swallows spend much of the day foraging and gradually spend more time at the colony throughout the summer. Withers (1977) recorded the daily activities of cliff swallows in California during different time periods of the summer migration. During nest construction, swallows spent 9.5 h each day foraging, 3.0 h building nest, and 11.5 h in nest; during incubation, 6.8 h were spent foraging, 0.4 h refurbishing nest, and 16.8 h in nest; and during nestling period, 7.5 h foraging, 0.2 h refurbishing nest, and 16.3 h in nest.

Cliff swallow nests are gourd-shaped structures made of pellets of mud and clay, which are plastered to sides of buildings, bridges, under eaves of barns, houses, public buildings, and on the sides of cliffs (Figure 6). The nest chamber is globular in shape and often has a tubular entrance tunnel. The cliff swallow nests are sparsely lined with grasses, hair, or feathers. Like the barn swallow, both sexes will travel between their nesting site and mud sources collecting mud pellets in their beaks. Nest construction typically takes 1 to 2 weeks, with an averaging rate of about 2.5 cm a day. Distances traveled to mud sources may range from 6 to 805 m from the swallow colony (Emlen 1954), but has also been reported as a mean distance of 745 m in a study by Gautheir and Thomas (1993). Cliff swallows will collect mud from puddles forming after a rain, if they are closer to their nesting site. The quality of mud varies from colony to colony according to local conditions. Poorer quality nests made of sandy silt are more susceptible to damage or destruction when compared to smaller soil texture sizes. Several types of mud were commonly found in a single nest (n = 152) in a study conducted by Emlen (1954), and on average a nest will contain 900 to 1,200 mud pellets (Harrison 1975). Humid weather often causes the collapse of nests, in which case the swallows have to rebuild in order to lay and brood their eggs. Dried grass is used for nest lining, but "never as much as is commonly found in nests of the Barn Swallow" (Emlen 1954, 21).

The dimensions for an average cliff swallow nest were reported by Harrison (1975) as follows: the overall length is approximately 19.7 cm, the width at the base of the nest is approximately 16.0 cm, and the opening averages 4.4 cm high by 5.1 cm wide. Entrance tubes, if present, range from 12.7 to 15.2 cm in length. Running a rough calculation for volume (20 cm x 16 cm x 14 cm) resulted with an average nest volume of 4,480 cm^3. Dimensions of 15 sample nests taken by Emlen (1954) varied from 14.0 to 26.7 cm in overall length with a mean of 19.6 cm and from 14.0 to 20.3 cm in basal width with a mean of 16.0 cm. The entrance opening ranged from 3.3 to 5.1 cm (mean 4.3 cm) high and from 3.8 to 6.9 cm (mean 5.1 cm) wide. The height at the back of the nest ranged from 10.2 to 11.4 cm. Using these dimensions, an average nest volume of 3,520 cm^3 can be estimated from the measurements 20 cm x 16 cm x 11 cm. Emlen (1954) also listed the thickness of the floor and walls, which ranged from 0.6 to 1.7 cm (mean 1.1 cm).

Literature representing cliff swallow nest mass is limited, but not absent. Emlen (1954) reported two average-sized nests weighing 578 and 816 g when thoroughly dry. Gauthier and Thomas (1993) reported the average nest mass in different categories depending on whether they were detached (i.e., separate from other nests), semi-detached (sharing one wall with a neighboring nest), or row nests (sharing two walls with neighboring nests). The mean nest mass for these three categories was 652.8 ± 75.3 g (n = 37) for detached nests, 602.7 ± 91.4 g (n = 24) for semi-detached nests, and 573.1 ± 58.1 g (n = 8) for row nests. The detached nests weighed 13.9% more than the row nests and required 1,813 mud pellets compared to 1,592 pellets.

Cliff swallows nest in dense colonies, where hundreds and even thousands of nests may be present (Emlen 1954; Harrison 1975; Brown 1985 and 1988). Harrison (1975) reported a maximum count of 800 nests in a colony with a mean number of 15 nests per colony; however, Brown (1988) conducted an extensive study revealing a range of nest count from 2 to 3000 nests in a colony with a mean of 323.6 and SD of 510.0. This study was conducted from 1982 to1986 and involved 218 colonies totaling 70,545 nests in or near Keith, Garden, and Lincoln counties in southwestern Nebraska. Brown (1988) reported the most common nest count as 350 nests, and excluded uninhabited nests. After the primary construction of these nests, cliff swallows were observed continually adding fresh mud to damaged areas throughout the breeding season.

Using an average cliff swallow nest mass reported by Emlen (1954), 697 g, and extrapolating the mud sediment transfer in Brown's study area, the total amount of sediment transport would be approximately 49 metric tons. Using the more conservative average for row nest mass as reported by Gauthier and Thomas (1993) (573.1 g), the total mud transport would be approximately 40 metric tons.

The Cave Swallow (Petrochelidon fulva)

The cave swallow (*Petrochelidon fulva*) is a loosely colonial passerine that resides in northern South America, Central America, the West Indies, Mexico and the southwestern United States (A.O.U. 1998; West 1995). Their physiology is similar to the more widely distributed cliff swallow. The cave swallow can be identified by its reddish brown throat and rump and tinged flanks of the same color (Perez-Rivera 2009) (Figure 8).

Cave swallows are acrobatic flying birds, capable of catching insects on the wing. Cave swallows often fly through dense vegetation while foraging and maneuver well in crowded conditions (Strickler and West 2011). Flight patterns of cave swallows will vary depending upon terrain of their nesting site. If entering a sinkhole nesting site, they will "parachute" with set wings, floating and occasionally flapping. To exit, they make spiral movements as they ascend the sinkhole. When approaching culverts, bridges, and cave entrances the flight becomes more horizontal (Strickler and West 2011).

Daily activities are not well quantified for cave swallows, but estimates for breeding adults suggest they spend time as follows: in flight 83% of time, perched or feeding young at nest 16%, on ground gathering nest material or bathing <1% (Strickler and West 2011).

Figure 8: Cave swallow in the Alkek Parking Garage on Texas State University- San Marcos campus (left) and cave swallows in nest (Pérez-Rivera 2009) (right).

The breeding range stretches from the Yucatan through the Antilles to southern New Mexico and central Texas (A.O.U. 1998) (Figure 9). The cave swallow breeding season in Texas extends from late March to late August. Since the mid 1980s they have been sighted wintering in Texas, but it is more common for them to winter in Mexico or Central America, (Lasley and Sexton 1987; McNair and Post 2001). Breeding cave swallows in Texas were first discovered in caves and sinkholes in 1915 (Thayer 1915). Prior to 1970, there were approximately 30 nesting locations, all found in the Edwards Plateau region of central Texas (Selander and Baker 1957; Baker 1962; Reddell 1967). Since 1970, their nesting range has extended in all directions, and colonizing of artificial structures, such as bridges and culverts, has taken place (Martin 1974; Palmer 1988).

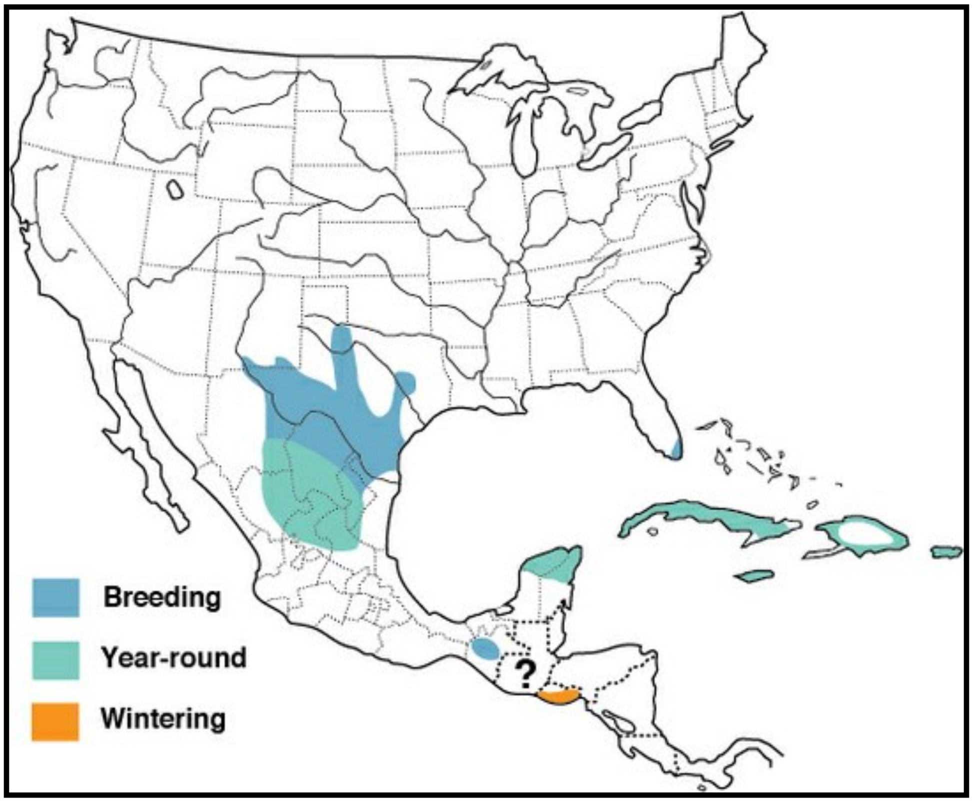


Figure 9: Distribution of the cave swallow in North America (Arnold 2001).

The literature on cave swallows focuses on the expansion of their nesting locations and breeding, rather than the dimensions and mass of their nests. Nest counts are given in several articles, and their nests are often compared to those of the barn and cliff swallow. Swallow colonies can have anywhere up to 1,500 or more nests (Selander and Baker 1957; West 1995; Weaver and Brown 2005). Some nests resemble those of barn swallows in shape, whereas others have incomplete tunnel entrances similar to cliff swallow nests. The majority of their nests are half-cup shaped with flared rims, but variation exists both between and within colonies (Figure 8). Weaver and Brown (2005) reported on 17 colonies ranging in nest population from 5 to 243. Huels (1985) summarized the nest settlement of a lone male cave swallow between four cliff swallow nests on the University of Arizona's campus. Although the dimensions of the nest are not included, geomorphic agency is apparent in the study:

> "I saw only the Cave Swallow on the broken nest. He appeared to center his activity at this nest. He frequently chased and displayed in flight to flying Cliff Swallows, and he added about 2 cm of mud to the rim of the nest before temporarily shifting his activity to another nest" (Huels 1985, 441).

CHAPTER 3

STUDY SITE GEOGRAPHY

This study will involve the investigation of fifteen swallow colonies along Interstate 35 and within the city limits of San Marcos, Texas. San Marcos is located at 29º 52' 59" North latitude by 97º 56' 28" West longitude. The land area is 47 sq. km with an estimated population of 49,565 for 2009 (US Census Bureau 2011). Each of the fifteen sites is either an overpass or a bridge section of the interstate as it passes over or under other roads and/or streams (Figure 10). The section of Interstate 35 ranges from Exit 210 in the north to Exit 199 in the south. The highway runs in a Northeast-Southwest direction with a slight deviation from a straight path. In addition to these locations, the Alkek Parking Garage, on the campus of Texas State University-San Marcos, is a separate study site and is also within the city limits of San Marcos.

Climate of San Marcos, Texas

The climate of this region of Central Texas is the subhumid transition zone between humid subtropical and subtropical semi-arid climates (Larkin and Bomar 1983).

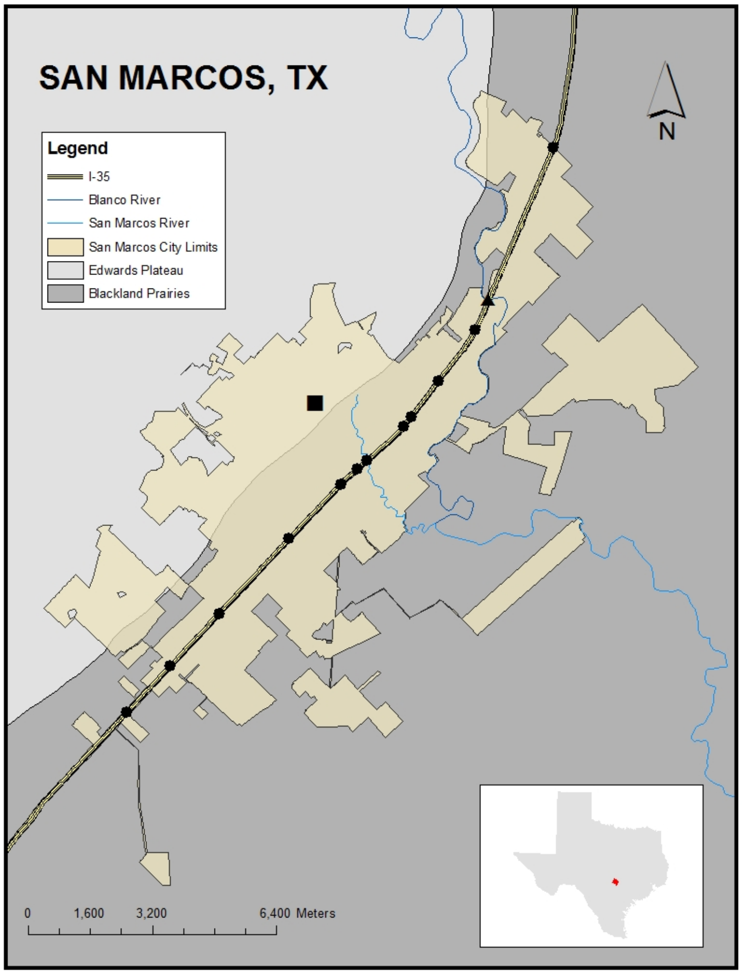


Figure 10: This map of San Marcos, Texas was created using ArcGIS version 9.2 and data gathered from TPWD (2010), the US Census Bureau (2010), and the City of San Marcos (2012). The fifteen bridge and overpass study sites are shown on the map using twelve black circles and one black triangle. The triangle represents three bridges at one site, which is where Interstate 35 and two frontage roads cross the Blanco River. The black square marks the location of the Alkek Parking Garage. The parking garage is the only site that is on the Edwards Plateau; all other sites are on the Blackland Prairie.

Generally, this region goes from semi-arid to humid from west to east. Average high and low temperatures for San Marcos, Texas range from 16°C and 4°C, respectively, in January to 35°C and 23°C, respectively, in both July and August (US NOAA 2011). This region has a long growing season of approximately 250 days (Larkin and Bomar 1983). The precipitation for this area fluctuates year to year; however, the majority of the precipitation will occur in both the spring and fall seasons. The average yearly precipitation for San Marcos, Texas, is 945 mm but has ranged from as little as 380 mm to as much as 1,500 mm per year between 1981 and 2010 (US NOAA 2011).

Geomorphology and Soils

The 694,700 sq. km area of the State of Texas is broken into ten ecoregions: 1) East Texas Pineywoods, 2) Gulf Coast Prairies and Marshes, 3) Post Oak Savannah, 4) Blackland Prairies, 5) Cross Timbers and Prairies, 6) South Texas Plains, 7) Edwards Plateau, 8) Rolling Plains, 9) High Plains, and 10) West of the Pecos or Trans-pecos (TPWD 2008). San Marcos overlaps two regions: Region 7, the Edwards Plateau and Region 4, the Blackland Prairies. The fifteen bridge sites are all located on the Blackland Prairie to the southeast of the Balcones Escarpment, whereas the Alkek Parking Garage site is located on the Edwards Plateau. A distinct difference exists in the underlying geology between the Edwards Plateau and the Blackland Prairies Ecological Regions. The Blackland Prairie is gently rolling with an elevation range of roughly 90 to 250 m above sea level (Texas Forest Service 2008). The underlying geology of this region consists of Upper Cretaceous marine chalks, marls, limestones, and shales (TPWD 2008).

The soils of this region are calcareous, alkaline, heavy clay soils that are very dark in color and rich in nutrients for agriculture. Most of zonal soils are classified as mollisols, but there are widespread montmorillonitic vertisols (Batte 1984).

The Edwards Plateau is a geologically distinctive region of Texas that covers 93,240 sq. km or approximately 17% of the state (Lockwood 2001). It is primarily underlain by Cretaceous limestones that slopes in elevation from the northwest to southeast; elevation ranges from 716 m at Ozona in the west to 168 m at Austin to the east (Lockwood 2001). San Marcos is at the lower end, at 189 m of elevation. Soils in the region are thinner and rockier than those in the Blackland Prairie (Batte 1984).

The study sites are all within the city limits of San Marcos, Texas, which is located in Hays County. Hays County is positioned in the southeastern border of the Edwards Plateau and along the Balcones Escarpment. The Balcones Escarpment has numerous normal faults, cross faults, grabens, horsts, step faults, and en echelon faults and is considered to be a tensional structural system (Grimshaw and Woodruff 1986). The geology on either side of the escarpment differs; in the west, Lower Cretaceous stratigraphic units made of limestones, dolomites, and marls are exposed at the surface, whereas to the east, Upper Cretaceous, nonresistant chalk and calcareous clay units are exposed. The existing fault-line scarp, stretching from Waco to San Antonio on the eastern border of the Edwards Plateau, is the result of differential erosion. As a result, the agricultural use of the land east and west has been historically different; cropland is found in the east and ranching in the west (Grimshaw and Woodruff 1986; TPWD 2008).

Vegetation

The Blackland Prairies were historically a region of tall-grass prairies, but the vast majority of this land has been converted to cropland and other agricultural enterprises such as livestock grazing (TPWD 2008). Cotton, corn, milo, and wheat are some of the most commonly grown crops. Urban expansion into this ecological region also contributes to the loss of native vegetation. Mesquite (*Prosopis glandulosa*), Hackberry (*Celtis occidentalis*), Elm (*Ulmus crassifolia*), and Osage Orange (*Maclura pomifera*) are common woody vegetation found in the Blackland Prairies. Along steep or sloping terrain, woody vegetation consists of Eastern Red Cedar (*Juniperus virginiana*), Ashe Juniper (*Juniperus ashei*), Cedar Elm (*Ulmus crassifolia*), Texas Persimmon (*Diospyros texana*), Elbowbush (*Forestiera pubescens*), Deciduous Holly (*Ilex decidua*), and Live Oak (*Quercus fusiformis*) (Correll and Johnson 1970; McMahan et al. 1984; Griffith et al. 2004).

The vegetation community on the Edwards Plateau has undergone tremendous change since the mid-1800s with the settlement of Europeans. Prior to the colonization, the Hill Country was a grassland savannah, maintained in balance by grazing bison and antelope, as well as by wild fires (Armstrong et al. 1991). Years of livestock grazing in fenced-off areas and fire suppression have caused dramatic changes to the landscape. Today, this region is more woodland and shrubland than grassland and is characterized by poor quality browse, forb, and grass plants. The midgrass and tallgrass communities of the past have been replaced by shortgrass communities (TPWD 2007). Much of the plant diversity has been reduced, and Ashe Juniper (*Juniperus ashei*), once restricted to canyon areas, is now the dominant plant species. In the Balcones Canyonlands, the southeastern portion of the Hill Country and region of the Alkek Parking Garage site, the vegetation is dominated by woodlands with grasslands in limited areas (Riskind and Diamond 1988). The woodlands are composed of Ashe Juniper-oak with a canopy roughly 6 m high. The underlying topography for this type of woodland is typically shallow soils on steep slopes (Riskind and Diamond 1988; Griffith et al. 2004). Trees commonly found in the Hill Country include: Plateau live oak, Texas oak, Texas persimmon, and Ashe juniper (Griffith et al. 2004). Riparian trees include sycamore, ash, black willow, little walnut, and eastern cottonwood, white pecan, American elm, and plateau live oak (Correll and Johnson 1970; McMahan et al. 1984; Griffith et al. 2004).

CHAPTER 4

METHODOLOGY

The methodology for this dissertation includes the following components: 1) an overview of the methods to determine total sediment transport and annual sediment transport by swallows, 2) description of the sample collection, and 3) discussion of the statistical measurements implemented in the study. Swallow mud-nests have been collected for multiple purposes in the literature, and the process of collecting nests by hand with the aid of a ladder and bags to store individual nests can be attributed to Brown and Brown (1996); however where nests were positioned out of arms reach from the ladder, pvc pipe was used to remove the nests from the site, while standing on the ground. Mass measurements for the purpose of statistical comparisons between mud-nest types are currently absent in the literature. The overview section will elaborate on the processes implemented in this study.

Overview

Calculations for total sediment displacement from the clast transport of mud-nesting swallows in Central Texas were made from nest counts and the calculated median mass sampled from one of the fifteen colony sites along Interstate 35. Two counts were conducted for each swallow colony: 1) a count of fully intact nests and 2) a count of partially eroded nests. Nests that appeared to be at least 50% intact were considered partially eroded. The following equation (Equation 1) was applied to estimate the total existing sediment per site: total existing sediment = $[(n_f * M) + (n_p * 0.50M)]$, where n_f is the number of fully intact nests present in November 2011, n_p is the number of partially eroded nests present in November 2011, and M is the median nest mass of the gourd-shaped mud-nest sample. Accurate nest counts were conducted by analyzing photographs of the swallow colonies taken after the 2011 nesting season. These photographs were taken in November 2011. The digital photographs were uploaded to a personal computer and iPhoto software was used to filter the images to ensure the clearest view of the nests.

Swallows are well known to reuse existing nests from year to year or to repair partially eroded nests. Understanding the total existing sediment at a colony does not reveal the quantity of sediment transported by swallows annually. Two studies were implemented to address this research question, each concentrating on separate scenarios.

The first study analyzed the Alkek Parking Garage on campus at Texas State University-San Marcos. This location represents the conditions of a newly settled colony. Although swallows have previously colonized this site for at least four years, all nests were removed in March 2011 by the campus parking authority. It should be noted that the removal of the nests was not a response to this research; it was conducted in response to complaints made by university staff and faculty whose vehicles were subject to the fecal droppings. In March 2011, the garage was visited to ensure all nests were being removed from the site. The swallows did return during the summer of 2011 and re-colonized the garage. A nest count was conducted in October 2011 to see how many nests were built in one season. This count was conducted with the aid of one assistant. The researchers walked beneath the ceiling joints and recorded a tally mark for each nest observed. Walking beneath the ceiling joints proved to be the most organized approach and prevented recounting a single nest or missing a nest in the count. The annual sediment transport to this colony, representing a new colony, was estimated using the following equation (Equation 2): annual sediment transport = n_f * M, where n_f is the number of nests (note that there were no partially eroded nests because of the removal of all pre-existing sediment in March 2011) and M is the median nest mass for the cup-shaped mud-nest sample.

The second study of annual sediment transport focused on the fifteen bridge sites along Interstate 35. All but one of these sites had both fully intact and partially intact nests present before the swallows return in 2011. The one exception had no evidence of swallow colonization; however, the site is located above a water source and has the bridge structure to support swallow nests. It is currently unclear why swallows have not colonized this bridge. The site was included to see if any swallows colonized during the summer of 2011. Unfortunately, swallows did not nest at this site. Speculations as to why Site H was not chosen for nesting are addressed in the Chapter 6 Discussion and Conclusions. Site H was not included in any statistical analysis.

To estimate the amount of sediment transport by swallows at the remaining fourteen sites in one nesting season, digital photographs taken before and after swallow nesting were compared. Using iPhoto software on a personal computer, all photographs were digitally adjusted to ensure a clear view of each nest. Counts were conducted of all fully intact nests and partially intact nests. The photographs for this study were taken in March 2011 and in November 2011. The difference in existing sediment between March and November was used to estimate the quantity of mud transported by swallows in the summer of 2011. The formula for estimating the annual sediment transport by swallows to pre-existing sites is as follows (Equation 3): Annual sediment transport = $[(n_{f2} * M) + (n_{p2} * 0.50M)] – [(n_{f1} * M) + (n_{p1} * 0.50M)]$, where n_{f1} and n_{p1} are the number of full nests and partially eroded nests for March 2011, respectively, n_{f2} and n_{p2} are the number of full nests and partially eroded nests present in November 2011, respectively, and M is the median nest mass of the gourd-shaped nest sample.

In order to understand the variation in productivity among the swallow colonies, the percentage increase in sediment per site from March to November 2011 was calculated. The percentage increase was determined by dividing the annual sediment transport per site by the total existing sediment in March 2011, then multiplying by one hundred (Equation 4): Percentage Increase per Site =

$$\frac{[(n_{f2} * M) + (n_{p2} * 0.50M)] - [(n_{f1} * M) + (n_{p1} * 0.50M)]}{[(n_{f1} * M) + (n_{p1} * 0.50M)]} * 100$$

where n_{f1} and n_{p1} are the number of full nests and partially eroded nests for March 2011, respectively, n_{f2} and n_{p2} are the number of full nests and partially eroded nests present in November 2011, respectively, and M is the median nest mass of the gourd-shaped nest sample.

Currently, it is unclear whether a larger swallow colony transports a greater percentage of sediment, and therefore, is more geomorphically productive than a smaller colony. Making the assumptions that colony size is reflected by the total existing amount of sediment at the end of a summer season, the total sediment present in November 2011 was used to reflect colony size. Percentage increase in sediment per site was used to reflect swallow productivity.

The barn, cave, and cliff swallows all construct their nests entirely of sediment; however, structural differences exist between the cup-shaped nests of cave and barn swallows and the gourd-shaped nests of cliff swallows. Understanding the difference in nest mass between the two structures will indicate the geomorphic agency involved in the process of nest construction.

Sample Collection

The swallows of Central Texas construct mud-nests that are either cup-shaped or gourd-shaped. Both types of nests were found within the study site. Peer-reviewed literature has yet to determine whether there is a significant difference in mass between these two types of mud-nests; therefore, two samples of 30 nests each were collected to answer this question. One sample, described in more detail below, was collected from one of the bridges over Interstate 35. The second sample was collected in the Alkek Parking Garage. In addition, the median mass from the appropriate sample was applied to the counts of nests of the same shape to calculate more accurate estimations of total existing sediment per site and annual sediment transport per site.

A thirty-nest sample was taken from one of the Interstate 35 bridges running over the Blanco River. This site was chosen as the sampling site for two reasons. First, the greatest number of fully intact nests was found there. Second, this site is one of two sites that do not have heavy traffic flow. Sampling nests in close proximity to traffic could potentially disrupt the process and presents danger to both the researcher and to motorists. Thirty fully intact nests were removed with the aid of two assistants, fifteen feet of pvc pipe, thirty one-gallon garbage bags, and a plastic tarp (Figure 11). The pvc pipe was used to knock the nests down from their position along joints in the bridge structure (Figure 12). This process was conducted one nest at a time. To prevent loss of sediment upon falling to the ground, the tarp was laid below. The tarp was then folded to group the loose sediment and lifted to empty the sediment into a one-gallon garbage bag. This process was repeated thirty times. Using a spring scale, each nest was weighed individually while inside of a garbage bag. To prevent the added weight of the bag in the calculations, an empty bag was weighed. The weight of the empty bag was subtracted from each measurement of nest mass.

Figure 11: Tarp and pvc pipe used for sample collection at Site B1.

Figure 12: Sample collection at Site B1.

The nests in the parking garage are of a different structural design than those sampled at the Blanco Bridge colony along Interstate 35 (i.e., the garage nests are cup-shaped and the bridge nests are gourd-shaped). Thirty cup-shaped nests were previously sampled from the Alkek Parking Garage on November 7th, 2009. These nests were extracted with the aid of one assistant, a six-foot stepladder, a paint scraper, and heavy-duty garbage bags. One researcher would climb the ladder and scrape the nest from its position, and the other researcher would catch the falling nest in a garbage bag. This method was different than the one used at the Blanco River bridge colony because of the difference in elevation of the nests. The nests in the parking garage were closer to ground level and accessible using the six-foot stepladder; whereas, the nests at the bridge site were positioned out of arms reach from the same stepladder. Held in individual garbage bags, each nest was attached to a spring scale to measure mass. An empty garbage bag was weighed separately to subtract the weight of the bag from the individual nest mass measurements.

Statistical Analysis

The mass measurements for the gourd-shaped nest sample were entered into PASWstatistics 18.0 software to calculate mean, median, mode, and standard deviation. A Shapiro-Wilk Test of Normality was run to determine if the data were normally distributed. This test was chosen based on the smaller sample size, $n = 30$. With data that are not normally distributed, the median mass was more appropriate to apply to the nest count than the mean. The mean was not applied to the nest count to prevent outliers from distorting the average. The mode is not best suited to apply to the nest count because nest mass was ratio scale.

The cup-shaped nest sample taken from the Alkek Parking Garage was entered into PASWStatistics 18.0 software to calculate nest mass mean, median, mode, and standard deviation. A Shapiro-Wilk Test of Normality was run to determine whether the data were normally distributed. Since the data were not normally distributed, the median was chosen to be applied rather the mean and mode for the reasons detailed above.

Determining the correlation between swallow colony size and annual productivity was tested using Spearman's rank correlation coefficient. The variables included in this test were: 1) total existing sediment per site in November 2011 and 2) percentage increase in sediment per site. The null hypothesis stated that there is no between these two variables:

H_0: There is no association between the total sediment present in November 2011 and annual percentage increase in sediment per site.

H_1: There is an association between the total sediment present in November 2011 and annual percentage increase in sediment per site.

To better understand the geomorphic agency involved in the construction of the two structure types of mud-nests, a Mann-Whitney U Test was conducted between the two nest samples [one sample of gourd-shape nests (n=30) and one sample of cup-shaped nests (n=30)]. This nonparametric test was run to determine whether or not a significant difference in the nest mass exists between the two independent samples. The null hypothesis stated that there is no significant difference between the masses of each nest shape:

> H_0: There is no significant difference between the mass of a gourd-shaped mud-nest and the mass of a cup-shaped mud-nest ($\alpha = 0.05$).
>
> H_1: There is a significant difference between the mass of a gourd-shaped mud-nest and the mass of a cup-shaped mud-nest.

CHAPTER 5

RESULTS

The total number of nests sampled was 60, a combination of two samples, 30 cup-shaped nests and 30 gourd-shaped nests. The samples were first tested separately to determine whether they were normally distributed. The null hypothesis for the Shapiro-Wilk Test of Normality states that the data are normally distributed. The data for the cup-shaped nests yield a significance value less than 0.05; therefore, the null hypothesis is rejected, 0.011 < 0.05 (Table 1). The data for the gourd-shaped nests also yield a significance value less than 0.05; therefore, the null hypothesis is rejected, 0.002 < 0.05.

Table 1: Shapiro-Wilk Test of Normality for the 30 cup-shaped nests sampled from the Alkek Parking Garage.

Tests of Normality

		Shapiro-Wilk		
	Cup_Nests	Statistic	df	Sig.
Cup_Nest_Mass	Cup	.905	30	.011

Table 2: Shapiro-Wilk Test of Normality for the 30 gourd-shaped nests sampled from the Interstate 35 bridge running over the Blanco River.

Tests of Normality

	Gourd_Nests	Shapiro-Wilk		
		Statistic	df	Sig.
Gourd_Nest_Mass	gourd	.876	30	.002

The average mass of the cup-shaped nest sample was 1,044 g ± 563 g, ranging from 320 g to 2,140 g (n=30) (Table 3). Since the data were not normally distributed, the median nest mass (830 g) was used in the estimations of total sediment present and annual sediment transport to the Alkek Parking Garage.

Table 3: Descriptive statistics for the cup-shaped nest sample taken from the Alkek Parking Garage. The measurements are in grams, n = 30.

Statistics

Cup_Nest_Mass

N	Valid	30
	Missing	0
Mean		1043.67
Median		830.00
Mode		550[a]
Std. Deviation		562.926
Minimum		320
Maximum		2140

a. Multiple modes exist. The smallest value is shown

The average mass of the gourd-shaped nest sample was 382 g ± 129 g, ranging from 240 g to 1640 g (n=30) (Table 4). Since the data were not normally distributed, the median nest mass (365 g) was used in the estimations of total sediment present and annual sediment transport to the 14 bridge sites along Interstate 35.

Table 4: Descriptive statistics for the gourd-shaped nest sample taken from the Interstate 35 bridge running over the Blanco River. The measurements are in grams, n = 30.

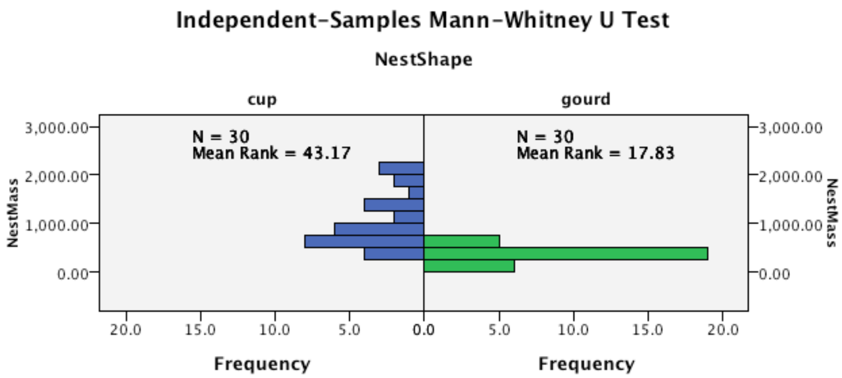
Statistics

Gourd_Nest_Mass

N	Valid	30
	Missing	0
Mean		381.67
Median		365.00
Mode		240
Std. Deviation		129.217
Minimum		240
Maximum		640

Mass Difference Between Mud-Nest Types

Prior to conducting an analysis of total existing sediment per site and annual sediment transport per site, it was decided to first address whether there was a significant difference in nest mass between cup-shaped and gourd-shaped nests. With a known difference in nest mass between nest shapes, appropriate samples were used to calculate estimations for total and annual sediment present at sites (i.e., applying the median mass of the cup-shaped nest sample to the Alkek Parking Garage count and the median mass of the gourd-shaped nest sample to the bridge site counts). Independent-Samples, Mann-Whitney U Test was conducted to determine whether or not there was a significant difference in nest mass between the two types of nest shape (Table 5 and Figure 13). The null hypothesis for this tests states that there is no significant difference between the mass of a cup-shaped nest and a gourd-shaped nest. The significance value for this test was $p < 0.001$; therefore, the null hypothesis was rejected. There is a significant difference in nest mass between the two types of nests (median gourd-shaped nest mass = 365 g; median cup-shaped nest = 830 g) ($\alpha = 0.05$).



Total N	60
Mann-Whitney U	830.000
Wilcoxon W	1,295.000
Test Statistic	830.000
Standard Error	67.564
Standardized Test Statistic	5.624
Asymptotic Sig. (2-sided test)	.000

Figure 13: Results of the Mann-Whitney U Test (p <0.001).

Table 5: The Mann-Whitney U Test yields a significance value of p<0.001, which is less than 0.05; therefore, the null hypothesis is rejected.

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of NestMass is the same across categories of NestShape.	Independent-Samples Mann-Whitney U Test	.000	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

Nest Count Data

Nest count data were used in the calculations of total existing sediment per site and annual sediment transport per site. The Alkek Parking Garage was unique in that it did not have any pre-existing sediment for the swallows to use in their 2011 nesting. The total count of fully intact nests for this location was 233 nests. Because the Texas State University-San Marcos parking authority removed all of the nests prior to the nesting season, there were no partially intact nests to be counted. The nest count can be compared with those at the fourteen bridge sites (Table 6, Table 7, Figure 14, Figure 15, Figure 16, and Figure 17).

Table 6: Fully intact nest counts.

Site	Fully Intact Nests in March 2011		Site	Fully Intact Nests in November 2011
Site B2	2251		Site B2	2485
Site B1	812		Site B1	844
Site I	127		Site B3	365
Site B3	120		Site A	316
Site G	97		Alkek	233
Site C	85		Site I	183
Site K	58		Site G	146
Site L	45		Site C	139
Site F	41		Site L	123
Site D	30		Site J	75
Site A	28		Site K	68
Site E	25		Site D	65
Site M	23		Site F	62
Site J	21		Site E	51
Alkek	0		Site M	29

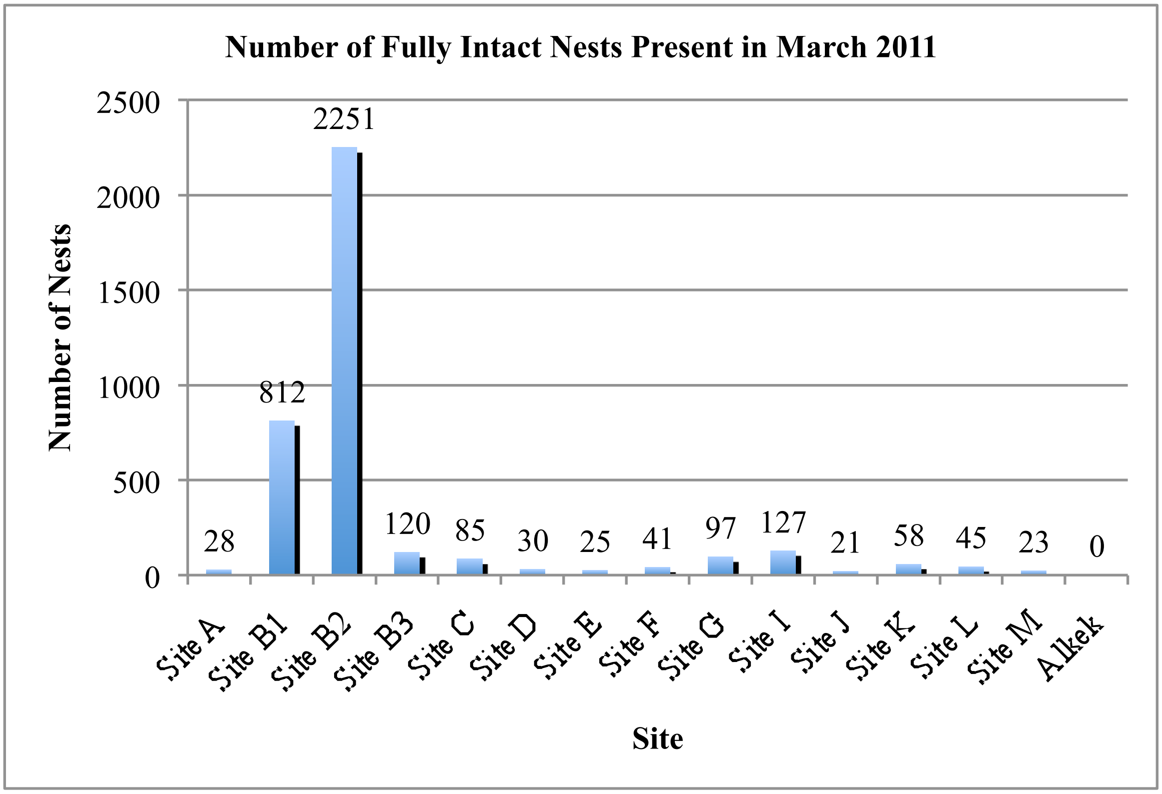


Figure 14: Number of fully intact nests present in March 2011.

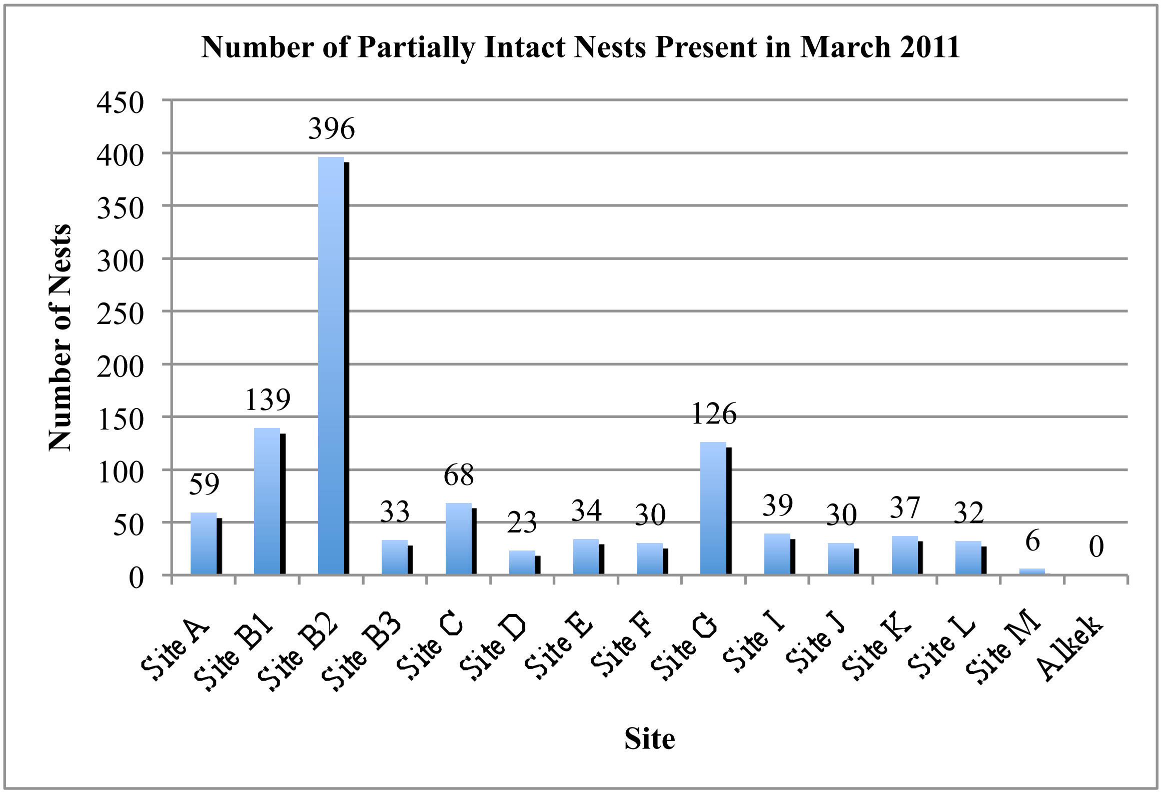


Figure 15: Number of partially intact nests present in March 2011.

Table 7: Partially intact nest counts.

Site	Partially Intact Nests in March 2011		Site	Partially Intact Nests in November 2011
Site B2	396		Site B2	255
Site B1	139		Site B1	110
Site G	126		Site B3	57
Site C	68		Site G	44
Site A	59		Site C	42
Site I	39		Site L	35
Site K	37		Site A	31
Site E	34		Site K	30
Site B3	33		Site J	28
Site L	32		Site D	16
Site F	30		Site E	14
Site J	30		Site I	9
Site D	23		Site F	6
Site M	6		Site M	5
Alkek	0		Alkek	0

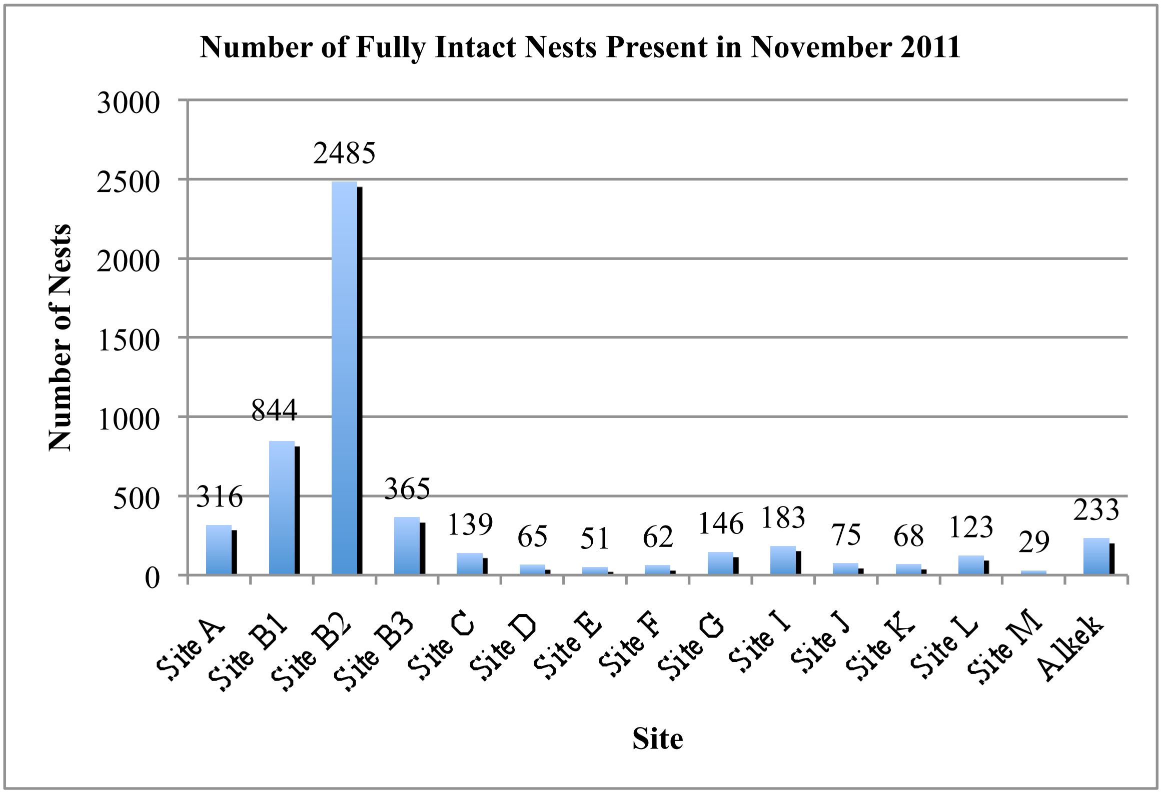


Figure 16: Number of fully intact nests present in November 2011.

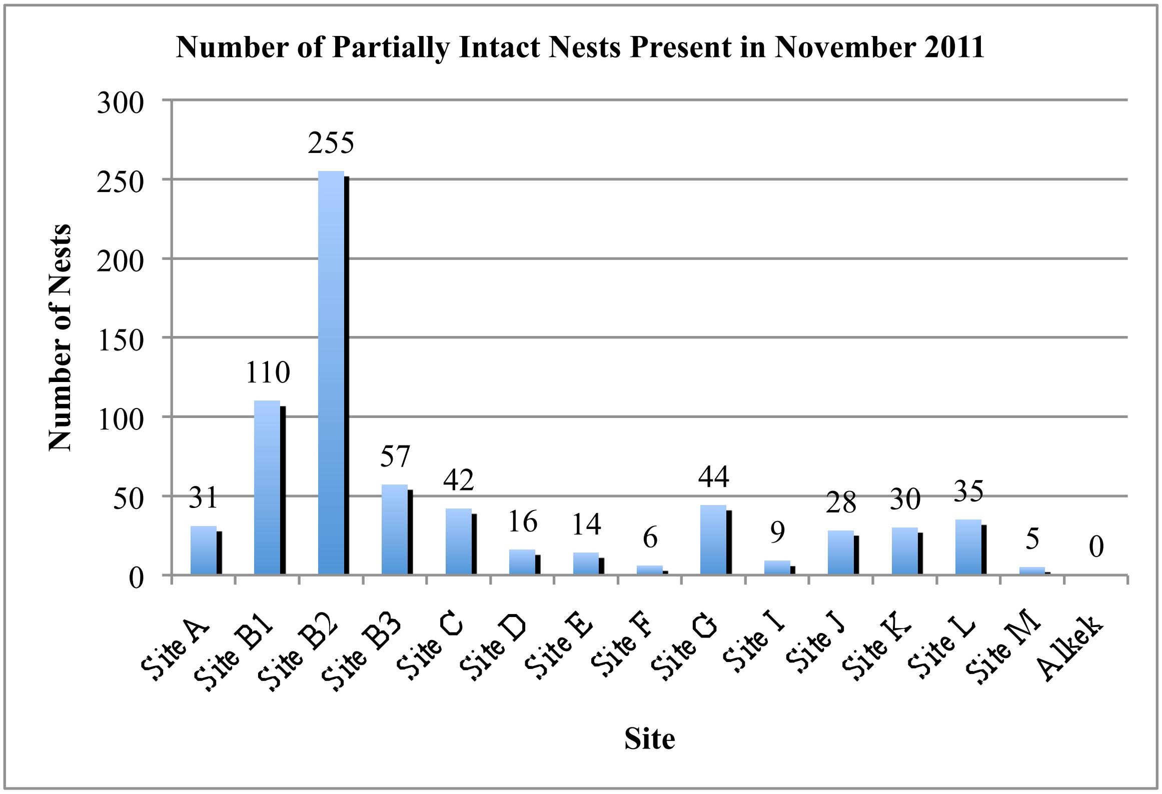


Figure 17: Number of partially intact nests present in November 2011.

Total Existing Sediment per Site (November 2011)

Total mass was calculated using Equations 1 and 2. The median mass of the cup-shaped nest sample was applied to the Alkek Parking Garage, and the median mass of the gourd-shaped nest sample was applied to the Interstate 35 bridge sites. The combined total mass of the existing sediment across all sites in November 2011 is 2,125 kg, over two metric tons. Excluding one bridge site that was not colonized, existing sediment ranged from 11.5 kg at Site M to 953.6 kg at Site B2 (Table 8, Figure 18, and Figure 19). The combined sediment mass for the three bridges located over the Blanco River (Sites B1, B2, and B3) was 1,425.3 kg, accounting for 67% of the overall sediment mass for all sites. The total amount of existing sediment at the Alkek Parking Garage was 193.4 kg for comparison.

Table 8: Total existing sediment per site.

Site	Total Existing Sediment per Site (kg)
Site B2	953.6
Site B1	328.1
Alkek	193.4
Site B3	143.6
Site A	121.0
Site I	68.4
Site G	61.3
Site C	58.4
Site L	51.3
Site J	32.5
Site K	30.3
Site D	26.6
Site F	23.7
Site E	21.2
Site M	11.5

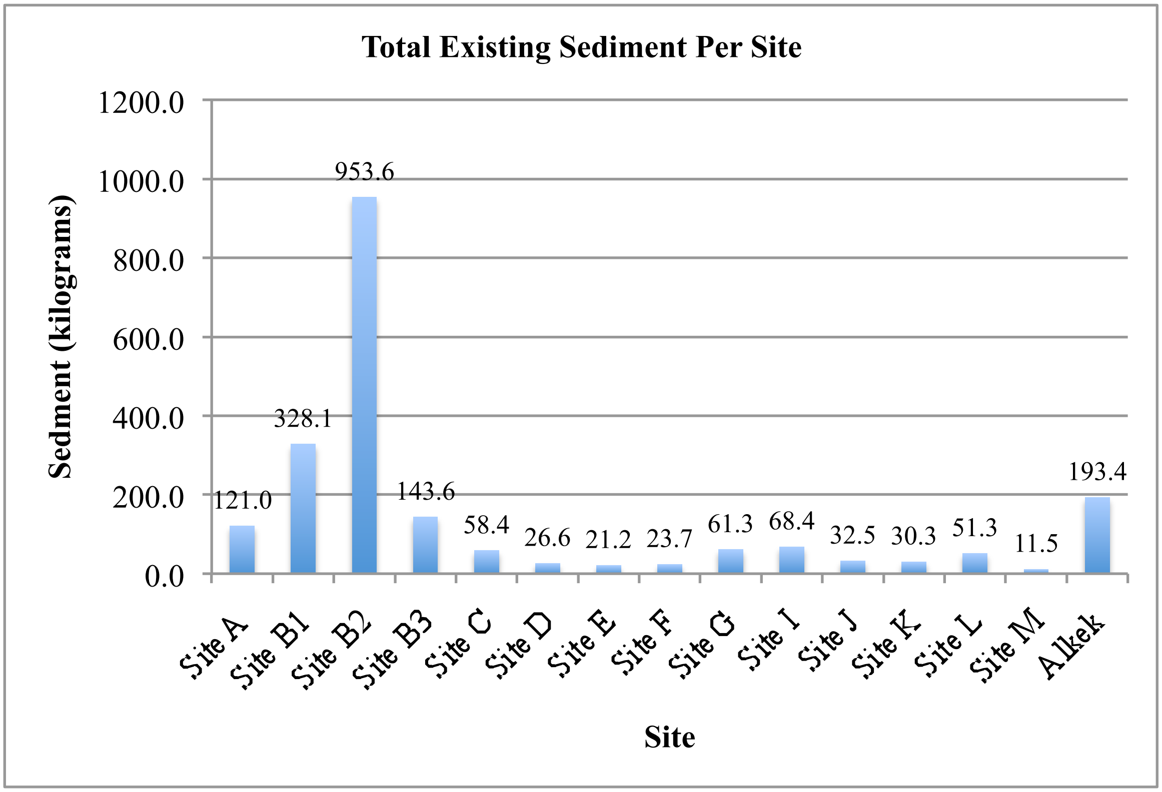


Figure 18: Total existing sediment per site (November 2011). The Interstate 35 bridge sites are labeled in alphabetical order starting in the northwest with Site A and continuing southwest to Site M. The Alkek Parking Garage is labeled as "Alkek".

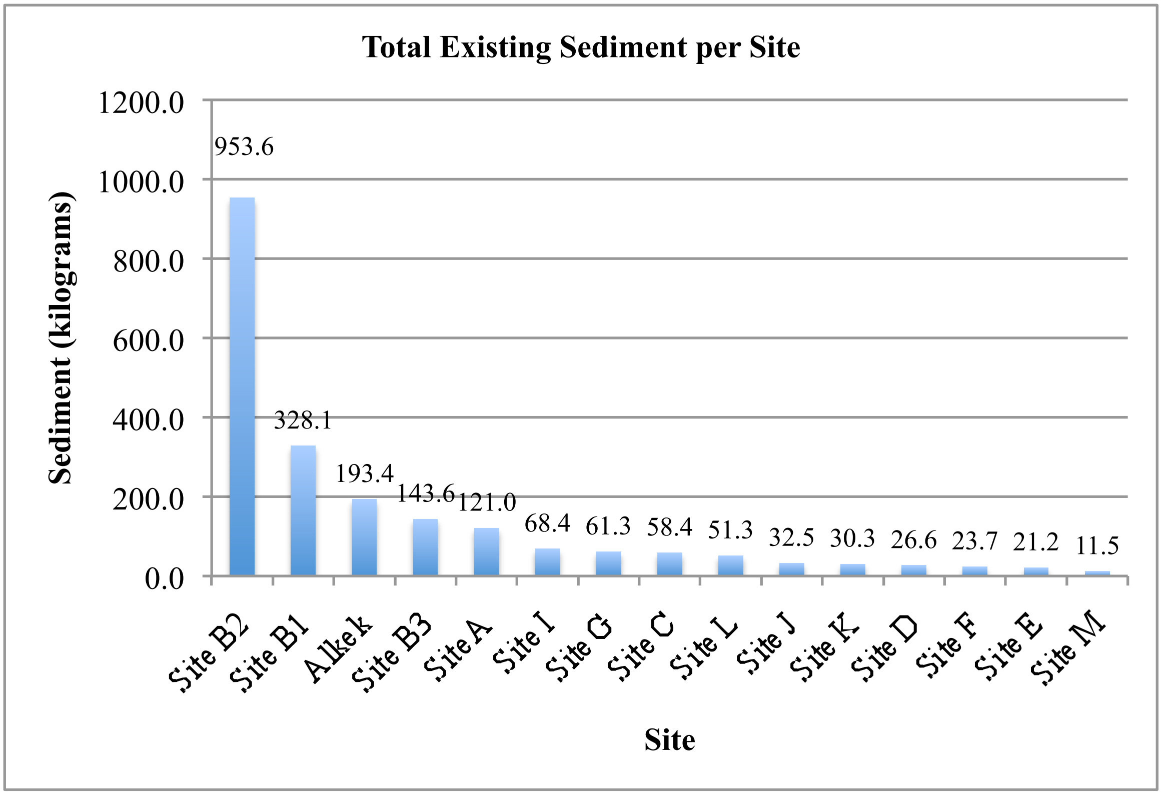


Figure 19: Total existing sediment per site in ranked order (November 2011).

Annual Sediment Transport: "New Colony"

The Alkek Parking Garage had no pre-existing sediment as of March 2011 when all nests were removed by the Texas State University-San Marcos Parking Authority. By November 2011 there were 233 nests. Using Equation 3, the median mass of the cup-shaped nest sample, 830 g, the annual transport of sediment to this simulated new colony was 193.4 kg. As expected, this amount of sediment increase far exceeds that of the 14 Interstate 35 bridge sites, which all had a substantial quantity of pre-existing sediment (Table 9, Figure 20, and Figure 21). The annual sediment transport values for the pre-existing colonies were also calculated by Equation 3.

Table 9: Annual sediment transport per site.

Site	**Annual Sediment Transport per Site (kg)**
Alkek	193.4
Site A	100.0
Site B3	93.8
Site B2	59.7
Site L	29.0
Site J	19.3
Site C	15.0
Site I	15.0
Site D	11.5
Site B1	6.4
Site E	5.8
Site F	3.3
Site G	2.9
Site K	2.4
Site M	2.0

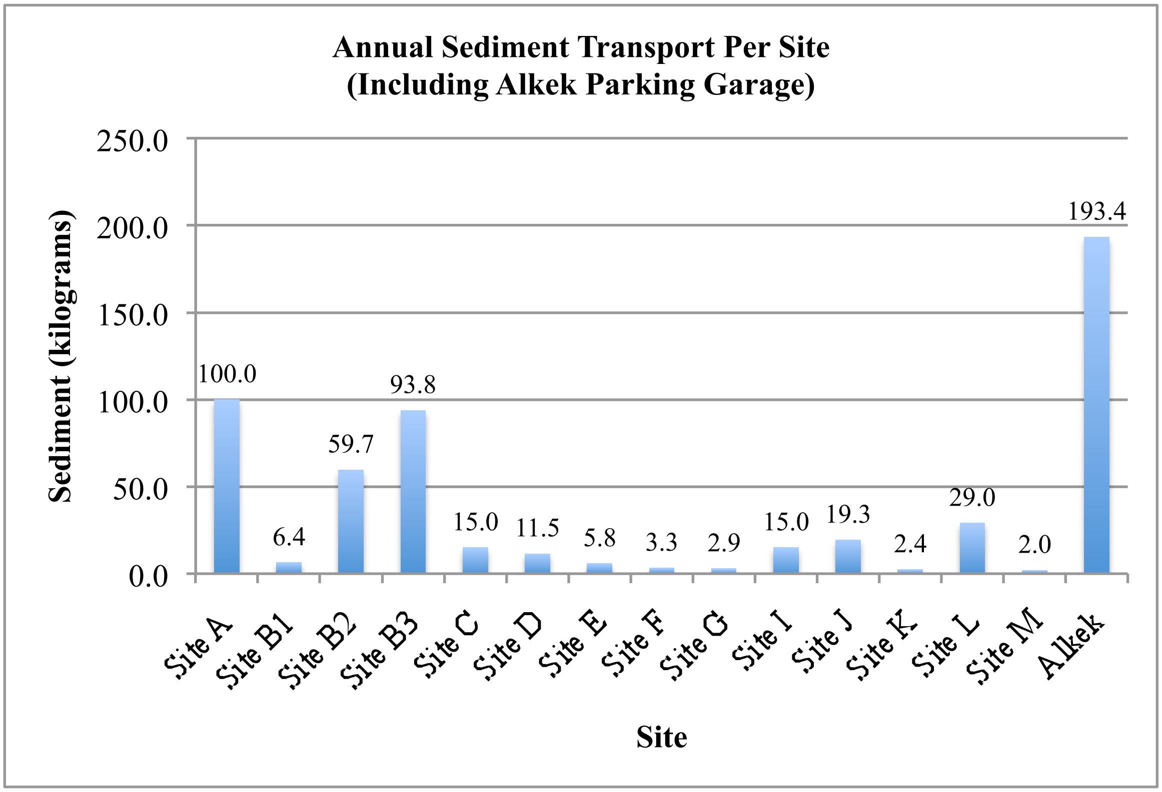


Figure 20: Annual sediment transport per site (March 2011 to November 2011).

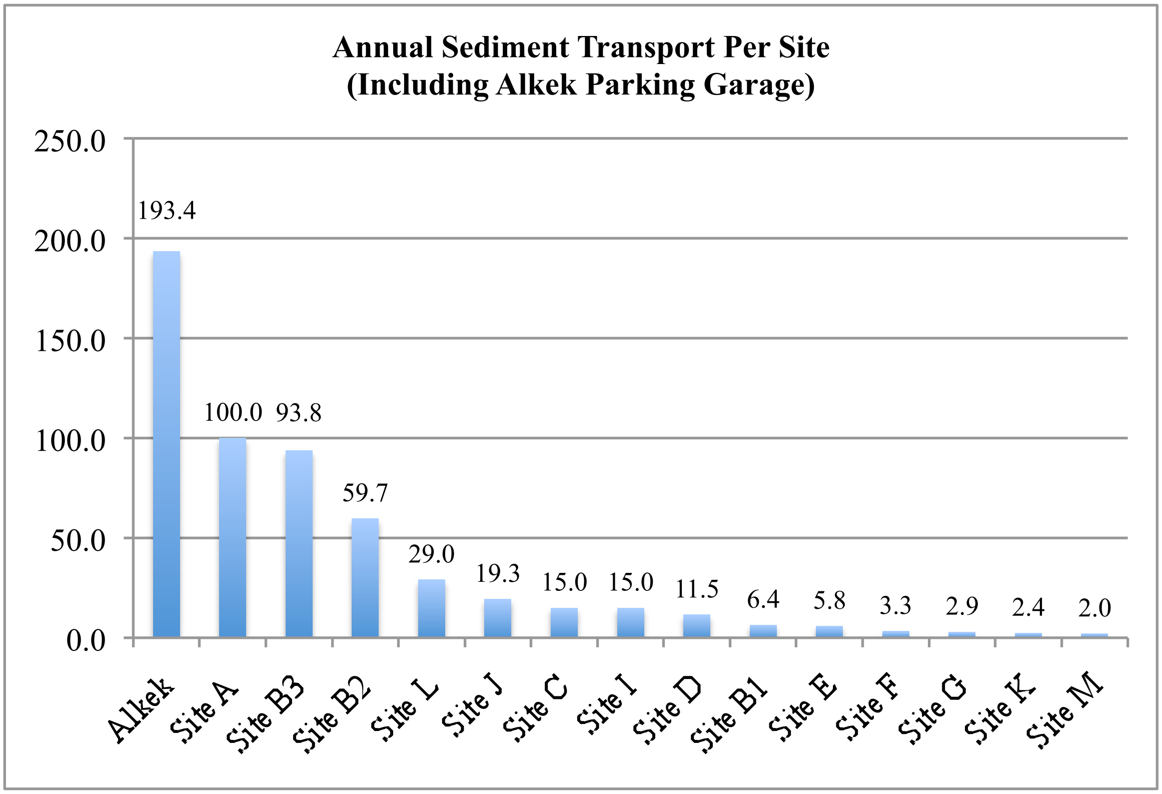


Figure 21: Annual sediment transport per site in ranked order (March 2011 to November 2011).

Annual Sediment Transport: Pre-Existing Colonies

The annual transport varied from site to site across the 14 pre-existing colonies, ranging from 2 kg of sediment at Site M to 100 kg at Site A (Figure 22 and 23). The total annual sediment transport across all pre-existing colonies was 366.1 kg. The greatest amount of annual sediment transport was concentrated near the Blanco River, where site A had an increase of 100 kg of sediment (over one quarter of the total annual sediment transport to pre-existing colonies), and sites B1, B2, and B3 had a combined increase in sediment of 159.9 kg, or 44% of the total annual transport for the Interstate 35 sites.

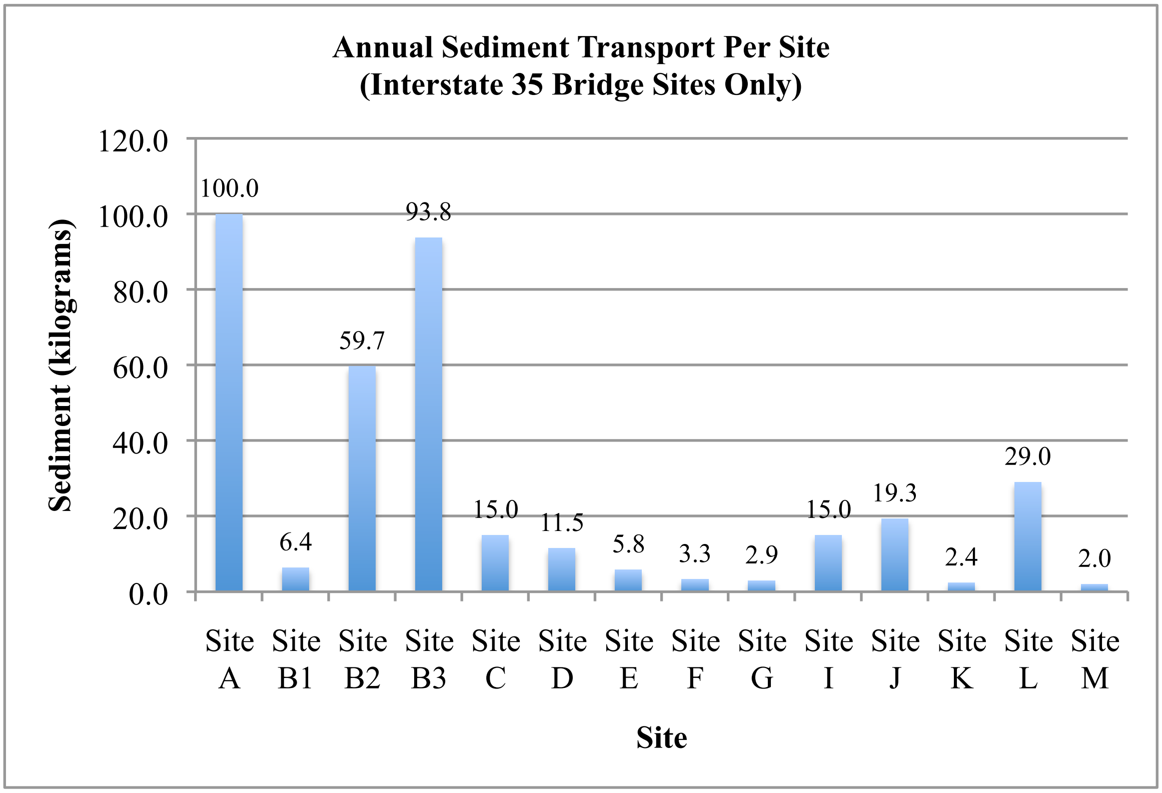


Figure 22: Annual sediment transport per site showing only the pre-existing colonies located along Interstate 35.

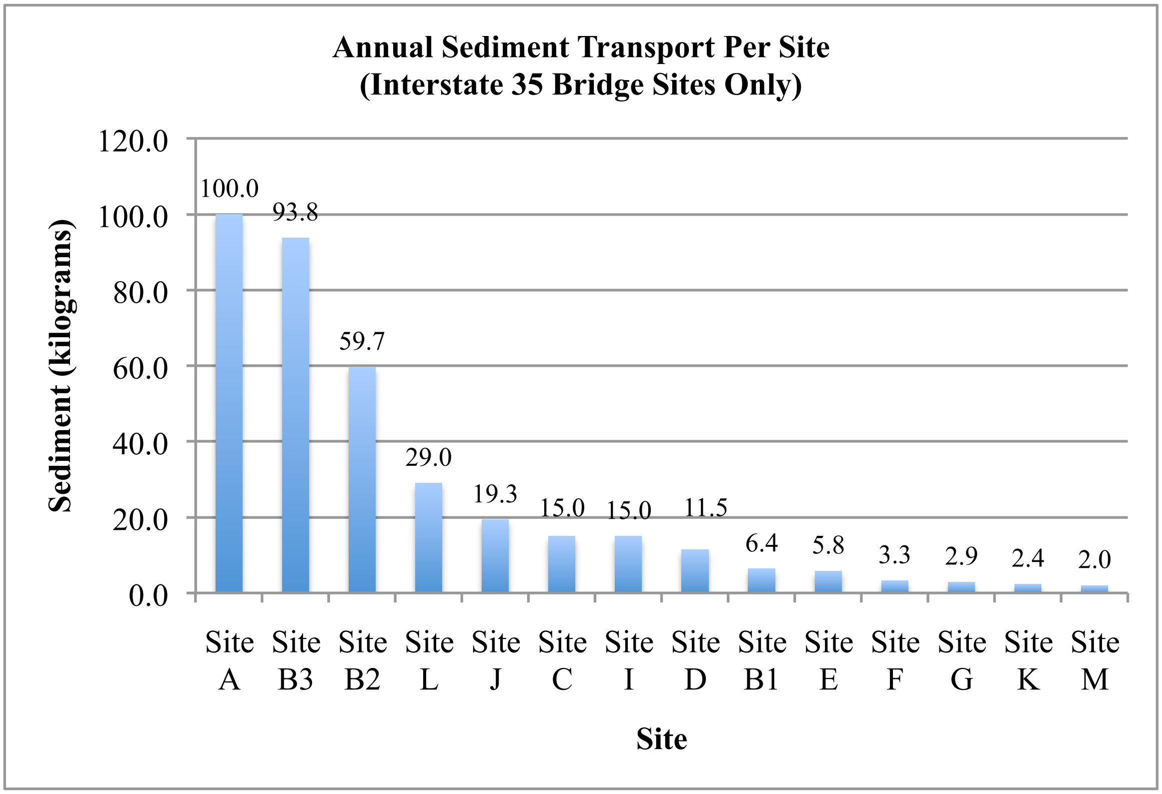


Figure 23: Annual sediment transport per site showing only the pre-existing colonies located along Interstate 35 in ranked order.

Percentage Increase in Sediment per Site

Equation 4 was used to calculate the percentage increase in sediment per site. As in total existing sediment per site and annual sediment transport per site, variation in percentage increase in sediment per site between March 2011 and November 2011 occurred across the Interstate 35 sites (Table 10, Figure 24 and Figure 25). The variations in rates of sediment increase per site differ from both the annual sediment transport and the total existing sediment per site. Sites with the greatest number of nests did not experience the greatest increase in sediment and sites with smaller numbers of nests did not necessarily have little increase in sediment over the summer of 2011. A

Spearman's Rank Order correlation was run to determine the relationship between total existing sediment per site and percentage increase in sediment per site. There was no significant correlation between the two ($r_s = -0.10$, $p = 0.74$) (Table 11). Ranking sites from greatest to least amount of annual sediment transport does not perfectly match a ranking of greatest to least percentage increase in sediment. The rates of sediment increase per site are more closely aligned with the annual sediment.

Table 10: Percentage increase in sediment per site.

Site	Percentage Increase in Sediment per Site
Site A	477%
Site B3	188%
Site J	147%
Site L	130%
Site D	76%
Site E	38%
Site C	34%
Site I	28%
Site M	21%
Site F	16%
Site K	8%
Site B2	7%
Site G	5%
Site B1	2%

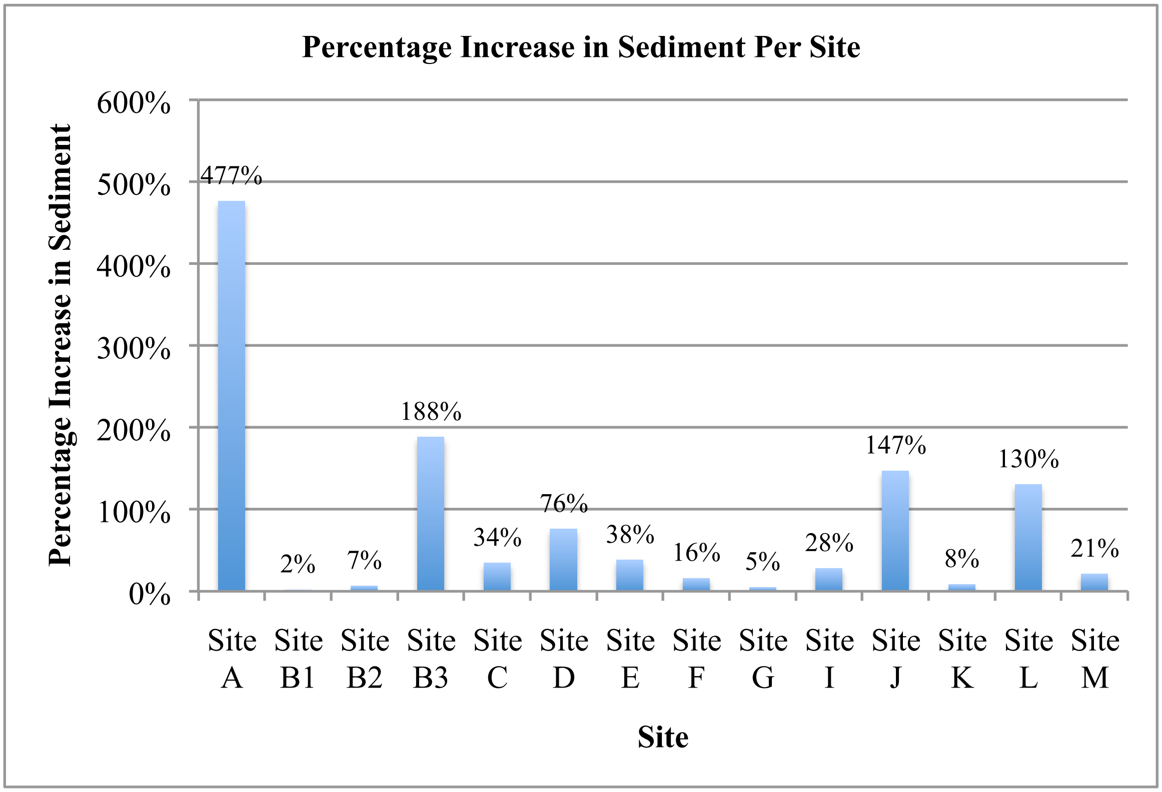


Figure 24: Percentage increase in sediment per site (March 2011 to November 2011).

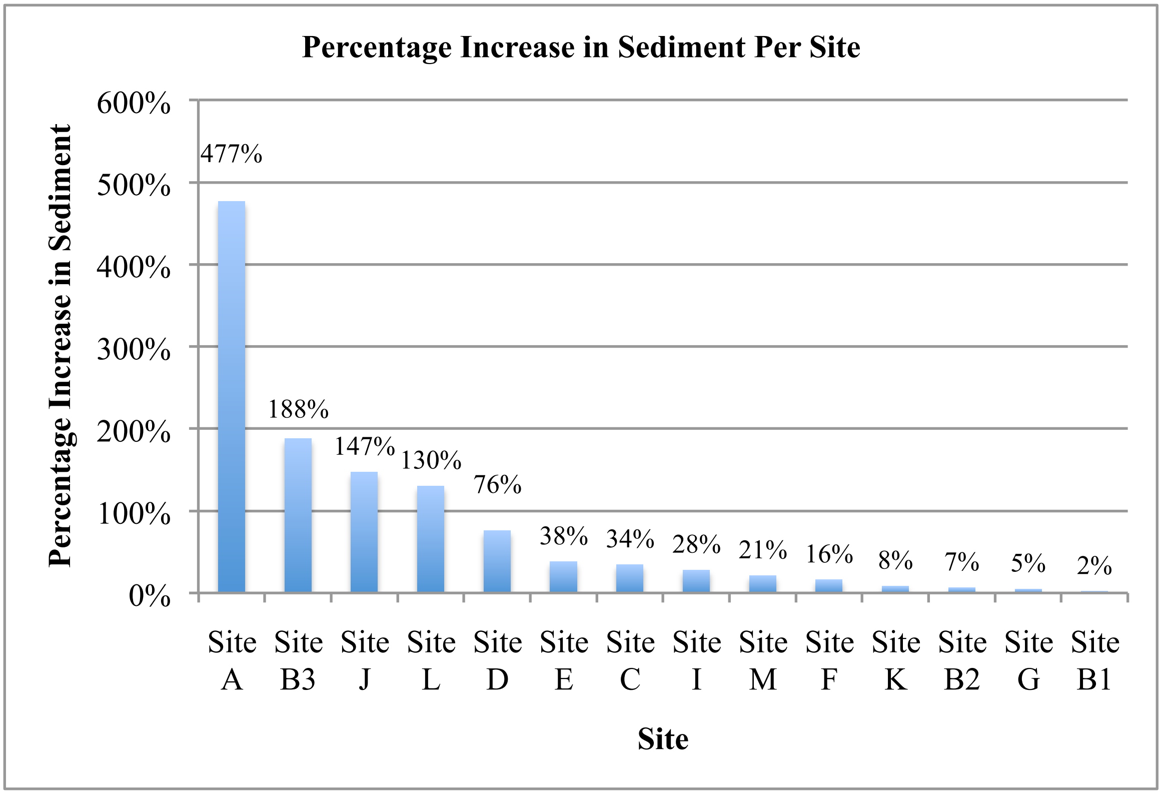


Figure 25: Percentage increase in sediment per site in ranked order (March 2011 to November 2011).

Table 11: Spearman's Rank Order correlation reveals there is no significant correlation between total existing sediment per site and percentage increase in sediment per site (p = 0.737).

Correlations				
			Tot_Sed	Per_Inc
Spearman's rho	Tot_Sed	Correlation Coefficient	1.000	-.099
		Sig. (2-tailed)	.	.737
		N	14	14
	Per_Inc	Correlation Coefficient	-.099	1.000
		Sig. (2-tailed)	.737	.
		N	14	14

CHAPTER 6

DISCUSSION AND CONCLUSIONS

The purpose of this study was to quantify the geomorphic agency of the mud-nesting swallows of Central Texas. The cave, cliff, and barn swallows each collect thousands of mud pellets to construct the nests in their colonies. Furthermore, swallow colonies are found through both natural and artificial locations within Central Texas, creating the potential for vast amounts of sediment transport. This chapter discusses the results of total sediment per site, annual sediment transport, annual percentage increase in sediment, and variations in mud-nest mass. In addition, there is a discussion on why Site H was the only bridge site to not have a swallow colony and a section on the geomorphic implications at the mud sources. This chapter will conclude with a summary of this study and related future research.

Distribution of Sediment across Study Sites

Through the processes of erosion, transportation, and deposition, swallows have been responsible for transporting over two metric tons of sediment within the study site, and over half of a metric ton in one summer among the study sites. The bridge sites long Interstate 35 represent a corridor that extends approximately 18.5 km. The total existing sediment per site is not evenly distributed, nor does the distribution increase or decrease linearly along this corridor.

It is interesting to compare sites over water with those that are not positioned over water. The average existing sediment for the 14 bridge sites is 138 kg. The average for the four bridges (Sites B1, B2, B3, and G) that run over a water source is 371.7 kg compared to the other ten bridges that average 44.5 kg per site. Seventy-four percent of the existing sediment across all of the Interstate 35 bridges is located under three bridges running over the Blanco River (Sites B1, B2, and B3) (Figure 26). Incorporating Site A, fourth highest in sediment mass and in close proximity to the Blanco River, accounts for 80% of the total existing sediment along this corridor of Interstate 35. The Blanco River's influence on the Site B colonies is unclear. Having a colony positioned above a river does not necessarily allow for, or cause, an increase in nesting; however, it is likely a variable. Water provides a source for drinking and for mud gathering. It is also likely that other variables are influencing the success at the Blanco River sites.

Figure 26: Site B2 had the greatest amount of sediment of the study sites in November 2011. Seen here are cliff swallows colonizing the bridge.

The colony at Site G presides over the San Marcos River and has substantially fewer nests than the bridges over the Blanco River. There were 146 fully intact nests at Site G in November 2011 compared to 844, 2,485, and 365 nests at Sites B1, B2, and B3, respectively. The San Marcos River has perennial flow, is spring fed, and its source is within 5 km of the colony. In contrast, the Blanco experiences seasonal flow and the area below the Site B colonies occasionally runs low and even stops flowing, suggesting the San Marcos would be a better location for a colony if a permanent water source below the colony was the primary variable for site selection. Additionally, Site H, the only bridge within the study to not house a swallow colony, has the structure to support mud-nests and runs over a small tributary of the San Marcos River. It is unclear why swallows have not colonized Site H; however, this is the only site that has no road or walkway running below it and vegetation covers a considerable portion of the passages on both sides below the bridge (Figure 27). All but one of the other bridge sites, as well as the Alkek Parking Garage, are clear of vegetation or other obstructions to flight into and out of the area. The exception is Site G, the bridge over the San Marcos River. It is clear at one end but obscured on the other (Figure 28 and Figure 29). It is interesting to note that the nesting locations are predominantly on the open side of the bridge, and no nests are positioned on the side that is obscured by vegetation.

Figure 27: Site H had no swallow colony. Although the bridge structure has beams to support swallow nests and a stream below it, the entrances at both sides below the bridge are obstructed by vegetation growth.

Figure 28: Site G was obstructed by vegetation growth at one end, seen here. The bridge at the far end of this photo had no nests present and the beams under the main bridge, in the forefront, had no nests on the side near the vegetation in the far end of this photo.

Figure 29: Site G was unobstructed at one end, seen here. This site had nests present near this open end of the bridge.

Distribution of Annual Sediment Transport and Percentage Increase in Sediment

As suspected, the annual sediment transport to the "new colony" at the Alkek Parking Garage experienced, by far, the greatest increase in sediment. The swallows constructed 233 nests without the use of pre-existing sediment. The estimated total mass of annual sediment transported to the parking garage by swallows was 193.4 kg, nearly double that of the second greatest annual sediment transport site, Site A (Table 9). The 14 pre-existing colonies had an average of 269 fully intact nests and 75 partially eroded nests per site in March 2011 to reuse and reconstruct, respectively. The average annual sediment transport to the pre-existing colonies was 26.1 kg, which is 167.3 kg less than that brought into the “new colony”.

Annual sediment transport varied across all sites along the Interstate 35 corridor at the 14 pre-existing colonies. Swallows were most active at Site A, where they transported an estimated 100 kg of sediment during the summer of 2011. The percentage increase in sediment from March to November 2011 at Site A was also the greatest across the pre-existing colonies (477%). It is not clear why this site, which was fourth highest in total sediment for the pre-existing colonies, had the most activity. One possibility is that the swallows are branching out from the Site B colonies; however, there is no apparent evidence supporting this speculation. Another possibility is that this site experienced a greater percentage decrease prior to the swallows’ return in April 2011. Data were not collected in November 2010 to compare with March 2011 to estimate percentage decrease to support this speculation. Additionally, the bridge at Site A does not appear to have any disadvantages regarding nest retention during the winter months (i.e., this site does not seem to have greater exposure to weathering or be more prone to water leakage compared with the other sites).

Also surprising was the high percentage increase at Site L (130%) (Table 10). This site is several kilometers southwest of the higher density colonies at Sites A, B1, B2, and B3. It is one of four sites to experience a percentage increase in sediment greater than 100%. There are no visible water sources near this site, and the San Marcos River, the closer of the two rivers, is several kilometers away. It is interesting to note that this bridge is right next to the main entrance of a major outlet shopping mall, which experiences heavy traffic throughout the year. Any association this shopping center has with the productivity of Site L is unclear, and it may just be a coincidence that an active swallow colony is positioned near a shopping center. Noise pollution should not be a factor, because all sites along the Interstate 35 corridor are subject to almost continuous vehicle traffic running over the bridges supporting their colony. Future studies might include the study of correlations of human variables with the degree of swallow activity; however, such study is not within the scope of this dissertation.

Site J (147% increase in sediment) is also located along a commercial district with limited natural environment located on either side of the bridge. The two adjacent sites northeast and southwest of Site J experienced minimal percentage increase in sediment, but Site M, approximately 2 km southwest experienced a greater percentage increase in sediment. Site M is positioned near a large Toyota dealership on one side of the interstate and a large field on the other. The field is most likely used for foraging and mud gathering during spring precipitation; however, any relationship with the Toyota dealership is not suspected.

The Spearman's rank correlation coefficient found there to be no association between the variables of total existing sediment per site and percentage increase in sediment per site (Table 11). Some sites that had a lot of existing sediment had minimum percentage increase in sediment, whereas other sites with a lot of existing sediment experienced great percentage increase in sediment. The results also showed sites with minimum existing sediment to experience both high and low percentage increases in sediment.

Site B2, which had the greatest number of existing sediment in November and one of the highest amounts of annual sediment transport, experienced only minimal percentage increase (Table 8, Table 9, and Table 10). This mismatch most likely contributed to the great amount of pre-existing sediment in March 2011 diminishing the percentage increase. Site B3, on the contrary, experienced the second greatest percentage increase in sediment (Table 10). It can be speculated that swallows had colonized Site B2 in greater abundance the previous summer (2010) and had shifted to site B3 in greater number during the summer of 2012. Unfortunately, data were not collected to support this speculation. Another possibility is that more swallows colonized this area than had in the previous migration. Site B3 presented the greatest nesting surface area with only 120 full nests and 33 partially eroded nests present in March 2011 compared with 812 full nests (139 partially eroded nests) and 2,251 full nests (369 partially eroded nests) present at Sites B1 and B2, respectively (Table 6 and Table 7). Having more nests present at Sites B1 and B2 also suggests that more of these nests were reused or repaired during the summer, preventing greater percentage increase in sediment.

Mud-Nest Geomorphology

The Mann-Whitney U Test revealed that the cup-shaped swallow nest mass was significantly greater than the gourd-shaped nest mass (Table 5). Constructing nests that are greater in mass contributes to a greater geomorphic process. Both cave swallows and barn swallows construct cup-shaped swallow nests, suggesting their potential for greater geomorphic agency compared with the cliff swallow, which construct gourd-shaped nests. Having larger nests is, however, only one variable in the geomorphic equation. The number of nests constructed annually is also of importance. Because the quantity of cup-shaped nests at the Alkek Parking Garage was similar to the quantity of gourd-shaped nests at the bridge sites, the geomorphic agency of cup-shaped constructing swallow sites may be considered greater. As mentioned, the barn and cave swallows both build cup-shaped nests; however, their gregariousness is not as similar. The high-density swallow colony in the Alkek Parking Garage is all cave swallows. Barn swallows tend to nest in low-density colonies or independently in pairs. Too little evidence is presented to declare all cave swallows as the greatest geomorphic agent among the mud-nesting swallows of Central Texas, but it is a first step.

Mud Source Geomorphology

This research required many visits to each colony, which took place over a year. The majority of visits were conducted during the summer of 2011 and spring of 2012, during which time swallow activity was observed and noted. Activities conducted by the swallows in the study area were always conducted in great number. Shortly after the swallows return from winter migration, they begin the nesting process. Investigation of the geomorphic influence at the mud source is outside of the scope of this dissertation; however, it is worthy of mention. With over half a metric ton of sediment being transported by swallows to the study sites annually, it begs the question, “where is this sediment coming from?”

In total, this study analyzed the activity of thousands of swallows. If each swallow were to gather sediment for its nest at separate locations, perhaps the geomorphic process would be negligible at the numerous mud source sites. Swallows, however, collect their mud in large groups, at times making thousands of trips to a mud source. Swallows were seen gathering mud at two separate study sites (Site B1 and Site A).

At Site B1, the mud source was directly below the bridge (Figure 30 and Figure 31). Not all of this sediment was carried to nests directly above the mud source, so transportation of the sediment did extend both vertically and horizontally away from the source. For the sediment that was transported directly above the mud source, the geomorphic processes of soil turnover and soil disturbance are at work. The nests will eventually decay or at least partially decay over time, returning the sediment near its origin but in an altered state. Sediment transported away from this source was confined to the Site B colonies, all within a 1 km radius from the mud source.

Figure 30: Swallows gathering mud for nesting below Site B1.

Figure 31: A mud source for swallows at Site B1.

At Site A, the mud source was observed approximately 50 m from the center of the swallow colony (Figure 32 and Figure 33). Swallows were observed transporting mud from this source to locations over Interstate 35. Nest decay that takes place at Site A will eventually experience either wind transportation or surface runoff after a precipitation event. It is interesting to consider that some of the decayed sediment may adhere to vehicles passing under the colony and be transported anywhere from tens to thousands of kilometers away.

Figure 32: Swallows gather mud for nesting approximately 50 m from Site A.

Figure 33: A mud source for the swallow colony at Site A.

Swallows in this study may have used perhaps hundreds of other mud sources in this study area. There is, however, insufficient data to determine mud source characteristics; nonetheless, it is interesting to note that both of the documented mud sources were formed by vehicle tire tracks that eroded depressions. Water from recent precipitation collected into these depressions and swallows were able to take advantage of this opportunity. Observations of several locations of vehicle-related depressions were made at various study sites; however, only a small percentage held water from recent precipitation events. The mud source at Site B1 held water for at least a month prior to making observations of swallows utilizing it for nesting purposes. The ponding had experienced a great decrease in water storage over that time period (Figure 34).

Figure 34: The mud source observed at Site B1 approximately one month before swallows utilized it gathering mud.

These ephemeral ponding locations certainly benefit the swallows regarding energy expenditure. It is most likely that the colony sites that experienced high percentages of annual increase in sediment, but were several kilometers from permanent water sources such as the San Marcos River and Blanco River, utilized similar ephemeral ponding locations to gather mud.

Conclusions

This dissertation has provided a quantitative analysis of sediment erosion, transportation, and deposition conducted by the three mud-nesting swallows of Central Texas, namely the barn swallow (*Hirundo rustica*), the cave swallow (*Petrochelidon fulva*), and the cliff swallow (*Petrochelidon pyrrhonota*). Swallows were investigated for their geomorphic role on the landscape, specifically addressing: 1) how much sediment is existing at the colonies positioned under fifteen bridges and one parking garage, 2) what is the annual sediment transport per site, and 3) is there a significant difference between cup-shaped and gourd-shaped swallow mud-nests. This dissertation is a contribution to the growing subdiscipline of *zoogeomorphology*, the study of animals as geomorphic agents.

Total existing sediment varied per site and totaled over 2 metric tons across the study area. The average existing sediment for the 14 bridge sites was 138 kg, seventy-four percent of which was located under the three bridges running over the Blanco River. Site H was the only site along the Interstate 35 corridor swallows have not colonized. It is likely that the vegetation cover of a considerable portion of the passages on both sides below the bridge have discouraged colony establishment.

Swallows transported over half of a metric ton of sediment in one summer among the study sites. The annual sediment transport to the "new colony" at the Alkek Parking Garage experienced, by far, the greatest increase in sediment with the construction of 233 nests and an estimated total mass of 193.4 kg. Among the pre-existing colonies, swallows were most active at Site A, transporting an estimated 100 kg while other sites experienced only minimal annual additions of sediment.

This study has shown that cup-shaped mud-nests have significantly larger mud mass than gourd-shaped mud-nest. Both cave swallows and barn swallows construct cup-shaped nests, suggesting their potential for greater geomorphic agency compared to the cliff swallow, which construct gourd-shaped nests.

Future Research

This study was the first to quantify the geomorphic agency of mud-nesting swallows. Future studies concerning the zoogeomorphology of mud-nesting swallows may address the following: 1) rates of erosion at mud sources, 2) net positive or negative effects of urbanization in swallow habitat, and 3) swallow colonies as systems with dynamic equilibrium in sediment mass.

Swallows collect their mud in large groups, at times making hundreds or thousands of trips to a single mud source. Future studies may attempt to record the average number of mud sources used per site along with the average number of swallows utilizing the mud source and the number of trips made to the location. Measurements of the site disturbance could also be made. The mud sources identified in this study were already disturbance sites created by motor vehicles. Studies addressing the amount of disturbance at these sites made solely by swallows would provide further quantifications of their geomorphic agency.

In this study, all of the swallow colonies were located at artificial sites. All three of the mud-nesting swallows originally nested in natural environments such as caverns or on cliffs. As urbanization and suburbanization continue to expand, more locations will become available for swallows to colonize, which would be a positive effect, contributing to greater populations of swallows. This is not to say with certainty that urbanization and suburbanization are always beneficial to swallow populations. Increased development also has several variables that could negatively correlate with swallow population growth. Some examples of potentially negative variables might include decreased foraging surface area, water pollution, human disturbance or removal of nests, increased swallow mortality resulting from contact with traveling motor vehicles, or decrease of available mud sources for nest construction. At this point, only speculations can be made about positive or negative associations between urbanization/suburbanization and swallow population growth. From a geomorphic perspective, understanding the influences of human development on swallow colonization will have indirect geomorphic influence on the landscape. Greater number of swallow colonies will ultimately result in more geomorphic activity.

Many studies in physical geography address natural systems. Future studies may analyze swallow colonies as a system with inputs of sediment by means of mud nesting and outputs of sediment via nest decay. This study has only addressed the amount and percentage increase of sediment per site; however, future studies of sediment decrease, resulting from nest decay, per site during the winter months may provide insight into a dynamic equilibrium of swallow-related sediment present at colonies year-round. Calculating averages in rates of sediment increase and decrease per site would be a way to better understand the flow of sediment into colonies over time.

APPENDIX

PHOTOS OF SWALLOW COLONY STUDY SITES

Alkek Parking Garage.

Site A

Site B1.

Site B2.

Site B3.

Site C.

Site D.

Site E.

Site F.

Site G.

Site I.

Site J.

Site K.

Site L.

Site M.

REFERENCES

Abrahams, A.D., A.J. Parsons, and J. Wainwright. 1996. Interactions between semi-natural vegetation and hydrogeomorphological processes. *Geomorphology* 13: 37-48.

Anderson, D.C. and J.A. MacMahon. 1981. Population dynamics and bioenergetics of a fossorial herbivore, *Thomomys talpoides* (Rodentia: Geomyidae) in a spruce-fir sere. *Ecological Monographs* 51: 179-202.

Andersson, S. 1989. Tool use by the fan-tailed raven (*Corvus rhipidurus*). *Condor* 91: 999.

A.O.U. (American Ornithologists' Union). 1983. *Checklist of North American birds,* Sixth edition. Lawrence, Kansas: American Ornithologist' Union.

--- 1998. *Check-List of North American birds*, Seventh edition. Washington, DC: American Ornithologists' Union.

Armstrong, W.E., D.E. Harmel, M.J. Anderegg, and M.S. Traweek. 1991. Texas Parks and Wildlife Department. *Vegetation of the Kerr wildlife management area and its preference by white-tailed deer*. Federal Aid Report Series No. 30.

Baer, L.D. and D.R. Butler. 2000. Space-time modeling of grizzly bears. *Geographical Review* 90(2): 206-221.

Baker, J.K. 1962. Associations of Cave Swallows with Cliff and Barn Swallows. *Condor* 64: 326.

Baptist, M.J. and E. Mosselman. 2002. Biogeomorphological modelling of secondary channels in the Waal river. In *River Flow 2002 Symposium* ed. D. Bousmar and Y. Zech. 773-782. Belgium: Louvain-la-Neuve.

Baptist, M.J., W.E. Penning, H. Duel, A.J.M. Smits, G.W. Geerling, G.E.M. Van der Lee, and J.S.L. Van Alphen. 2004. Assessment of cyclic floodplain rejuvenation on flood levels and biodiversity in the Rhine River. *River Research and Applications* 20: 285-297.

Batte, Charles D. 1984. Soil survey of Comal and Hays counties, Texas. Washington D.C.: U.S. Department of Agriculture.

Beever, E.A., R.J. Tausch, W.E. Thogmartin. 2008. Multi-scale responses of vegetation to removal of horse grazing from Great Basin (USA) mountain ranges. *Plant Ecology* 196(2): 163-184.

Bertram, B.C.R. 1992. *The Ostrich Communal Nesting System*. Princeton, NJ: Princeton University Press.

Beyer, W.N., E.E. Conner, and E. Gerould. 1994. Estimates of soil ingestion by wildlife. *Journal of Wildlife Management* 58: 375-382.

Blake, C. H. 1948. The flight of swallows. *Auk* 65: 54-62.

Brightsmith, D.J. 2004. Effects of weather on parrot geophagy in Tambopata, Peru. *The Wilson Bulletin* 116(2): 134-145.

Brightsmith, D.J. and A. Muñoz-Najar. 2004. Avian geophagy and soil characteristics in Southeastern Peru. *Biotropica* 36(4): 534-543.

Brown, C.R. 1985. *The costs and benefits of coloniality in the cliff swallow*. Dissertation. Princeton, New Jersey: Princeton University.

-------------- 1988. Enhanced foraging efficiency through information centers: A benefit of coloniality in cliff swallows. *Ecology* 69(3): 602-613.

Brown, C.R. and M.B. Brown. 1995. Cliff swallow (*Petrochelidon pyrrhonota*). In *The birds of North America Online.* ed. A. Poole. Ithaca, NY: Cornell Lab of Ornithology. http://bna.birds.cornell.edu/bna/species/149 (last accessed 10 November 2011).

-----------------------------------. 1999. Barn Swallow (*Hirundo rustica*). In *The birds of North America*. ed. A. Poole and F. Gill. 452. Philadelphia: The Birds of North America, Inc.

Brown, L.J. and A. Root. 1971. The breeding behaviour of the lesser flamingo *Phoeniconaias minor*. *Ibis* 113: 147-172.

Burger, J. and M. Gochfeld. 2003. Parrot behavior at a Rio Manu (Peru) clay lick: Temporal patterns, associations, and antipredator responses. *Acta Ethologica*. 6: 23-34.

Butler, D.R. 1989. The failure of beaver dams and resulting outburst flooding: A geomorphic hazard of the southeastern piedmont. *Geographical Bulletin* 31: 29-38.

------------- 1991a. Beavers as agents of biogeomorphic change: A review and suggestions for teaching exercises. *Journal of Geography* 90: 210-217.

------------- 1991b. The reintroduction of the beaver into the South. *Southeastern Geographer* 31: 39-43.

------------- 1992. The grizzly bear as an erosional agent in mountainous terrain. *Zeitschrift für Geomorphologie* 36: 179-189.

------------- 1993. The impact of mountain goat migration on unconsolidated slopes in Glacier National Park, Montana. *Geographical Bulletin* 35(2): 98-106.

------------- 1995. *Zoogeomorphology: animals as geomorphic agents*. New York, NY: Cambridge University Press.

------------- 2000. Zoogeomorphology. In *Oxford Companion to the Earth.* ed. P.J. Hancock and B.J. Skinner. 1117-1118. Oxford, England: Oxford University Press.

------------- 2003. Geomorphology. In *Geography in America at the dawn of the 21st century*. ed. G.L. Gail and C.J. Willmott. 56-71. New York, NY: Oxford University Press.

------------- 2006. Human-induced changes in animal populations and distributions, and the subsequent effects on fluvial systems. *Geomorphology* 79: 448-459.

Butler, D.R. and G.P. Malanson. 1994. Canadian landform examples – Beaver landforms. *Canadian Geographer* 38: 76-79.

-------------------------------------- 2005. The geomorphic influences of beaver dams and failures of beaver dams. *Geomorphology* 79: 448-459.

Butler, D.R., G.P. Malanson, and J.A. Kupfer. 1992. Beaver, treefall, and cutbank erosion in Midwestern rivers. *Abstracts, Annual Meeting of the Association of American Geographers,* San Diego 29-30.

Cadée, G.C. 1989. Size-selective transport of shells by birds and its palaeoecological implications. *Palaeontology* 32: 429-427.

Cane, J.H. 2003. Annual displacement of soil in nest tumuli of alkali bees (*Nomia melanderi*) (*Hymenoptera: Apiformes: Halictidae*) across an agricultural landscape. *Journal of the Kansas Entomological Society* 76(2): 172-176.

City of San Marcos. 2012. GIS / Mapping A Division of Development Services. *City of San Marcos GIS Website.* http://www.ci.san-marcos.tx.us/departments/engineering/GISIntroduction.html (last accessed 29 January 2012).

Connors, L.M., E. Kiviat, P.M. Groffman, and R.S. Ostfeld. 2000. Muskrat (*Ondatra zibethicus*) disturbance to vegetation and potential net nitrogen mineralization and nitrification rates in a freshwater tidal marsh. *American Midland Naturalist* 143(1): 53-63.

Darwin, C. 1838. On the formation of the mould. *Proceedings of the Geological Society of London* 2: 574-576.

Darwin, C. 1881. *The formation of vegetable mould through the action of worms with some observations on their habits*. London: John Murray.

Davic, R.D. and H.H. Welsh Jr. 2004. On the ecological roles of salamanders. *Annual Review of Ecology, Evolution, and Systematics* 35: 405-434.

Diamond, J., K.D. Bishop, and J.D. Gilardi.1999. Geophagy in New Guinea birds. *Ibis* 141: 181-193.

Dionne, J.C. 1985. Tidal marsh erosion by geese, St. Lawrence estuary, Québec. *Géographie Physique et Quaternaire* 39: 99-105.

Dyer, P.K. and G.J.E. Hill. 1991. A solution to the problem of determining the occupancy status of wedge-tailed shearwater *Puffinus pacificus* burrows. *Emu* 91: 20-25.

------------------------------- 1992. Active breeding burrows of the wedge-tailed shearwater in the Capricorn Group, Great Barrier Reef. *Emu* 147-151.

Ehrlich, P., D. Dobkin, and D. Wheye. 1988. *The Birders Handbook: A Field Guide to the Natural History of North American Birds*. New York: Simon and Schuster Inc.

Eldridge, D.J. 2004. Mounds of the American badger (*Taxidea taxus*): significant features of North American shrub-steppe ecosystems. *Journal of Mammalogy* 85(6): 1060-1067.

Emlen, J.T. 1954. Territory, nest building, and pair formation in the cliff swallow. *The Auk* 71(1): 16-35.

Emmons, L.H. and N.M. Stark. 1979. Elemental composition of a natural mineral lick in Amazonia. *Biotropica* 11: 311-313.

Friedman, J.M., W.R. Osterkamp, and W.M. Lewis. 1996. The role of vegetation and bed-level fluctuations in the process of channel narrowing. *Geomorphology* 14: 341-351.

Fritz, K.M., W.K. Dodds, J. Pontius. 1999. The effects of bison crossings on the macroinvertebrate community in a tallgrass prairie stream. *American Midland Naturalist* 141(2): 253-265.

Furness, R.W. 1991. The occurrence of burrow-nesting among birds and its influence on soil fertility and stability. *Symposium of the Zoological Society of London* 63: 53-67.

Gaunt, A.S. 1965. Fossorial adaptations in the bank swallow, *Riparia riparia* (Linnaeus). *University of Kansas Science Bulletin* 46: 99-146.

Gauthier, M. and D.W. Thomas. 1993. Nest site selection and cost of nest building by Cliff Swallows (*Hirundo pyrrhonota*). *Canadian Journal of Zoology* 71: 1120-1123.

Godfrey, G.K. and P. Crowcroft. 1960. *The life of the mole, Talpa europeaea L*. London: Museum Press.

Gough, G.A. and J.R. Sauer. 1997. *Patuxent Bird Glossary*. Patuxent Wildlife Research Center, Laurel, MD. http://www.mbr-pwrc.usgs.gov/Infocenter/Glossary/glossary.html (last accessed 18 August 2011).

Govers, G. and J. Poesen. 1998. Field experiments on the transport of rock fragments by animal trampling on scree slopes. *Geomorphology* 23: 193-203.

Gregory, K.J. 1976. Channel capacity and lichen limits. *Earth Surface Processes* 1: 273-285.

Grimshaw, T.W. and C.M. Woodruff. 1986. *Structural Style in an En Echelon Fault System, Balcones Fault Zone, Central Texas: Geomorphologic and Hydrologic Implications.* The Baclcones Escarpment. http://www.lib.utexas.edu/geo/balcones_escarpment/pages71-76.html (last accessed 26 July 2011).

Grinnell. J. and A.H. Miller. 1944. The distribution of the birds of California. *Pacific Coast Avifauna* 27: 1-608.

Hall, K., J. Boelhouwers, and K. Driscoll. 1999. Animals as erosion agents in the alpine zone: some data and observations from Canada, Lesotho, and Tibet. *Arctic, Antarctic, and Alpine Research* 31(4): 436-446.

Hall, K.J. and A.J. Williams. 1981. Animals as agents of erosion at sub-Antarctic Marion Island. *South African Journal of Antarctic Research* 10-11: 18-24.

Hansell, M. 1984. *Animal architecture and building behaviour*. London: Longman.

------------- 2000. *Bird nests and construction behaviour*. Cambridge, United Kingdom: Cambridge University Press.

Harris, M.P. and T.R. Birkhead. 1985. Breeding ecology of the Atlantic Alcidae. In *The Atlantic Alcidae.* ed. D.N Nettleship and T.R. Birkhead. 156-204. London: Academic Press.

Harrison, H.H. 1975. *A field guide to birds' nests of 285 species found breeding in the United States east of the Mississippi River*. Boston, MA: Houghton Mifflin Company Boston.

Heine, J.C. and T.W. Speir. 1989. Ornithogenic soils of the Cape Bird Adélie penguin rookeries, Antarctica. *Polar Biology* 10: 89-99.

Hickman, G.C. and L.N. Brown. 1973. Mound-building behaviour of the southeastern pocket gopher (Geomys pinetis). *Journal of Mammalogy* 54: 786-789, 971-974.

Hill, G.J.E. and A. Barnes. 1989. Census and distribution of wedge-tailed shearwater *Puffinus pacificus* burrows on Heron Island, November 1985. *Emu* 89: 135-139.

Hobson, K.A. 1989. Pebbles in nests of double-crested cormorants. *Wilson Bulletin* 101: 107-108.

Huels, T.R. 1985. Cave swallow paired with cliff swallows. *The Condor* 87(3): 441-442.

Hulscher, S.J.M.H. and G.M. Brink. 2001. Comparison between predicted and observed sand waves and sand banks in the North Sea. *Journal of Geophysical Research* 106(C5): 9327-9338.

Hupp, C.R. 1986. Vegetation and bank-slope development. *Proceedings of the Fourth Federal Interagency Sedimentation Converence*. Volume 2, Sub-Committee on Sedimentation of the Interagency Advisory Committee on Water Data. Las Vegas, Nevada, 5-92.

Hupp, C.R. and W.R. Osterkamp. 1985. Bottomland vegetation distribution along Passage Creek, Virginia, in relation to fluvial landforms. *Ecology* 66: 670-681.

Hupp, C.R. and A. Simon. 1991. Bank accretion and the development of vegetated depositional surfaces along modified alluvial channels. *Geomorphology* 4: 111-124.

Jefferies, R.L. 1988. Pattern and process in Arctic coastal vegetation in response to foraging by lesser snow geese. *Ecology* 72: 2101-2109.

Jefferies, R.L., A. Jensen, and K.F. Abraham. 1979. Vegetational development and the effect of geese on vegetation at La Perouse Bay, Manitoba. *Canadian Journal of Botany* 57: 1439-1450.

John, R.D. 1991. Observations on soil requirements for nesting bank swallows, *Riparia riparia*. *Canadian Field-Naturalist* 105: 251-254.

Johnson, D.L. 1993. Dynamic denudation evolution of tropical, subtropical and temperate landscapes with three-tiered soils: Toward a general theory of landscape evolution. *Quaternary International* 17: 67-78.

Johnson, W.C., R.L. Burgess, and W.R. Keammerer. 1976. Forest overstory vegetation and environment on the Missouri River floodplain in North Dakota. *Ecological Monographs* 46: 59-84.

Joly, Y., Y. Frenot, and P. Vernon. 1987. Environmental modifications of a subantarctic peat-bog by the wandering albatross (*Diomedea exulans*): A preliminary study. *Polar Biology* 8: 61-72.

Keith, S., E.K. Urban, and C.H. Fry. 1992. *The birds of Africa Vol. 4*. London: Academic Press.

Kilgore, D.L. and K.L. Knudsen. 1977. Analysis of materials in cliff and barn swallow nests: Relationship between mud selection and nest architecture. *Wilson Bulletin* 89(4): 562-571.

Lane, L.J., M.H. Nichols, and J.R. Simanton. 1995. Spatial variability of cover affecting erosion and sediment yield in overland flow. In *Effects of scale on interpretation and management of sediment and water quality* ed. W.R. Osterkamp. 147-152. International Association of Hydrological Sciences Publication 226, 301 pages.

Larkin, T.J. and G.W. Bomar. 1983. *Climatic atlas of Texas.* Austin, TX: Texas Department of Water Resources, LP-192.

Lasley, G.W. and C. Sexton. 1987. The winter season: south Texas region. *American Birds* 41: 300–303.

Link, R. 2004. *Living with wildlife in the Pacific Northwest*. Washington: University of Washington Press.

Lockwood, M. 2001. *Birds of the Texas hill country*. Austin, TX: University of Texas Press.

Lockwood, M. and B. Freeman. 2004. *The TOS handbook of Texas birds*. College Station, TX: Texas A & M University Press.

Malanson, G.P. 1999. Considering complexity. Annals of the Association of American Geographers 89(4): 746-753.

Marston, R.A. 1982. The geomorphic significance of log steps in forest streams. *Annals Association of American Geographers* 72: 99-108.

Martin, R.F. 1974. Syntopic culvert nesting of Cave and Barn Swallows in Texas. *The Auk* 91: 776–782.

McNair, D.B. and W. Post. 2001. Review of the occurrence of vagrant Cave Swallows in the United States and Canada. *Journal of Field Ornithology* 72: 485–503.

Meilke, G. 1977. Mound building by pocket gophers (Geomyidae): their impact on soils and vegetation in North America. *Journal of Biogeography* 4: 171-180.

Milton, S.J., W.R.J. Dean, and W.R. Siegfried. 1994. Food selection by ostrich in southern Africa. *Journal of Wildlife Management* 58: 234-248.

Mitchell, P. 1988. The influences of vegetation, animals and mircro-organisms on soil processes. In *Biogeomorphology*. ed. H.A. Viles. 43-82. New York: Basil Blackwell.

Møller, A. P. 1991. Sexual ornament size and the cost of fluctuating asymmetry. *Proceedings of the Royal Society B: Biological Sciences* 243: 59-62.

Møller A.P. 2006. Rapid change in nest size of a bird related to change in a secondary sexual character. *Behavioral Ecology* 17: 108-116.

Mosley, P.M. 1981. The influence of organic debris on channel orphology and bedload transport in a New Zealand forest stream. *Earth Surface Processes* 6: 571-579.

Müller-Schwarze, D. 1984. *The behaviour of penguins*. Albany, NY: State University of New York Press.

Munn, C.A. 1994. Macaws: Winged rainbows. *National Geographic* 184: 118-40.

Murgatroyd, A.L. and J.L. Ternan. 1983. The impact of deforestation on stream bank erosion and channel form. *Earth Surface Processes and Landforms* 8: 357-369.

Naiman, R.J. and K.H. Rogers. 1997. Large animals and system-level characteristics in river corridors. *BioScience* 47(8): 521-529.

National Research Council. 1997. *Rediscovering Geography, new relevance for science and society*. Washington, D.C.: National Academy Press.

Nettleship, D.N and T.R. Birkhead. 1985. *The Atlantic Alcidae: the evolution, distribution and biology of the Auks inhabiting the Atlantic Ocean and adjacent water areas*. London: Academic Press.

Norberg, R.A. 1994. Swallow tail streamer is a mechanical device for self-deflection of tail leading edge, enhancing aerodynamic efficiency and flight maneuverability. *Proceedings of the Royal Society B: Biological Sciences* 257: 227-233.

Osterkamp, W.R., and C.R. Hupp. 1984. Geomorphic and vegetative characteristics along three northern Virginia streams. *Geological Society of America Bulletin* 95: 1093-1101.

Palmer, P.C. 1988. Cave swallow range continues to expand. *American Birds* 42: 174-176.

Peréz-Rivera, R.A. 2009. Changes in the breeding habits and season of the cave swallow (*Petrochelidon fulva*) in Puerto Rico. *Revista Umbral* 1: 160-168.

Powell, L.L., T.U. Powell, G.V.N. Powell, and D.J. Brightsmith. 2009. Parrots take it with a grain of salt: available sodium content may drive collpa (clay lick) selection in Southeastern Peru. *Biotropica* 41(3): 279-282.

Reddell, J.R. 1967. A checklist of the cave fauna of Texas III. *Texas Journal of Science* 19: 184–226.

Risikind, D.H. and D.D. Diamond. 1988. An introduction to environments and vegetation. In *Edwards Plateau vegetation: plant ecological studies in Central Texas.* ed. B.B. Amos and F.R. Gehlbach. 1-16. Waco, Texas: Baylor University.

Robbins, C.S., B. Bruun, and H.S. Zim. 1966. *Birds of North America*. New York: Western Publishing Company, Inc.

Ross, B.A., J.R. Tester, and W.J. Breckenridge. 1968. Ecology of mima-type mounds in northwestern Minnesota. *Ecology* 49: 172-177.

Rowley, I. 1970. The use of mud in nest-building: A review of the incidence and taxonomic importance. *Ostrich Suppliment* 8: 139-148.

Salmon, T.P. and W.P. Gorenzel. 1981. *Cliff Swallows: How to Live with Them*. Oakland: University California Divison of Agriculture and Science. Leaflet 21264.

Scatena, F.N. and A.E. Lugo. 1996. Geomorphology, disturbance, and the soil and vegetation of two subtropical wet steepland watersheds of Puerto Rico. *Geomorphology* 13: 199-213.

Selander, R.K. and J.K. Baker. 1957. The Cave Swallow in Texas. *Condor* 59: 345–363.

Snyder, L. 1993. Puffin cavity nests. *Wildbird* 7: 76.

Soler, J.J., J.J. Cuervot, A.P. Møller, and F. DeLopes. 1998. Nest building is a sexually selected behaviour in the barn swallow. *Animal Behaviour* 56: 1435-1442.

Soler, J.J., M. Martin-Vivaldi, C. Haussy, and A.P. Møller. 2007. Intra and interspecific relationships between nest size and immunity. *Behavior Ecology* 18: 781-791.

Splettstoesser, J.F. 1985. Note on rock striations caused by penguin feet, Falkland Islands. *Arctic and Alpine Research* 17: 107-111.

Statzner, B., E.F. Fievet, J. Champagne, R. Morel, E. Herouin. 2000. Crayfish as geomorphic agents and ecosystem engineers: biological behavior affects sand and gravel erosion in experimental streams. *Limnology and Oceanography* 45(5): 1030-1040.

Stine, M.B. and D.R. Butler. 2011. A content analysis of biogeomorphology within geomorphology textbooks. *Geomorphology* 125: 336-342.

Stokes, D.L. and P.D. Boersma. 1991. Effects of substrate on the distribution of Magellanic penguin (*Spheniscus magellanicus*) burrows. *Auk* 108: 923-933.

Strickler, S. and S. West. 2011. Cave swallow (*Petrochelidon fulva*). In *The Birds of North America Online.* ed. A. Poole. Ithaca, NY: Cornell Lab of Ornithology. http://bna.birds.cornell.edu/bna/species/141 (last accessed 10 November 2011).

Terres, J.K. 1980. *The Audubon society encyclopedia of North American birds*. New York: Alfred A. Knopf.

Texas Forest Service. 2008. Trees of Texas. *Texas Eco-Regions.* http://texastreeid.tamu.edu/content/texasEcoRegions/BlacklandPrairies/ (last accessed 28 January 2012).

Texas Parks and Wildlife Department (TPWD). 2007. *Hill Country Wildlife Management, Historical Perspective*. http://www.tpwd.state.tx.us/landwater/land/habitats/hillcountry/ (last accessed 26 July 2011).

Texas Parks and Wildlife Department (TPWD). 2008. *Blackland Prairie Ecological Region*. http://www.tpwd.state.tx.us/landwater/land/habitats/cross_timbers/ecoregions/blackland.phtml (last accessed 28 January 2012).

Texas Parks and Wildlife Department (TPWD). 2008. *Map of Texas Ecoregions*. http://www.tpwd.state.tx.us/learning/texas_nature_trackers/hummingbird_roundup/identification/county_ecoregions/ (last accessed 28 January 2012).

Texas Parks and Wildlife Department (TPWD). 2008. *Texas Partners in Flight, Ecological Regions of Texas*. http://www.tpwd.state.tx.us/huntwild/wild/birding/pif/assist/pif_regions/ (last accessed 26 July 2011).

Texas Parks and Wildlife Department (TPWD). 2010. *GIS Lab Data Downloads*. http://www.tpwd.state.tx.us/landwater/land/maps/gis/data_downloads/ (last accessed 29 January 2012).

Thayer, J.E. 1915. Two species of cliff swallows nesting in Kerr County, Texas. *The Auk* 32: 102-103.

Thouless, C.R., J.H. Fanshawe, and B.C.R. Bertram. 1989. Egyptian vultures *Neophron percnopterus* and ostrich *Struthio camelus* eggs: The origins of stone-throwing behaviour. *Ibis* 131: 9-15.

Trimble, S.W. and A.C. Mendel. 1995. The cow as a geomorphic agent – A critical review. *Geomorphology* 13: 233-253.

Troy, S. and M.A. Elgar. 1991. Brush-turkey incubation mounds: Mate attraction in a promiscuous mating system. *Trends in Ecology and Evolution* 6: 202-203.

Turner, A. and C.A. Rose. 1989. *Handbook to the Swallows and Martins of the World*. London: Christopher Helm.

U.S. Census Bureau. 2011. U.S. Census Beurau. *2010 TIGER/Line® Shapefiles*. http://www.census.gov/cgi-bin/geo/shapefiles2010/main (last accessed 29 January 2012).

U.S. Census Bureau. 2011. U.S. Census Beurau. *Factsheet: San Marcos city, Texas, 2005-2009*. http://factfinder.census.gov/servlet/ACSSAFFFacts?_event=&geo_id=16000US4865600&_geoContext=01000US%7C04000US48%7C16000US4865600&_street=&_county=san+marcos%2C+tx&_cityTown=san+marcos%2C+tx&_state=04000US48&_zip=&_lang=en&_sse=on&ActiveGeoDiv=geoSelect&_useEV=&pctxt=fph&pgsl=160&_submenuId=factsheet_1&ds_name=DEC_2000_SAFF&_ci_nbr=null&qr_name=null&reg=null%3Anull&_keyword=&_industry= (last accessed 26 July 2011).

U.S. National Oceanic and Atmospheric Administration (US NOAA). 2004. *Climatography of the United States No. 20 1971-2000*. http://hurricane.ncdc.noaa.gov/climatenormals/clim20/tx/417983.pdf (last accessed 26 July 2011).

U.S. National Oceanic and Atmospheric Administration (US NOAA). 2011. Climatological Data: Annual Summary. Asheville, NC: U.S. National Climate Data Center.

Van Lawick-Goodall, J. 1968. Tool-using bird: The Egyptian vulture. *National Geographic* 133: 630-641.

Verbeek, N.A.M. and R. Boasson. 1984. Local alteration of alpine calcicolous vegetation by birds: Do the birds create hummocks? *Arctic and Alpine Research* 16: 337-341.

Viles, H. 1988. *Biogeomorphology*. New York: Basil Blackwell.

Ward, S. 1996. Energy expenditure of female barn swallows *Hirundo rustica* during egg formation. *Physiological Zoology* 69(4): 930-951.

Weaver, H.B. and C.R. Brown. 2005. Colony size, reproductive success, and colony choice in cave swallows *Petrochelidon fulva*. *Ibis* 147: 381-390.

West, S. 1995. Cave Swallow (*Hirundo fulva*). In *The birds of North America*, no. 141. ed. A. Poole and F. Gill. Philadelphia: Academy of Natural Sciences, and Washington, DC: American Ornithologists' Union.

Wink, M., A. Hofer, M. Bilfinger, E. Englert, M. Martin, and D. Schneider. 1993. Geese and dietary allelochemicals–food palatability and geophagy. *Chemoecology* 4: 93-107.

Winkler, D.W. and F.H. Sheldon. 1993. Evolution of nest construction in swallows (*Hirundinidae*): A molecular phylogenetic perspective. *Proceedings of the National Academy of Science* 90: 5703–5707.

Yanosky, T.M. 1982. Hydrologic influences from ring widths of flood damaged trees, Potomac River, Maryland. *Environmental Geology* 4: 43-52.

VITA

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