CREATING A SUITABILITY MAP OF NESTING HABITAT FOR THE GOLDEN-CHEEKED WARBLER (*Dendroica chrysoparia*) IN HAYS COUNTY, TEXAS

THESIS

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CHAPTER 1

INTRODUCTION

Throughout history, and as reflected in the fossil record, species have periodically become extinct as a result of natural causes, often through the process of natural selection. However, extinction rates have increased dramatically in recent decades (Skillman 2000). Today, reductions in populations or disappearances of species can often be attributed to the results of human actions.

Many human activities can pose serious threats to plant and animal habitats, with a resultant decrease in biodiversity. Urbanization, development, and agriculture have contributed to the decline of numerous plant and animal species, by encroaching upon increasing areas of the habitat they need to survive. Urban sprawl has caused the fragmentation and destruction of habitats for many species. Loss of habitat is a major factor in numerous species becoming threatened or endangered.

To some people, the protection of one small bird, a flower, or some other individual species may appear to be a rather trivial endeavor. However, each individual species plays a role in the continuing vitality of an ecosystem. The disappearance of one species has the potential to alter the entire ecosystem's viability. All of the creatures on this planet are related through a complex web of interdependence, and we have barely begun to understand the ways that some of these interdependencies work. It has been suggested that the extinction of one species can ultimately result in the extirpation of ten other species (Lougeay 1996). Once a cycle of extinctions begins, a chain reaction could ensue, causing the disappearance of countless species, some of which we may not even know exist. The resulting loss of biodiversity could have substantial impacts on the environment, causing changes that today we cannot imagine.

The United States Congress passed The Endangered Species Act (16 USC 1531-1544) on December 28, 1973. This action acknowledged that, due to a long cycle of economic growth and development without adequate regard for the environment, the future of many plant and animal species had become uncertain. The law expressed an awareness that each individual species serves an important purpose on this planet and has a right to exist: "these species of fish, wildlife, and plants are of esthetic, ecological, educational, historical, recreational, and scientific value to the Nation and its people" (U.S. Congress 1973, 1531.a3).

The Endangered Species Act provides a means for conservation of the habitats that threatened and endangered species depend upon for survival. A species is considered endangered if it "is in danger of extinction throughout all or a significant portion of its range" (U.S. Congress 1973, 1532.6). A threatened species is one that "is likely to become an endangered species within the foreseeable future" (U.S. Congress 1973, 1532.20). When a species is placed on the Threatened or Endangered lists, the government becomes empowered to regulate land uses in the critical ecosystems that these species inhabit. By conserving these critical habitats, the government provides species with a greater chance for survival. A species can be "emergency listed" if the Secretary of the Department of the Interior discovers that some activity is "posing a significant risk to the well-being of [a] species" (U.S. Congress 1973, 1533.b7), and that the situation requires urgent action, because the normal process for listing a species would require too much time, perhaps placing the species in even greater peril. This emergency listing provides the species with immediate protection under the Act, and the normal listing process can then be completed at a later date (U.S. Congress 1973, 1533).

Seventy-four federally threatened or endangered species have been identified within the State of Texas. Forty-six are animals, and the other 28 are plants (U.S. Fish and Wildlife Service 1999). In central Texas, the Golden-cheeked Warbler (*Dendroica chrysoparia*) (GCW) is one of the animals that has been severely affected by habitat loss. The GCW is a small, insectivorous, migratory songbird that comes to central Texas each spring to nest, and spends its winters in the pine-oak highlands of southern Mexico and Central America. This bird was emergency listed on the Endangered Species List on May 4, 1990, because of a significant decline in its population, resulting from the rapid destruction and fragmentation of habitats in both its breeding range and wintering grounds. The primary cause for the loss of nesting habitat in central Texas has been urban development (Beardmore 1994, Campbell 1995, Damude 1998, Ladd 1985, U.S. Fish and Wildlife Service 1996). The final ruling to list the GCW as endangered was published on December 27, 1990 (U.S. Fish and Wildlife Service 1990).

Urbanization has greatly affected the GCW because of the bird's remarkably specific habitat requirements. Central Texas is the only region on Earth that contains the Ashe juniper (*Juniperus ashei*) woodlands that the bird requires for nesting (Beardmore 1994, Campbell 1995, Damude 1998, Gass 1996, Ladd 1985, Moses 1996, Pulich 1976). Rapid urban population growth has been occurring in central Texas in recent years (U.S.

Census Bureau, Population Division 2000), particularly along the Interstate-35 corridor between north Austin and San Antonio (See Figure 1). This growth has resulted in large amounts of prime habitat being converted to other uses. In addition to urban expansion, agricultural and range management practices have also contributed to destruction of the GCW's habitat.

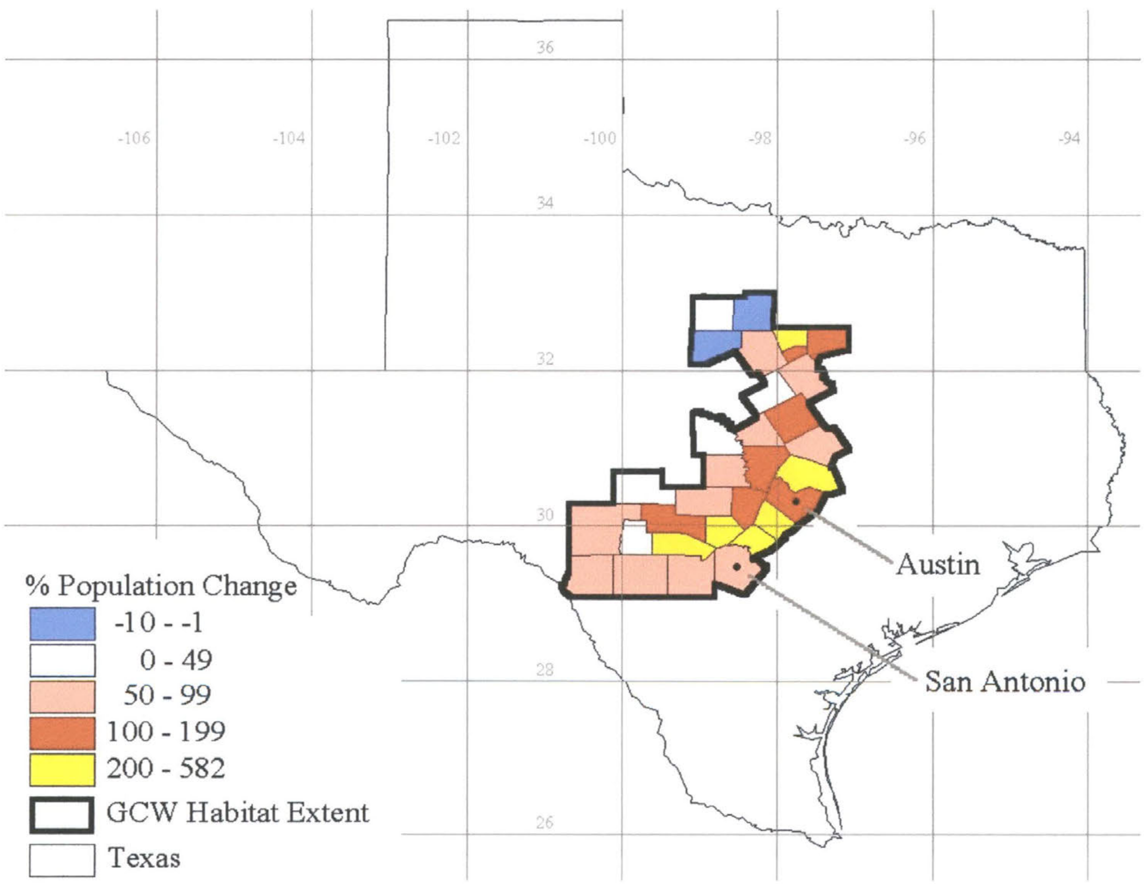


Figure 1. Population growth in the GCW nesting habitat by county, 1970 - 1999.
(Data from U.S. Census Bureau, Population Division 2000.)

Statement of the Problem

According to the Endangered Species Act of 1973, the United States has a responsibility to conserve all species facing extinction (U.S. Congress 1973, 1531). A first step in preserving the GCW is to ascertain the extent of its remaining habitat. It is essential to determine exactly where in central Texas suitable nesting habitat still remains, to protect these lands and steer future development away from these critical areas. This study utilizes remote sensing and geographic information systems (GIS), in an attempt to develop a suitability map that identifies and delineates the location and distribution of the nesting habitat of the Golden-cheeked Warbler (*Dendroica chrysoparia*) in Hays County, Texas.

CHAPTER 2

LITERATURE REVIEW

The first major scientific study to detail the GCW's complete life history was published by Warren Pulich in 1976. Even though this book was written 14 years prior to the bird officially being listed as endangered, Pulich recognized that the bird's continuing survival was in jeopardy. Even today, his book continues to be one of the definitive references for information about the bird and its habitat restrictions.

More recently, Campbell (1995) and Damude (1998) have provided concise, detailed summaries of the characteristics of the GCW, including its history and habitat requirements. Both authors presented condensed versions of the information contained in Pulich (1976), and included updated data on habitat requirements that had been determined since Pulich's publication. Campbell (1995) also included a set of management guidelines, designed for landowners wanting to maintain habitat on their land. Gass (1996) described the GCW's nesting behavior, expanding Pulich's (1976) overall description of nesting behavior, and providing a more detailed explanation of the bird's habits.

All sources are in agreement that the most serious threat to the GCW is loss of habitat through urbanization. However, other factors such as predators (e.g., Blue Jays [*Cyanocitta cristata*], snakes, cats) and nest parasites (primarily the Brown-headed

Cowbird [*Molothrus ater*]) also pose some concern (Engels and Sexton 1994, Gass 1996, U.S. Fish and Wildlife Service 1996).

Yaukey (1996) demonstrated that not all birds are negatively affected by urbanization. Some species are able to adapt, and can actually thrive in urban environments. He stated that "the species that disappear are those that require mature forest or dense ground cover" (Yaukey 1996, 70), and that "endangered and threatened species often survive poorly in urban areas" (Yaukey 1996, 71). In other words, some species with more generalized habitat requirements are capable of adapting to urbanization, but habitat specialists such as the GCW are often unable to adapt, and are therefore forced out of the area.

The most widely-addressed issues relating to the GCW tend to deal with the characterization and quantification of nesting habitat. Several studies (Campbell 1995, Ladd 1985, Pulich 1976, U.S. Fish and Wildlife Service 1996) have attempted to identify exactly what criteria are necessary for an area to provide suitable GCW habitat. DLS Associates (1994) examined the density of GCWs in habitats of varying qualities.

Studies have also been conducted that deal with locating patches of suitable nesting habitat (DLS Associates and WPTC Consulting Group 1994, Moses 1996, Shaw 1989, Shaw and Atkinson 1988). These studies involved the integration of GIS and either remote sensing techniques (Moses 1996, Shaw 1989, Shaw and Atkinson 1988) or interpretation of aerial photography (DLS Associates and WPTC Consulting Group 1994). Although not dealing specifically with GCWs, Imhoff et al. (1997) stressed the importance of assessing vegetation structure when delineating bird habitat, and the utility of employing remotely sensed data to map the vegetation structure.

Because of practical constraints with obtaining satellite or aerial imagery, nearly all of the research done to date has focused on small areal subsets of the GCW's habitat. The only studies completed that have considered the entire breeding range are Shaw (1989) and Shaw and Atkinson (1988). Both studies utilized the same set of satellite imagery, Landsat Multispectral Scanner (MSS) images, which have 80 meter resolution. The authors were able to cover the entire breeding range with portions of four Landsat scenes.

Although the entire breeding range was covered, the low resolution satellite data yielded results that were very generalized. Both studies provided an overview of the habitat extent, but the results were presented only on a countywide basis. This study utilizes Landsat Thematic Mapper (TM) imagery, which has a spatial resolution of 30 meters. Although this study does not cover as extensive an area as that covered by Shaw (1989) and Shaw and Atkinson (1988; my study analyzes only Hays County, TX), the increased resolution allows for more detailed, site-specific results. The use of Landsat TM imagery enables a researcher to differentiate between small-scale variations in land cover that would be too small in areal extent to be distinguished with the coarser resolution of the MSS imagery.

There are currently 31 counties in central Texas that are believed to contain suitable habitat for the GCW (Campbell 1995, Pulich 1976, U.S. Fish and Wildlife Service 1996; see Table 1 and Figure 2). The habitat is predominantly focused in the eastern and southern portions of the Edwards Plateau, in an area often referred to as the Hill Country. Additional habitat can be found in limited portions of the Llano Uplift (also known as the Central Mineral Region). Habitat also extends farther north into the

Lampasas Cut Plain (Damude 1998, Riskind and Diamond 1986, Swanson 1995). According to Pulich (1976), the GCW may also "be found in pockets of similar-type vegetation in small portions of the East and West Cross Timbers, and the extreme southern part of the Grand Prairie" (Pulich 1976, 65).

Table 1. Counties believed to contain nesting habitat for the Golden-cheeked Warbler

Counties with habitat			Counties where the GCW had been identified in the past, but probably no longer contain habitat
Bandera	Erath	Llano	Bastrop
Bell	Gillespie	Medina	Comanche
Bexar	Hamilton	Palo Pinto	Concho
Blanco	Hays	Real	Dallas
Bosque	Hood	San Saba	Ellis
Burnet	Johnson	Somervell	Hill
Comal	Kendall	Stephens	Lee
Coryell	Kerr	Travis	Mason
Eastland	Kimble	Uvalde	McLennan
Edwards	Kinney	Williamson	Menard
	Lampasas		Mills
			Tom Green

Sources: Campbell 1995, Pulich 1976, U.S. Fish & Wildlife Service 1996.

Even though 31 counties are thought to contain suitable habitat for the GCW, an overwhelming majority of the literature has dealt solely with portions of Travis County, surrounding the city of Austin (DLS Associates 1994, DLS Associates and WPTC Consulting Group 1994, Engels and Sexton 1994, Gass 1996, Moses 1996). Ladd (1985) examined a location in Kerr County. Most of the preceding studies also focused on public land, thus ignoring possible habitat that could potentially be located on private land. Since more than 97 percent of the land in Texas is privately owned (U.S. Fish and Wildlife Service 1996), significant portions of potential habitat may have been overlooked.

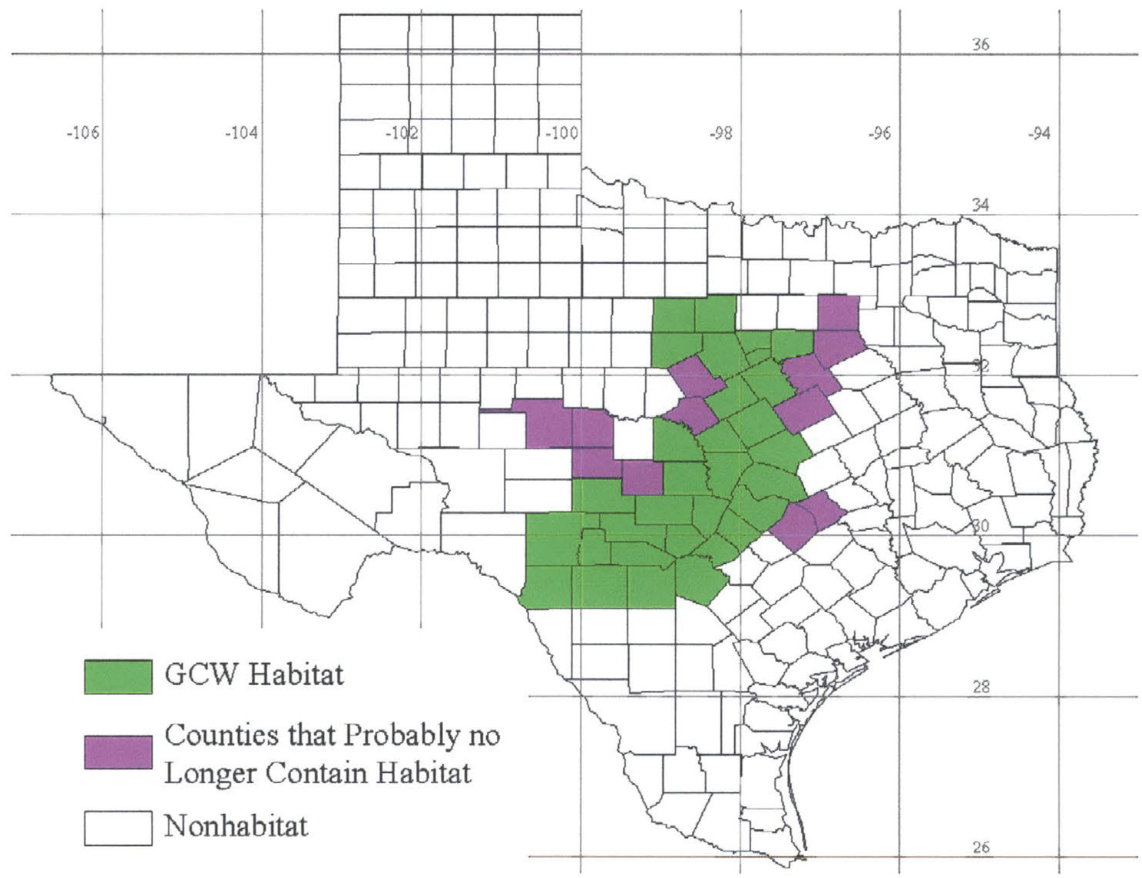


Figure 2. General location of nesting habitat for the Golden-cheeked Warbler. (Data from Campbell 1995, Pulich 1976, U.S. Fish and Wildlife Service 1996.)

Travis County is heavily developed, and much of what was once prime GCW habitat has already been lost. Attention needs to be focused on both public and private lands in other counties, to identify threatened habitats in other parts of the breeding range.

have recently begun experiencing increasing levels of urban development (U.S. Census Bureau, Population Division 2000; see Figure 1). Hays County represents an excellent example of this recent growth. Located on the western side of I-35, just south of Travis County (see Figure 3), Hays County potentially contains a great deal of prime GCW habitat. The county had historically been fairly rural, but its population is now beginning to experience significant increases. Cities and towns such as San Marcos, Wimberley, and Kyle are expanding quickly as people move into these areas. The county has experienced a population increase of 236% since 1970 (U.S. Census Bureau, Population Division 2000; see Figure 1), and that trend does not appear to be diminishing. Studies need to be conducted that delineate the locations of suitable GCW nesting habitat in rapidly growing areas (outside of Travis County), to understand where suitable nesting habitats are located. The sooner these habitats can be identified and mapped, the better chance there will be for preserving enough habitat to ensure the continuing survival of the GCW.

Although it would have been extremely useful to have this study undertaken for the GCW's entire breeding range, such an effort was outside the scope of this thesis. Obtaining suitable high-resolution satellite imagery and GIS data to cover all 31 counties could be difficult, and the necessary processing time required for such an extensive study area would have been unreasonable to undertake. This study therefore analyzes Hays County. This study can be used as a model for future mapping efforts in other counties.

As discussed above, Hays County has become subject to intense urbanization pressures. Since Hays is located at the eastern extent of the breeding range, it should represent a strategic portion of prime habitat, because the eastern portion of the breeding

As stated earlier, other areas of central Texas, particularly along the Interstate-35 corridor, range tends to contain larger expanses of prime habitat than the western portion (Campbell 1995). The higher amounts of average rainfalls in the east (Riskind and Diamond 1986, Swanson 1995) provide greater opportunity for the Ashe juniper vegetation association to thrive.

Hays County was therefore chosen as the study site for this analysis, because of its potential to contain significant amounts of prime habitat, its intensifying development pressures, and the relative lack of attention devoted to the county in the literature.

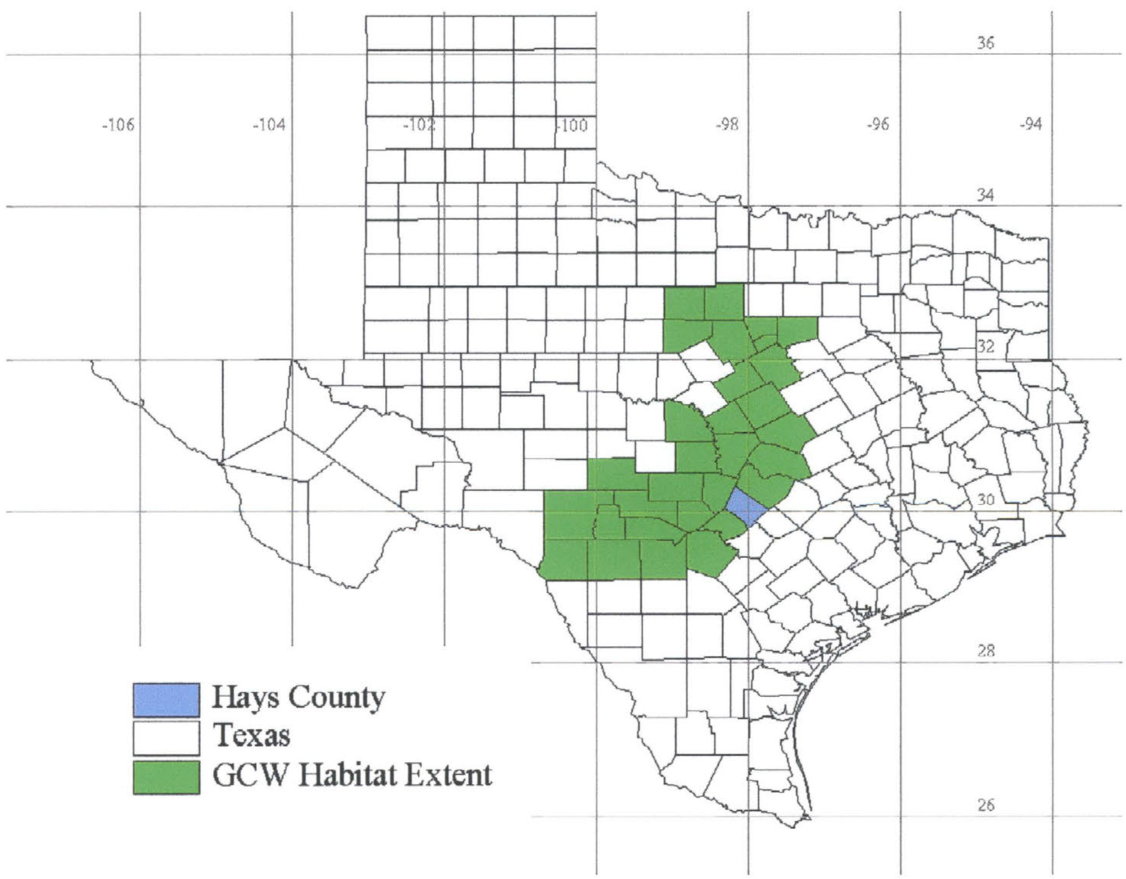


Figure 3. Location of study site: Hays County, Texas.

CHAPTER 3

METHODOLOGY

The possible locations of nesting habitat for the Golden-cheeked Warbler (GCW) were detected for Hays County, Texas, using an integration of remote sensing and geographic information systems (GIS). Remote sensing is a "technique of obtaining information about objects through the analysis of data collected by special instruments that are not in physical contact with the objects of investigation" (Avery and Berlin 1992, 1). GIS is "an organized collection of computer hardware, software, geographic data, and personnel designed to efficiently capture, store, update, manipulate, analyze, and display all forms of geographically referenced information" (Berry 1993, 227).

A combination of remote sensing and GIS techniques is extremely useful because it facilitates the integration of information and different types of data (e.g., satellite images, point data, DEMs, vector layers) and an efficient undertaking of more detailed spatial analyses than what could be accomplished using either tool separately. Since more parameters can be entered into the analysis, using this combination of techniques should enable a more accurate identification of the GCW habitat, thereby enabling future protection efforts to be more efficient.

Steps in the Analysis

The following steps were taken to locate areas of suitable nesting habitat for the GCW. The steps will be discussed in greater detail in subsequent paragraphs.

1. A Landsat ETM+ satellite image covering the study area (Hays County, Texas) was acquired.
2. The image was georeferenced to place it into a coordinate system.
3. The Hays County boundary line was overlain onto the image, and areas located outside the County were masked out and excluded from the analysis.
4. An unsupervised classification was executed on the image.
5. The classified image was interpreted visually to identify which land use/land cover class(es) represent the proper vegetation associations for habitat.
6. Based on this visual interpretation, the image was reclassified into three categories: 1) Suitable GCW Habitat, 2) Potential Habitat, and 3) Unsuitable Areas.
7. Vegetation patches in the Suitable or Potential categories that would be too small in areal extent to support GCWs were reassigned to the Unsuitable category.
8. Portions of the image were field-checked to assess the accuracy of the classification.
9. GIS data layers were combined with the vegetation data to determine an area's level of suitability as nesting habitat in greater detail. The following layers were included: Distance to Buildings, Distance to Roads, Distance to Water Bodies, and Slope.
10. The data were reclassified to create a map showing the habitat suitability after the addition of the GIS data. This map illustrates three ranked classes: 1) Prime Habitat, 2) Potential Habitat, and 3) Unsuitable Areas.

Satellite Imagery

The data used in this analysis were obtained primarily from satellite remotely-sensed imagery. The satellite scene was imaged by the Enhanced Thematic Mapper Plus (ETM+) sensor package on the Landsat 7 satellite (TNRIS 1999a). Spectral characteristics of the Landsat 7 sensor are summarized in Table 2. Six multispectral bands (bands 1-5 and 7) were used in this analysis (band 6 [thermal IR] and the panchromatic band were not available). All of Hays County, Texas was covered by the acquired scene. The image was analyzed with the Environment for Visualizing Images ($ENVI_{®}$) software, which is a commercially available, raster-based package that integrates the ability to process satellite imagery with GIS functions (Research Systems Inc. 1999a).

Before beginning the classification process, the image was georeferenced to a geographic coordinate system. An image-to-map registration was performed, using the four corners of the scene and the scene center as ground control points (GCPs; a GCP is "a point on the surface of Earth where both image coordinates [measured in rows and columns] and map coordinates [measured in degrees of latitude and longitude, feet, or meters] can be identified" [Jensen 1996, 124]). During the image-to-map registration process, GCPs are selected in the image, and their corresponding geographic coordinates are entered manually (Research Systems, Inc. 1999b). The map coordinates of the five GCPs were obtained from the image header file. Using these GCPs, a root-mean-square (RMS) error of 0.0032 was obtained (the RMS error describes how well the GCPs account for the geometric distortion present in the original image [Jensen 1996]). A commonly used threshold value for the acceptable amount of RMS error is 0.05, and smaller values indicate more accurate results.

Table 2. Landsat 7 (ETM+) sensor characteristics

Band	Wavelength (μm)	Resolution (m)	Characteristics
1	0.45 - 0.52	30	Blue-green or Green. Maximum water penetration. Coastal bathymetric and forest mapping; distinguishes soil from vegetation; deciduous from coniferous; identifies cultural features. Strong vegetation absorption.
2	0.52 - 0.61	30	Green. Matches green reflectance peak of vegetation. Assesses plant vigor; discriminates vegetation types; identifies cultural features.
3	0.63 - 0.69	30	Red. Chlorophyll absorption band. Discriminates vegetation types.
4	0.76 - 0.90	30	Near or Reflected Infrared. Detects biomass content; maps shorelines; discriminates vegetation type/vigor (centers in region of maximum sensitivity to plant vigor) & soil moisture. High land/water contrast; very strong vegetation reflectance.
5	1.55 - 1.75	30	Mid- or Reflected Infrared (MIR, RIR). Moisture content of soil & vegetation. Sensitive to plant water stress. Good contrast between vegetation types. Penetrates thin clouds. Discriminates snow from clouds; rock types.
6	10.4 - 12.5	60	Thermal IR. Nighttime images good for thermal mapping; estimating soil moisture/plant transpiration rates and for vegetation stress analysis.
7	2.09 - 2.35	30	MIR or RIR. Coincides with absorption bands caused by hydroxyl ions in minerals. Ratio of bands 5/7 thought useful for mapping hydrothermally altered rocks. Discriminates mineral & rock types. Sensitive to plant water stress.
Panchromatic	0.52 - 0.90	15	Combination of visible and Near Infrared wavelengths. Higher resolution provides greater discrimination of surface features.

Sources: Showalter 1989, 69, USGS 2000.

Due to the small number of GCPs, the image was warped (rubber-sheeted) using a first-degree resampling, scaling and translation (RST) method. Nearest neighbor resampling was used to shift the image to properly fit the chosen coordinate system, which uses the value of "the nearest pixel without any interpolation to create the warped image" (Research Systems, Inc. 1999b, 603). This method ensures that the digital numbers (DNs), or brightness values of the pixels, will not be altered during the registration process, which is important when performing a classification or similar analysis that depends upon the specific values of the DNs for interpretation. The image was placed into the Universal Transverse Mercator (UTM) coordinate system, Zone 14 North, with the WGS-84 datum.

Habitat Criterion and Image Classification

The spatial resolution of an image refers to the "limit on how small an object on the earth's surface can be and still be 'seen' by a sensor as being separate from its surroundings" (Lillesand and Kiefer 1994, 33). The resolution of a satellite image is determined by the ground size of one picture element (pixel) in that image. The pixels on Landsat ETM+ multispectral data represent 30 meters by 30 meters on the Earth's surface (see Table 2).

Surface features can be delineated in a remotely-sensed image by performing a classification analysis on the imagery. Image classification is a process of information extraction "that involves the application of pattern recognition theory to multispectral images. . . . [Classification] analyzes the spectral properties of various surface features . . . in a multiband image and sorts the spectral data into spectrally similar Types"

(Avery and Berlin 1992, 451). Based upon the spectral signatures present among the various bands of a satellite image, images can be statistically differentiated to identify multiple classes of surface features, with each class comprising a fairly homogeneous set of reflectance values.

The main limiting factor controlling the distribution of GCWs is the location of significantly-sized parcels of woodlands containing mature Ashe juniper (*Juniperus ashei*) trees (locally known as Texas Cedar). This study attempted to delineate the specific vegetation association (woodlands containing a mixture of mature Ashe juniper and deciduous trees) required by the GCW. Every object on the Earth's surface reflects electromagnetic radiation from the sun, and each type of surface material has a unique reflectance pattern. Reflectance values for trees will be distinguishable from those of grass, and some differences will be noticeable among individual tree species. A pixel covering multiple surfaces on the ground will represent the average reflectance value of those surfaces.

GCWs build their nests only in mature Ashe juniper trees. Nests are constructed using strips of bark that the bird peels off the trees, and the strips are bound together with cobwebs. The trees must reach at least twenty years in age and fifteen feet in height before the bird is able to peel off the strips of bark (Campbell 1995, Damude 1998, Pulich 1976, U.S. Fish and Wildlife Service 1996). To provide suitable habitat, these trees need to be located in fairly dense woodlands that are interspersed with various species of oak and other broad-leaved trees, which provide homes for the insects that comprise the bird's diet. The woodlands must average a minimum of 50 percent canopy cover to provide suitable habitat, and must be a minimum of three to six acres in size to be able to support one pair of nesting warblers (Campbell 1995, Damude 1998, Ladd 1985, Pulich 1976, U.S. Fish and Wildlife Service 1996).

There are two types of classifications that can be performed on an image: supervised and unsupervised. With supervised, the researcher defines training classes representing the land use/land cover types of interest (training classes are clusters of pixels with similar reflectance values). The computer then separates the rest of the pixels in the image into those classes, with each pixel being placed into the class that most accurately matches its reflectance signatures. An unsupervised classification also separates the pixels into classes, with each class representing pixels with similar reflectance signatures, but the clustering of pixels is based upon statistics only, rather than user-defined training classes (Research Systems, Inc., 1999b). An unsupervised classification was used for this analysis rather than supervised. Supervised was determined to not be feasible, because the relatively small number of reliable training sites (specific locations where GCWs are known to nest) would most likely not be sufficient to ensure accurate results (Diamond 2000).

When an unsupervised classification is performed on the satellite image, any woodlands exhibiting the characteristics described above should be identifiable as the same type of land cover, and therefore placed into the same class. Vegetation associations that meet the criteria for GCW habitat can therefore be determined, and separated from non-habitat land covers such as urbanized areas and water bodies.

The ENVI® software contains two unsupervised classifiers: Isodata and K-Means. Generally, both techniques classify the image by calculating class means distributed evenly throughout the image, and use a minimum distance technique to cluster pixels into the nearest class. The class means are then recalculated, and pixels are reclassified with respect to the new means. This process continues until a specified threshold is reached, or until a maximum number of iterations have been calculated. The difference between the two techniques is that Isodata provides greater flexibility with regards to the input parameters. For instance, Isodata enables the analyst to designate a suitable range rather than a specific number of classes, and to specify parameters such as a minimum number of pixels required to constitute a class. Several trial classifications were attempted, utilizing different input parameters, to obtain the result that most accurately discriminates the proper GCW habitat. Specifics regarding the parameters used in each trial classification are presented in Chapter 4.

Locating Suitable Habitat on the Classified Image

An unsupervised classification produces an image containing multiple land use/land cover classes, based upon the different reflectance patterns present throughout the image. However, the classification process is not capable of determining what specific type of land use/land cover each class represents on the ground. This determination is left up to the analyst. The classified image was therefore interpreted visually, using other maps of the area, USGS Digital Orthophoto Quarter Quadrangles (DOQQs), and past reports of GCW sightings (The Daily Record 1999, Pulich 1976), along with general knowledge of the area, to identify which of the land use/land cover classes were most likely to represent suitable GCW habitat.

Variations between habitat patches such as percent canopy cover, relative abundance of individual tree species, and topographic effects may sometimes provide enough spectral variance in reflectance values to result in suitable habitat being separated into more than one class. In addition, pixels centered over the edges of suitable habitat patches may be reflecting a mixture of both habitat and non-habitat, which would reflect differently than a pixel covering a homogeneous area of either class. Once the determination was made as to which classes represented areas with the proper vegetative composition to adequately support nesting GCWs, the image was reclassified into three categories:

1. Suitable Habitat, which is made up of the land use/land cover classes that are most likely to support GCWs;
2. Potential Habitat, which represents classes that are primarily located along the edges of the Suitable Habitat areas, and therefore most likely indicate transitional areas between Suitable Habitat and adjacent Unsuitable land covers (Potential Habitat pixels may be reflecting the average values from a mixture of both Suitable and Unsuitable habitat, or these areas may contain only marginally suitable habitat. The Potential Habitat category therefore represents areas of unknown habitat potential, which would require further analysis through direct field work to determine their actual habitat suitability); and
3. Unsuitable Areas, which includes all of the remaining classes, indicating areas that are not likely to support any GCWs (e.g., urban areas, agricultural fields, large water bodies).

Removal of Small Vegetation Patches

Although one pair of GCWs requires a nesting territory of approximately three to six acres in size, several studies (Campbell 1995, Ladd 1985, U.S. Fish and Wildlife Service 1996) suggest that habitat patches should actually be kept larger than that size, thus enabling each patch to support multiple sets of warblers. Habitat fragmentation causes several problems for GCWs, so maintaining larger patches of habitat is advantageous to the birds. As habitat patches become smaller and more isolated, male warblers can have difficulty attracting suitable mates to their territories (Damude 1998). Smaller habitat patches also increase the threat of nest parasitism by the Brown-headed Cowbird (*Molothrus ater*). Cowbirds tend to remain primarily along the edges of disturbed areas, rather than venturing deep into wooded areas. Therefore, as the size of a habitat patch decreases, the Cowbird has easier access to a larger proportion of the territory, providing it with a greater chance for locating and parasitizing nests (Damude 1998). The GCWs can therefore increase their chances for survival by nesting in larger areas of habitat, where they can remain farther away from the edges. Another advantage of using a larger minimum habitat size is that this excludes some smaller landowners from consideration, thereby releasing them from the regulations of the Endangered Species Act. This exclusion should help decrease landowner opposition to both the GCW and the Endangered Species Act.

Due to the reasons listed above, Campbell (1995) and U.S. Fish and Wildlife Service (1996) both recommend that areas considered to be patches of suitable GCW habitat should be a minimum of 12 acres in size, which could support two to four pairs of nesting warblers. Twelve acres was therefore used as the minimum habitat size for this analysis. Suitable vegetation patches smaller than 12 acres were therefore considered to be too limited in areal extent to adequately support GCWs for an extended period of time. However, there may be one exception to this size requirement. If one of these small patches (large enough to support one pair of warblers, but smaller than 12 acres) is in relatively close proximity to a larger area of suitable habitat, occasional use by GCWs may still be possible, as long as the larger area remains intact.

With a pixel resolution of 30 meters in the satellite image, 12 acres on the ground would be equal to 54 pixels in the image. Vegetation patches considered to be either Suitable or Potential Habitat that were smaller than 54 pixels in size were therefore reclassified to Unsuitable Habitat, with one exception. Because the minimum nesting territory size for a pair of GCWs is 3 acres, Prime Habitat vegetation patches that were 14 to 53 pixels in size (3.1 to 11.8 acres), and were located within "close proximity" of larger Prime Habitat patches, were reclassified to Potential Habitat, meaning that they might potentially be used by GCWs. "Close proximity" was determined by creating a buffer zone with a radius of 0.75 kilometers around all the large Prime Habitat vegetation patches. Small patches located within this buffer zone were considered to be in "close proximity." The DLS and WPTC (1994) study used a 1,000 foot buffer (1,000 ft = 0.30 km), U.S. Fish and Wildlife Service (1996) mentioned a distance of 3,100 feet (3,100 ft = 0.94 km), and Diamond (2000) suggested using a buffer of one kilometer. For this analysis, a buffer of 0.75 kilometers was chosen, which is the average of the three distances, and therefore represents a suitable compromise between them.

Accuracy Assessment

Portions of the image were field-checked to assess the accuracy of the classification process. A GIS layer of the roads in Hays County was overlain onto the reclassified image, and several accessible locations on the map were visited and visually examined. Estimation of classification accuracy was based upon the following characteristics: areas labeled as Suitable Habitat should contain woodlands with a mixture of Ashe juniper and deciduous hardwood trees, with a minimum of 50% canopy cover. Areas labeled as Unsuitable Habitat should not exhibit these characteristics. Since Potential Habitat represents transitional areas, where the GCW habitat potential cannot be adequately determined from the classification process, the accuracy of this category was not assessed.

Addition of Ancillary GIS Data to determine Level of Habitat Suitability

Suitable Habitat from the classified image represents areas in Hays County that contain the proper vegetation associations to constitute suitable nesting habitat for the GCW. However, the presence of the proper vegetation may not automatically guarantee that a site will be used by the birds. Ancillary information was therefore combined with the Suitable Habitat data to determine an area's level of suitability as nesting habitat in greater detail. Areas that satisfy all of the criteria for the ancillary GIS data were considered to represent prime GCW nesting habitat, while areas that satisfy only a few or none of the criteria were considered to represent only marginally suitable habitat.

The following ancillary GIS data layers were added to the vegetation data:

Distance to Buildings (greater than 300 feet), Distance to Roads (greater than 300 feet), Distance to Water Bodies, and Slope. The processing of the GIS layers for each of these layers was done in ArcView® GIS Version 3.1 (Environmental Systems Research Institute, Inc. 1999), except for Slope, which was processed using ENVI®.

Distance to Buildings and Distance to Roads

GCWs generally do not reside in the vicinity of populated areas, but rather stay deep within woodland areas, where they avoid contact with humans (Moses 1996). To account for this preference to remain secluded from people, the locations of all roads and buildings in Hays County were imported into ArcView®. Buffer zones with a radii of 300 feet (Campbell 1995) were created around the roads and buildings, and only patches of vegetation identified as Suitable Habitat that were located outside of this buffer zone were considered to represent prime habitat.

Distance to Water Bodies

GCWs need to have reasonable access to a reliable water source (e.g., a lake, pond, river, stream) for drinking and bathing (Damude 1998). I hypothesize that a GCW would be more likely to locate its nest closer to a body of water than farther away, so that it would not have to constantly fly extensive distances to reach water. Based upon this hypothesis, as the distance from a Suitable vegetation patch to the nearest source of water increases, the probability that the vegetation patch will actually be used by GCWs should decrease. To represent this hypothesis, the locations of perennial water bodies were imported into ArcView®, and a distance surface illustrating Proximity Zones to the water bodies was created. The distance of each Proximity Zone, and the level of habitat suitability each one is associated with, is presented in Table 3.

Table 3. Proximity Zones for the "Distance to Water Bodies" GIS data layer

Zone	Width of zone (km)	Total distance from nearest water body at outer edge of zone (km)	Level of habitat suitability
1	0.5	0.5	prime
2	0.5	1.0	relatively suitable
3	1.5	2.5	marginally suitable
4	2.5	5.0	potential
5	N/A	>5.0	unsuitable

Suitable Habitat areas located within the first Proximity Zone (closest to water) were considered prime habitat. Areas located in more distant proximity zones should still represent suitable, but not prime, habitat. However, areas located more than five kilometers away from a source of water (Zone 5) were no longer considered to represent suitable habitat, since that would be an excessive distance for the birds to travel on a regular basis. The choice of five kilometers was solely an educated guess that I made regarding an adequate distance. Data regarding how far a small bird will fly on a regular basis to reach water is unattainable. Although I believe proximity to water to be an important habitat parameter, no previous studies have incorporated this type of habitat criterion into their analyses. Even the Travis Audubon Society was unable to suggest a suitable distance to use (Rogers 2000).

Slope

According to the results of previous studies (Campbell 1995, Damude 1998, Ladd 1985, Moses 1996, Pulich 1976, Shaw and Atkinson 1988), GCW habitat appears to be located on hillsides much more frequently than on flat land. However, this slope factor is more likely not an actual habitat requirement, but rather due to the fact that steep slopes are more expensive for landowners to develop than flat areas. Higher development costs have resulted in more of the woodlands being left intact on steeper slopes, while land developers focus more of their efforts on flatter, more cost-efficient areas (Diamond 2000, Moses 1996, U.S. Fish and Wildlife Service 1996). GCWs therefore tend to be more prevalent in hilly areas because they have no choice; those are the areas where their habitat still remains.

The slope of the land was therefore included in this analysis, not as an actual habitat requirement, but to illustrate what proportion of the prime habitat is located on flat areas, relative to the proportion located on steeper slopes. This information should be useful for land use planners, to identify which habitat areas will require more strenuous protection from development.

The Slope was calculated from a United States Geological Survey (USGS) 30 meter digital elevation model (DEM). The 30 meter DEM was used because it coincides with the 30 meter resolution of the Landsat ETM+ multispectral image data. The USGS has created one DEM for each 7.5' quadrangle of the U.S. Hays County is covered by portions of twenty 7.5' quadrangles. The twenty corresponding DEMs were each downloaded from the website of the Texas Natural Resources Information System (TNRIS 1996b). Each DEM was then imported into ENVI®, and its projection was changed to match that of the satellite image. The 20 DEMs were then mosaicked together to create one large DEM covering the entire county.

Suitability Map

After processing, the ancillary data were combined with the vegetation data and reclassified to create a map showing habitat suitability throughout Hays County. Areas were ranked according to their level of habitat suitability, which was based upon the environmental characteristics that the GCW requires for nesting. Table 4 shows how the rankings were assigned to the various GIS attributes. Rankings range from 0 to 10, where a score of 0 represents an attribute that would make an area unsuitable for use as habitat, a score of 10 represents an attribute associated with prime habitat, and scores from 1 to 9 represent attributes that are not associated with prime habitat, but are associated with relatively suitable habitat (where habitat quality increases as the rank increases).

Table 4: GIS layer attribute rankings

GIS Layer	Attributes of Habitat	Rank
Vegetation (from the classified image)	Suitable Habitat	10
	Potential Habitat	1
	Unsuitable Habitat	0
Distance to Buildings and Distance to Roads	Outside 300ft buffer	10
	Inside 300ft buffer	1
Distance to Water Bodies	Proximity Zone: 1	10
	2	6
	3	3
	4	1
	5	0

When all of the layers were combined, the ranked values were multiplied on a pixel-by-pixel basis. This resulted in one image, with pixel values ranging from 0 to 1,000. This image was then reclassified to create the suitability map, which illustrates three ranked categories:

1. the locations of the remaining Prime nesting Habitat in Hays County, Texas, where GCWs are most likely to be located (areas with a score of 1,000 [10 for every layer]);
2. locations of Potentially suitable Habitat, where GCWs may possibly be located (areas with scores of 1 to 600); and
3. Unsuitable Areas, which would be unlikely to support GCWs (areas with a score of 0).

This suitability map was also draped over a 3-dimensional perspective view of the DEM, to illustrate where habitat is located in relation to terrain.

Prime Habitat is therefore being defined as woodland areas consisting of a mixture of Ashe juniper and deciduous hardwood trees (which had been labeled Suitable Habitat on the classified image), which are located a minimum of 300 feet from existing roads and buildings, and also located within 0.5 kilometers of a source of water. Potential Habitat represents areas exhibiting Prime Habitat vegetation from the classified image, but that are either too close to roads and/or buildings, or do not have water close by, or both, as well as areas that had been labeled as Potential Habitat on the classified image that are not located in Proximity Zone 5.

CHAPTER 4

RESULTS AND ANALYSIS

Results

Classification

Isodata and K-Means are the two unsupervised classifiers available in the ENVI® software. Three trial classifications were run using each of these classifiers, to determine the method that would most accurately discriminate the proper vegetation association. To keep the trial classifications consistent with each other, the default five percent change threshold was used, and 10 was the maximum number of iterations allowed for each classification. The ranges of the number of classes used for each of the three Isodata classifiers were as follows: 3 - 6 classes, 5 - 10 classes, and 3 - 20 classes. In each case, the number of distinct classes identified corresponded with the upper limit of the given range. For the three K-Means classifications, 10, 15, and 20 were used as the respective number of classes.

The trial classifications were interpreted visually to determine which one seemed to most accurately discriminate the type of vegetation associations suitable for GCW nesting habitat. Maps of the area, DOQQs, past reports of GCW sightings [The Daily Record 1999, Pulich 1976], and general knowledge of the area were used to identify which areas on the satellite image would be the most likely to contain suitable habitat.

In all six of the trial classifications, the first type of land cover to be identified was water. With the three Isodata classifications, vegetation was somewhat difficult to discern. In many areas the vegetation appeared to be dispersed into many categories, and mixed with various other land use/land cover classes, rather than being grouped together into a few fairly homogeneous classes. This mixture of classes, which is most likely due to variations in vegetation density, could complicate interpretation of the results. This finding corresponds with the author's past experiences when dealing with unsupervised classifications. The Isodata classifier seems to be better suited for discerning urban features than vegetation.

Alternatively, in all three of the K-Means trial classifications, the first few classes (after the water class) consistently discriminated among various types of vegetation. The K-Means classifier was therefore used in this analysis, due to the relative ease with which the classes representing vegetation could be identified on the classified image. The K-Means vegetation classes also seemed to be more homogeneous than those created by the Isodata classifier, which should indicate greater accuracy for this analysis.

As mentioned earlier, the number of land use/land cover classes generated during each of the three K-Means trial classifications was 10, 15, and 20, respectively. When visually examined and compared, the 10-class result appeared to slightly overestimate habitat extent, while the 20-class result seemed to slightly underestimate habitat. The 15-class result appeared to provide the most accurate portrayal of habitat extent, and was therefore used as the vegetation classification in this analysis.

Of the 15 distinct land use/land cover classes generated from the satellite scene by the K-Means classifier, the first three classes to be identified (after the water class) represented various vegetation associations. The next class that was identified delineated heavily urbanized areas. The 10 remaining classes represented various types of urban, residential, and agricultural land uses/land covers, none of which would signify suitable GCW habitat.

Based on the reference material mentioned above (e.g., maps, DOQQs), the first of the three vegetation classes that had been identified by the classification was the class deemed most likely to represent the proper vegetation association for GCW habitat. The second class (which primarily tended to be located around the edges of the first class) was assessed as transition areas between patches of suitable vegetation and unsuitable land covers, as well as some areas where the canopy cover of the vegetation appeared to be less dense than that of the first class. The third vegetation class was determined to represent more sparsely-vegetated areas, along with some residential areas, which would most likely not support GCWs. The accuracy of these land use/land cover determinations was validated during the field survey, the results of which are presented below in the section on Accuracy Assessment.

The results of the unsupervised classification were reclassified into three classes, based upon the probability that an area would have the proper vegetation association to support GCWs. The first of the three vegetation classes from the classification became Suitable Habitat (the vegetation most likely to provide adequate habitat). The second of the three classes became Potential Habitat (vegetation that may possibly support GCWs). The third of the three vegetation classes, along with the 12 non-vegetation classes, were grouped together into Unsuitable Areas (areas that most likely would not be used by the birds). The resulting habitat locations identified by the classification are illustrated in Figure 4. The Suitable and Potential Habitat categories were overlaid onto band 1 of the satellite scene, which can be seen in the Unsuitable Areas.

The next step in the analysis was to remove vegetation patches that would be too small in areal extent to support GCWs. The resulting habitat distribution is presented in Figure 5.

Accuracy Assessment

The accuracy of the unsupervised classification was assessed by traveling to and visually examining several field sites throughout portions of Hays County. A map designating the route that was traveled during the field survey is presented as Figure 6. Maps illustrating enlarged portions of the route are contained in Appendix 1. The results of the accuracy assessment are summarized in Table 5 in the form of a contingency table, which was created following the method utilized by Shaw (1989). The table identifies the number of errors of omission and commission encountered during the field assessment. Areas identified as Unsuitable Habitat by the classification, but which appeared to have the characteristics of suitable habitat when field-checked, were listed as errors of omission. Areas identified as Suitable Habitat by the classification process that, when visited, did not contain the proper vegetation association for nesting habitat, were considered to be errors of commission. Potential Habitat was not assessed due to its transitional nature. A total of 40 sites, spread throughout much of the county, were examined during the field survey. Thirty-seven of those sites were determined to have been correctly identified by the classification, and three had been incorrectly identified.

Figure 4. Areas in Hays County containing the proper vegetation association for GCW habitat (derived directly from classification of the satellite image).

Figure 5. Areas in Hays County containing the proper vegetation association for GCW habitat that are large enough to support GCWs.

Figure 6. Route traveled during field survey for accuracy assessment.

Based upon this appraisal, the assessed accuracy of the unsupervised classification was 92.5 percent.

Table 5. Contingency table assessing classification accuracy

		Field analysis	
		Contains suitable vegetation for habitat	Does not contain suitable vegetation
Classification	Suitable Habitat	19	1
	Unsuitable Habitat	2	18

Errors of omission (light grey: Unsuitable Habitat / Contains suitable vegetation) — Errors of commission (dark grey: Suitable Habitat / Does not contain suitable vegetation) — Correctly identified areas (white)

Ancillary GIS Data, and Problems Encountered with their Inclusion

The original intention of this study was to prepare the vegetation data derived from the image classification using the methodology described above, to create various GIS layers, and then to merge the results to develop the GCW habitat suitability map. However, due to numerous technical obstructions (which are discussed below), as well as time constraints, the creation of the full version of the habitat suitability map regretfully could not be accomplished.

A seemingly endless array of hardware, software, data acquisition, data compatibility, and other technical problems were encountered throughout the several months working on this project. For example, after the satellite image georeferencing problem was solved (the latitude/longitude coordinates of the image "corner points" included in the header file were discovered to actually correspond to the corners of the square-shaped window that the image was placed into, not the corners of the parallelogram-shaped image itself), the first major obstacle encountered was that none of the GIS vector layers would overlay onto the satellite image. Several attempts were made to integrate the layers with the image (by changing the projections of the GIS layers to coincide with that of the satellite image, using ENVI$_{®}$'s Convert Projection command, or using the Projection Utility associated with the new ArcView® Version 3.2), but none of these were successful; none of the vector layers would overlay onto the image. Different sets of data were obtained from multiple sources, but again, none of them could be successfully overlaid. The one set of data that did overlay onto the image was the DEM, after its projection was converted in ENVI$_{®}$.

Since the integration of the GIS data with the vegetation information from the classified satellite image appeared to be crucial for the completion of this analysis, some alternative means of overlaying the data had to be found. The method ultimately utilized was the following: all of the GIS layers, along with the satellite image, were imported into ArcView®. Each vector layer was then highlighted, "Edit Theme" was selected from the Edit pull-down menu, and, one at a time, the layers were repositioned and resized until they appeared to properly overlay onto the satellite image. I realize that this may not have been an extremely accurate method for combining the information, but many conventional strategies had been attempted unsuccessfully, and time constraints limited the ability to discover other alternatives.

Next, the realization was made that ArcView® was not calculating distances correctly on the satellite image. Since buffers of specific distances needed to be generated for several of the layers, this presented a significant problem. Distances appeared to be measured correctly on the original vector layers (before they were repositioned onto the satellite image), so the buffers had to be generated from the original vector layers, and then the buffers had to be repositioned and resized to overlay onto the satellite image. This method was used for the Buildings and Roads data, and their associated buffers. Close-up views of a portion of these data layers can be viewed in Figure 7 (Buildings) and Figure 8 (Roads). The location shown is a portion of the Village of Wimberley, Texas.

In addition to the buffering problem, there were other problems encountered with the Water Bodies layer. First of all, the vector layer I had obtained for use as the Water Bodies data had apparently not been digitized very accurately. Despite numerous attempts, I could not get the entire layer to properly overlay onto the satellite image.

The purpose of including the Water Bodies data was to generate proximity zones showing Distance to Water Bodies (refer to Table 4 on page 28). The Water Bodies data (which included all of the rivers and streams in Hays County), along with Proximity Zones 1 and 2, are illustrated in Figure 9. The outer edge of Proximity Zone 2 represents a distance of 1.0 km from any water body. Proximity Zone 5 represents areas more than 5.0 km away from the nearest body of water. However, as can be clearly seen in Figure 9, using the vector layer illustrated here, no areas in Hays County would be more than 5.0 km away from water. This overabundance of water bodies is more than likely due to the inclusion of intermittent streams in the data set, rather than just perennial. The reliability of results drawn from this GIS layer would therefore be somewhat questionable, because there would be no way to guarantee that each stream in the layer would actually have

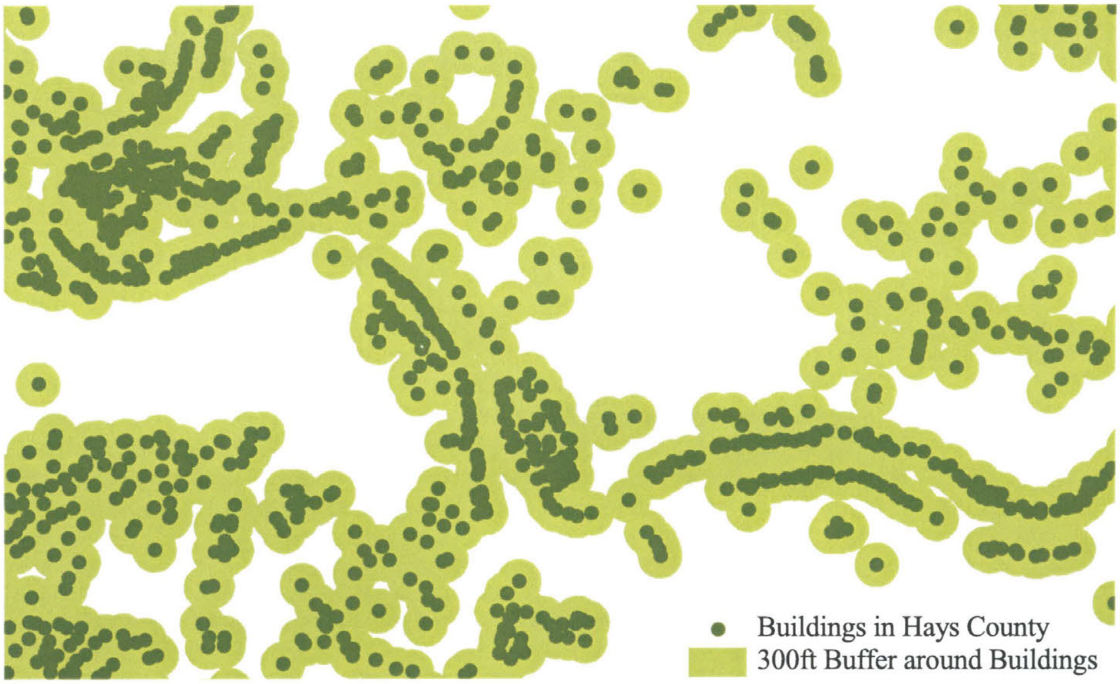


Figure 7. Close-up of a portion of the Buildings GIS data, along with their asssociated Buffer that was generated to use as the Distance to Buildings layer.

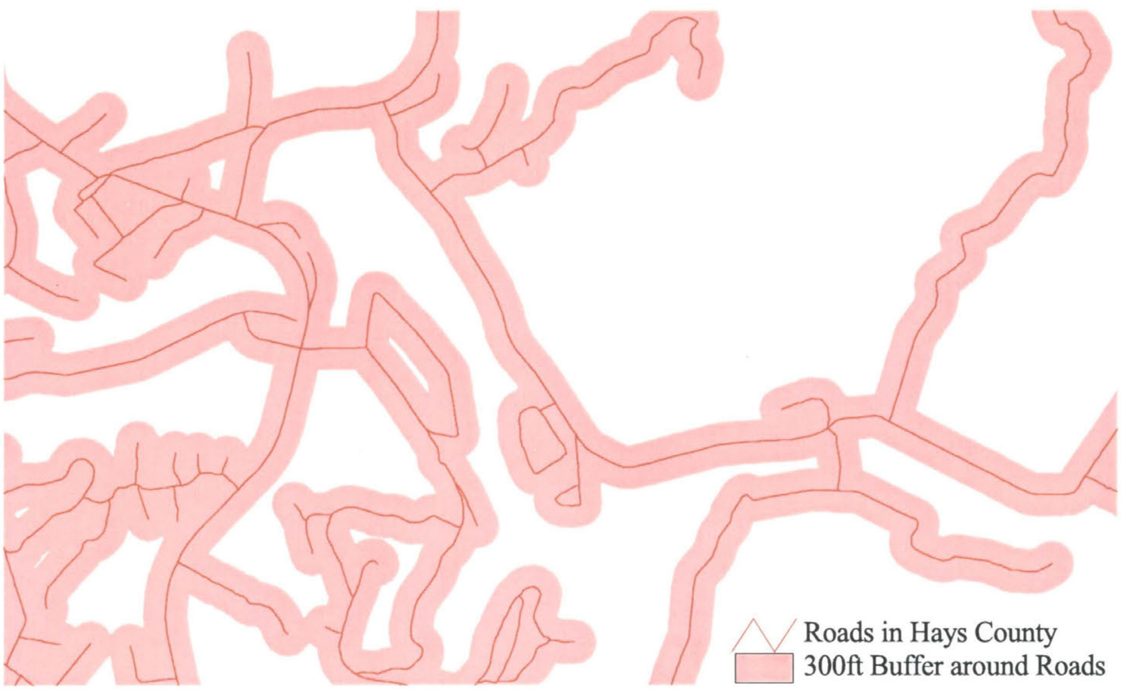


Figure 8. Close-up of a portion of the Roads GIS data, along with their associated Buffer that was generated to use as the Distance to Roads layer (area shown is the same as in Figure 7).

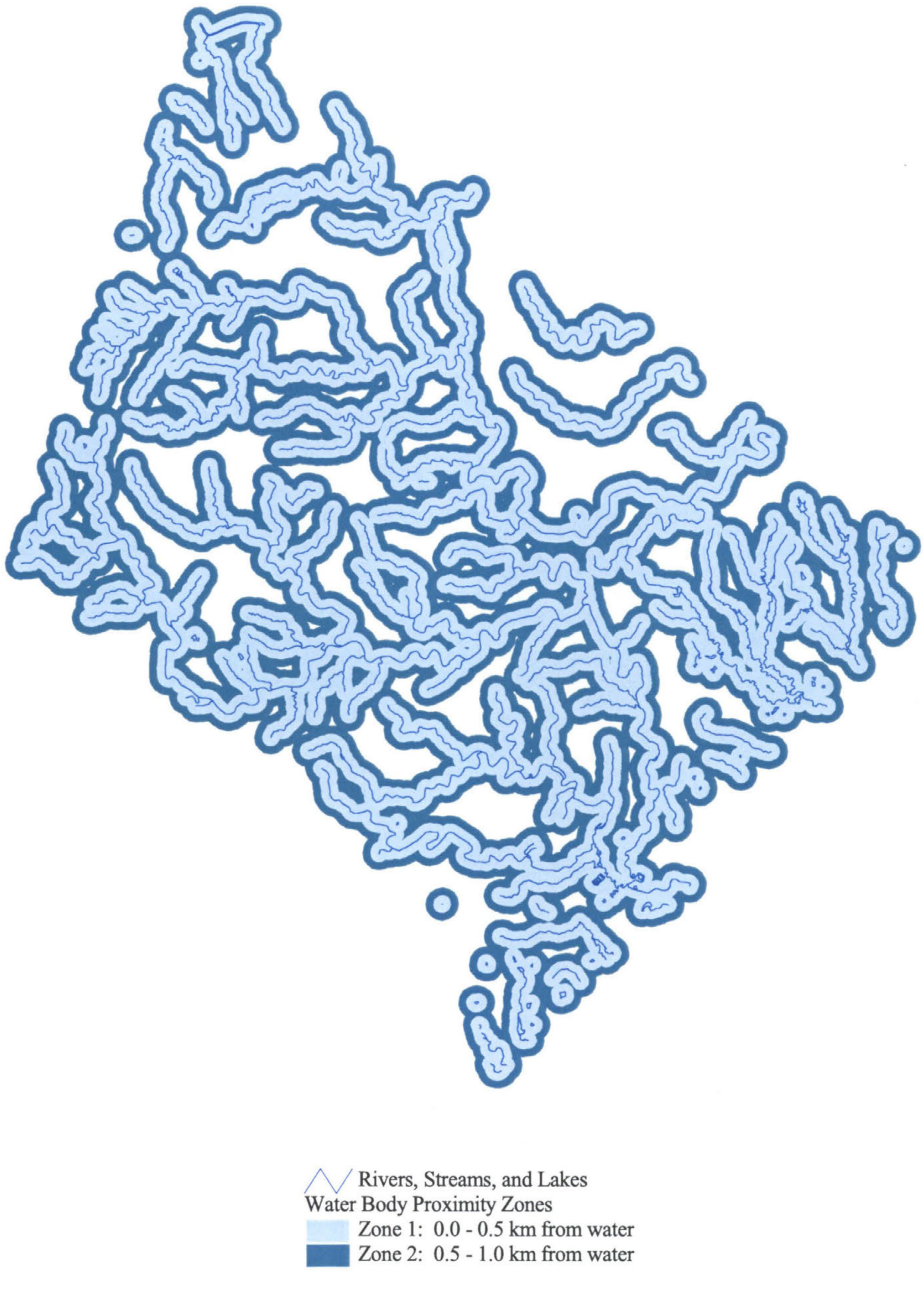


Figure 9. Original Water Bodies data illustrating Proximity Zones 1 and 2.

water in it during the spring and summer seasons, when the GCWs are in central Texas.

To compensate for this overabundance of streams, a replacement Water Bodies GIS layer was obtained. This layer only contains the major rivers and some lakes, and therefore may potentially underestimate the amount of available water (because no streams are included in the layer), but it seemed more secure to have a potential underestimation of the amount of water available, rather than to risk an extreme overestimation. This new Water Bodies layer, along with Proximity Zones 1 and 2, is presented in Figure 10 for comparison with the old layer in Figure 9. There is a significant difference in the amount of included land. The Replacement Water Bodies layer with all five Proximity Zones displayed is presented in Figure 11.

Once all of the aforementioned problems had been addressed, the ArcView® software refused to work with grid themes. In order to conduct any major type of spatial analysis in ArcView®, all layers (both vector files and images) are first converted into grids. This process assigns a number to each portion of the layer, which then enables calculations to be done among the various layers. That procedure was the rationale for creating the layer attribute rankings presented in Table 4 (on page 28). Conversion into grids was necessary in order to produce the habitat suitability map. The 300 foot buffer surrounding Buildings had been successfully converted to a grid file earlier However, once the other data layers were ready to be converted, ArcView® was not able to convert any of them. The computer would process the data for an extended period of time, behaving as if it was converting the data into a grid, but the only results obtained were error messages. The data was transferred to another computer, but the same problems were encountered. A complete regeneration of the Roads data was attempted on a third

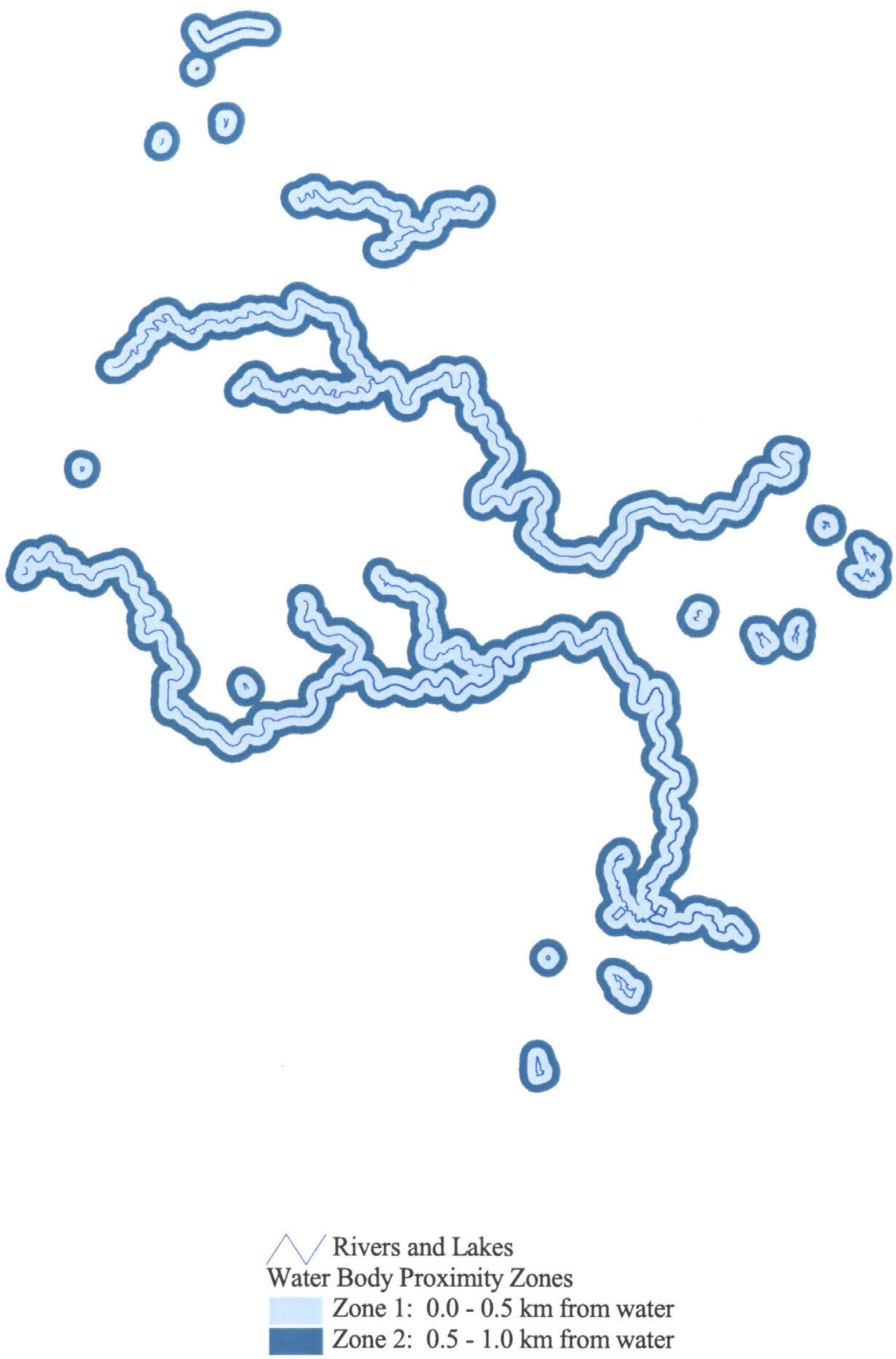


Figure 10. Replacement Water Bodies data illustrating Proximity Zones 1 and 2.

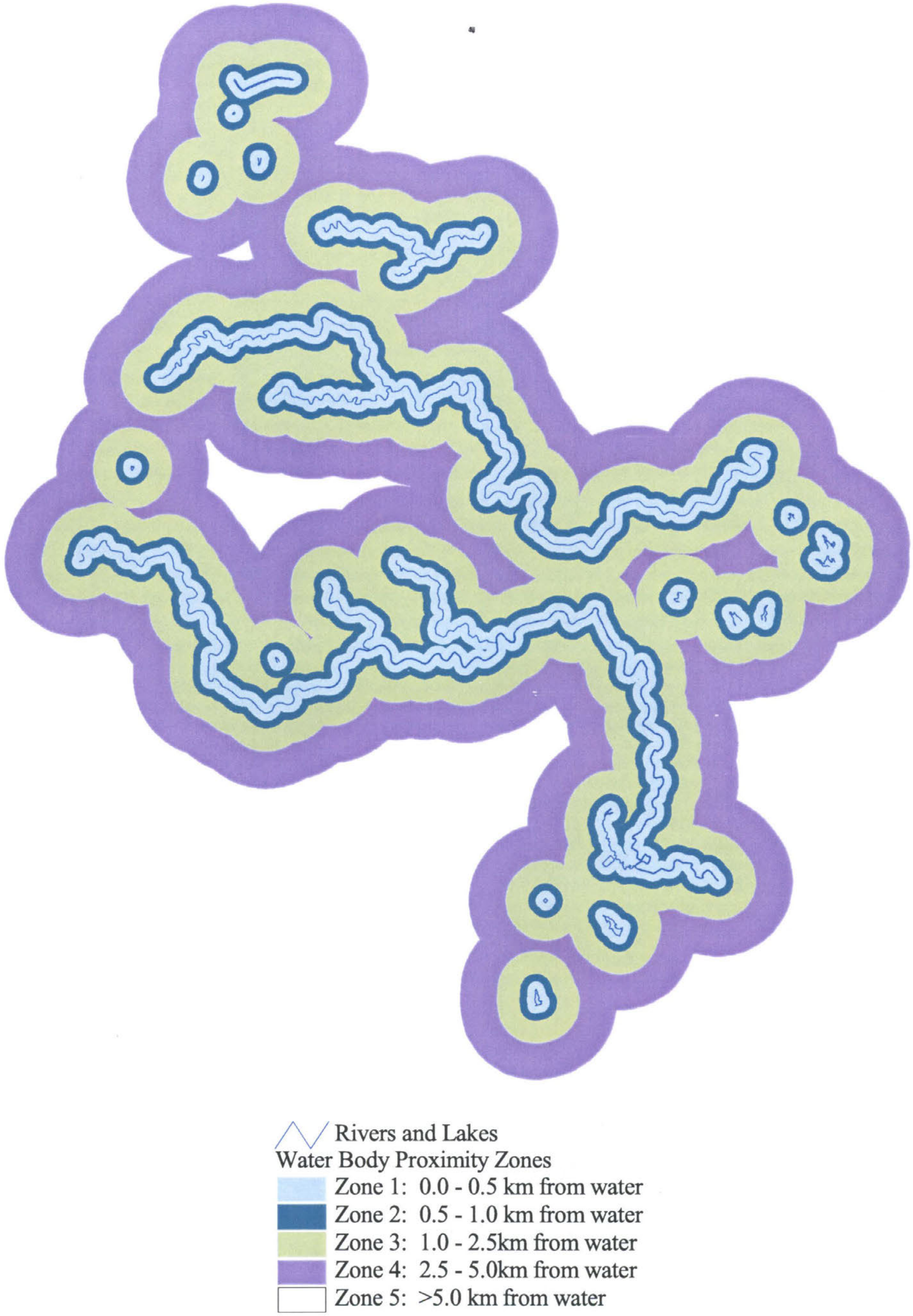


Figure 11. Replacement Water Bodies data, along with the five Proximity Zones that were generated to use as the Distance to Water Bodies layer.

computer, but the buffer still would not convert to a grid. No explanation as to the cause of this problem, or any possible solution, has been uncovered thus far.

Analysis

If the technological aspects of this project had run more smoothly, the layers created from the GIS data would have been overlaid onto the vegetation data from the classified image to create the suitability map, which would have illustrated the GCW habitat suitability for all of Hays County. The suitability map would have also been draped over a DEM, to illustrate where habitat is located in relation to terrain. However, due to the many unavoidable technical problems described above, that suitability map could not be created. To compensate for this, the vegetation data generated from the unsupervised classification of the satellite image is being presented as an initial habitat suitability map (see Figure 5 on page 35). Although it may not represent as accurate a portrayal of actual GCW habitat as could have been created with the inclusion of the GIS data, because the field survey classification accuracy was 92.5 percent, it is believed that the vegetation data provides a decent preliminary suitability map of GCW nesting habitat.

Table 6 calculates the amount of habitat that was identified by the classification process. Approximately 163,000 acres of Suitable Habitat was originally discovered by classifying the satellite imagery. After the patches of vegetation that would be too small in areal extent to actually constitute useable habitat were removed, the actual amount of Suitable GCW nesting Habitat was reduced to approximately 157,000 acres. That acreage constitutes 10 percent of the land in Hays County.

Table 6. Habitat extent based upon classification category distribution

7a. The original classified image

Class name	# of pixels	# of acres	% of image
Suitable habitat	734,899	163,368.05	10.34
Potential habitat	739,239	164,332.83	10.40
Unsuitable Areas	5,631,693	1,251,925.35	79.26
Entire image	7,105,813	1,579,622.23	100.00

7b. Classified image with small vegetation patches removed

Class name	# of pixels	# of acres	% of image
Suitable habitat	707,474	157,271.47	9.96
Potential habitat	610,834	135,788.40	8.60
Unsuitable Areas	5,787,505	1,286,562.36	81.44
Entire image	7,105,813	1,579,622.23	100.00

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

This study resulted in the production of a map of Hays County, Texas, which illustrates: 1) the locations of remaining suitable nesting habitats (based upon vegetation characteristics) where Golden-cheeked Warblers (GCWs) are most likely to be located, 2) potentially suitable habitats, where GCWs may be located, 3) and areas unsuitable for use as habitat, which are unlikely to support GCWs.

The results from this study could be used by planners, ranchers, and other land managers to direct future development away from fragile prime habitat locations, and toward areas of unsuitable habitat, thereby protecting the GCW, and providing it with a better chance for survival.

Methodological Concerns

Accuracy

One concern regarding the accuracy of this analysis (of both its intended and actual results) relates to the resolution of the satellite imagery. The spatial resolution of a Landsat ETM+ image is 30 meters. Although this is better than the 80 meter resolution used in the analyses by Shaw (1989) and Shaw and Atkinson (1988), it may have still resulted in inaccuracies in the classification, which stresses the importance of field verification of the classification results.

Another problem that may have affected the accuracy of the results is that GCWs require the Ashe junipers to be of a certain age and height for nesting. The trees must reach at least twenty years in age and fifteen feet in height before the bird is able to peel strips of bark off the trees, which are used to construct the nest (Campbell 1995, Damude 1998, Pulich 1976, U.S. Fish and Wildlife Service 1996). This information is normally not distinguishable from a Landsat ETM+ remotely-sensed image due to the resolution of the scene and the planimetric perspective, and therefore can only be obtained from direct field work. Although some general field assessment of the overall accuracy of the classification process was undertaken, conducting a detailed field survey of the Ashe juniper trees in each location of potential habitat identified by the classification is beyond the scope of this analysis. The assumption therefore had to be made that the woodlands determined to be habitat contain Ashe juniper trees of varying ages and heights, some of which would fit the criteria required by the GCWs.

Public Opinion

Not all people are in favor of protecting the GCW. Protecting these birds will require locating its prime habitats, and restricting urban and agricultural development in those locations. However, more than 97 percent of the land in Texas is privately owned (U.S. Fish and Wildlife Service 1996), and some landowners fear that if GCWs are found on their land, restrictions will be placed on what they are allowed to do with their land, and their properties will lose value. Resentment toward outside control of privately owned land is a fairly common problem encountered throughout the country with species protected by the Endangered Species Act (Feldman and Jonas 2000, Sugg 1998, U.S. Fish and Wildlife Service 1996). Private property rights are an extremely important concern to many people in Texas, and many landowners may be uncompromising about protecting their rights as landowners. Identifying GCW habitat on private property is a delicate situation, which needs to be handled diplomatically to avoid offending any of the parties involved. One suggestion would be to approach the landowners and discuss the issue with them before any attempts to access their land are made. Because of this situation, the 40 sites that were examined during the field survey were chosen based upon the ability to view them from public roads. No attempts were made to access private property.

Recommendations for Future Research

This study could be used as a model for additional research. By following the methods presented here as a guideline, more studies could be undertaken in other counties to delineate habitat throughout other portions of the GCW's breeding range in central Texas. More work could eventually result in accurate maps showing all of the remaining habitat for the GCW throughout central Texas.

One obvious aspect for future research would be to replicate the analysis, solving the problems encountered with using the GIS data. Since this study discusses some of the many problems that can be encountered during this type of analysis, it will hopefully present some insight for future researchers conducting similar analyses. The results obtained by including the GIS data could be compared to those of the vegetation data presented here, to assess how much the accuracy is increased by including the extra data.

Other future research could involve conducting more detailed field surveys of the habitat areas. This study has completed only a general field assessment to determine the accuracy of the classification process. An in-depth field study could be undertaken to assess the actual habitat potential of the Potential Habitat areas from the classification (since it represents transitional or unknown areas where the GCW habitat potential could not be definitively determined from the remote sensing analysis). Other possible studies could involve categorizing the average ages and heights of the Ashe juniper trees in the Prime Habitat vegetation areas, to assure that trees of the proper age and height actually are available to the GCWs, or determining what percentage of the prime habitat areas are actually being inhabited by nesting GCWs.

Once the unsupervised classification was executed on the satellite image, the identification of which classes represented suitable GCW habitat was determined by a visual assessment, based upon a variety of source data. The more knowledge the researcher can gain about the area being classified, including references such as locations of past GCW sightings or known habitat areas, the greater the accuracy that can be expected. However, in the absence of significant sources of such reference data, a reasonably reliable classification should still be obtainable. One of the requirements for GCW habitat is a forest canopy cover of at least 50%. Therefore, a classification that isolates the more densely vegetated areas in the satellite image should provide a fairly accurate portrayal of habitat location. In this study, the apparent vegetation density (as viewed on the satellite image and on a DOQQ) was taken into account when determining which of the six trial classifications was most accurate. And, as discussed earlier, this classification achieved a relatively high rate of accuracy.

Conclusion

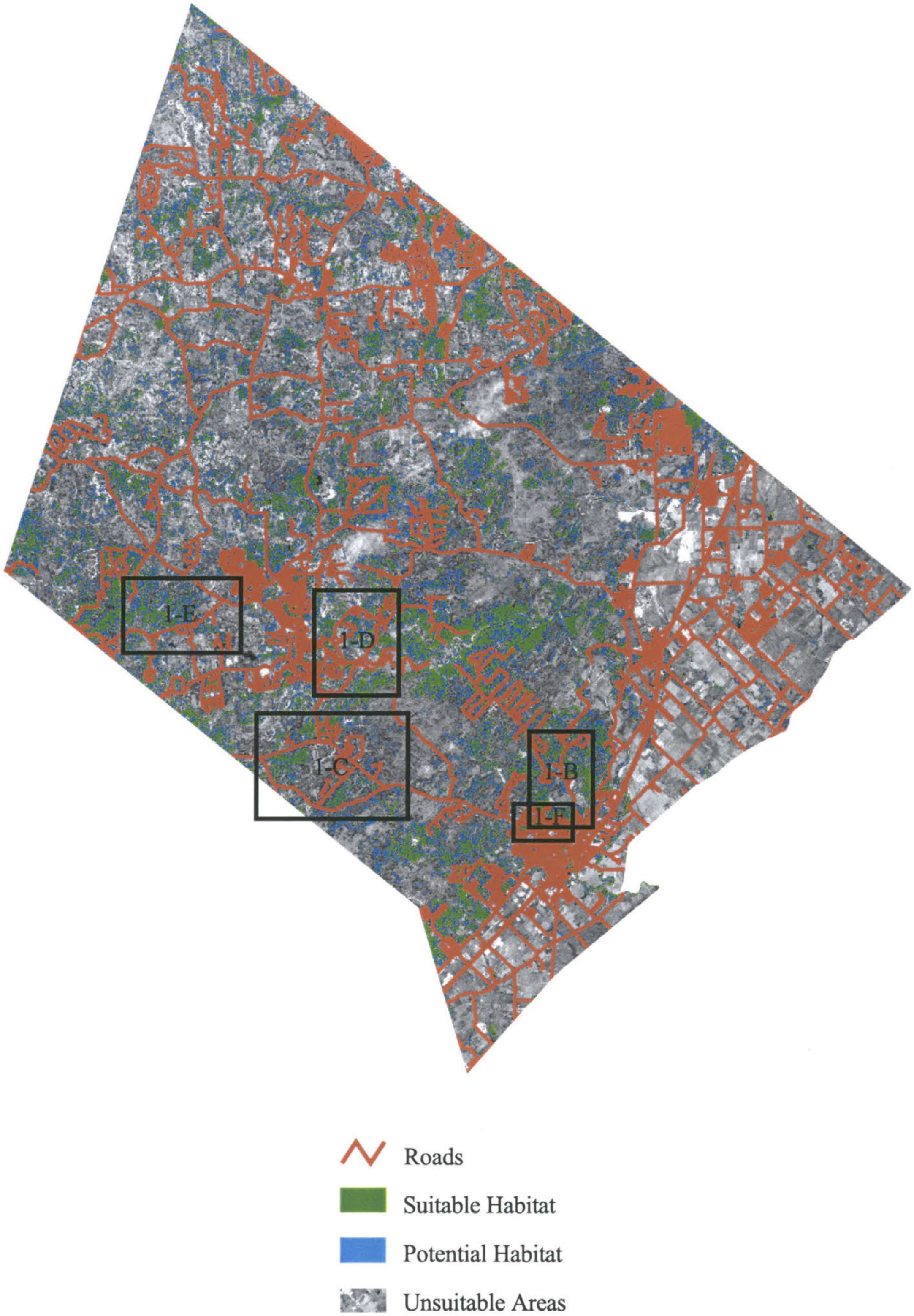
This study attempted to create a suitability map of nesting habitat for the Golden-cheeked Warbler in Hays County, Texas. Vegetation data was derived from an unsupervised classification of landsat ETM+ satellite imagery. The addition of ancillary GIS data regarding the distance to roads, distance to buildings, distance to water bodies, and slope was attempted, to provide a more accurate portrayal of habitat suitability. However, technical difficulties and time constraints prevented the successful inclusion of the GIS data.

The results of this study can be useful for government officials as well as private individuals. The habitat map produced here, although preliminary, can aid anyone wishing to locate the bird, by limiting the amount of area that would need to be searched. Efforts could be focused toward locations identified as Suitable Habitat on the map, thereby reducing the time, money, and other resources required for conservation efforts.

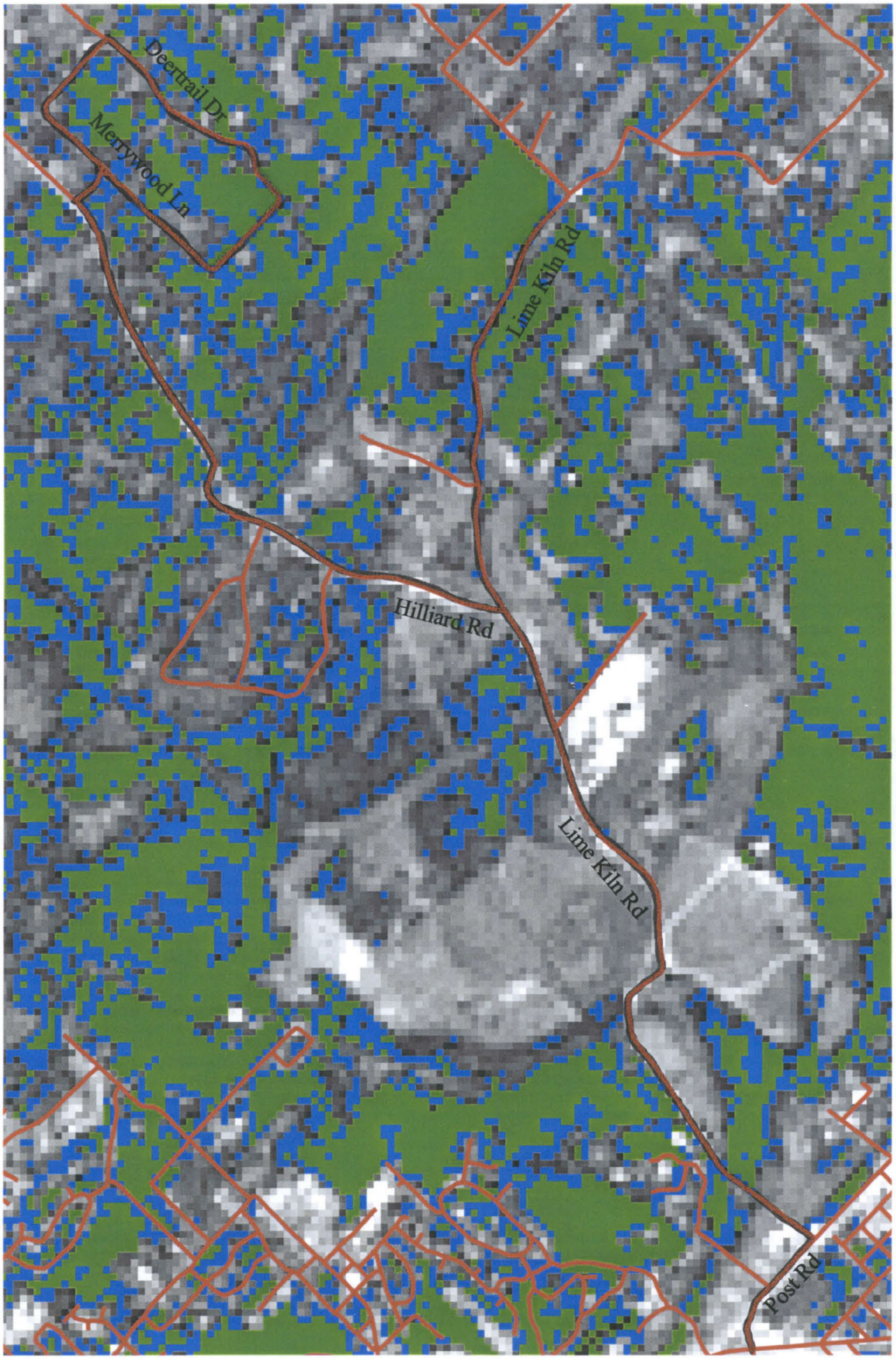
Although some of the original goals for this project could not be fulfilled, it is considered to have been a very useful endeavor. The vegetation data alone was ultimately discovered to be a relatively good indicator of GCW habitat. Hopefully, the many problems encountered during this analysis will aid future researchers conducting similar studies, so they can avoid some of the problems described here.

APPENDIX 1

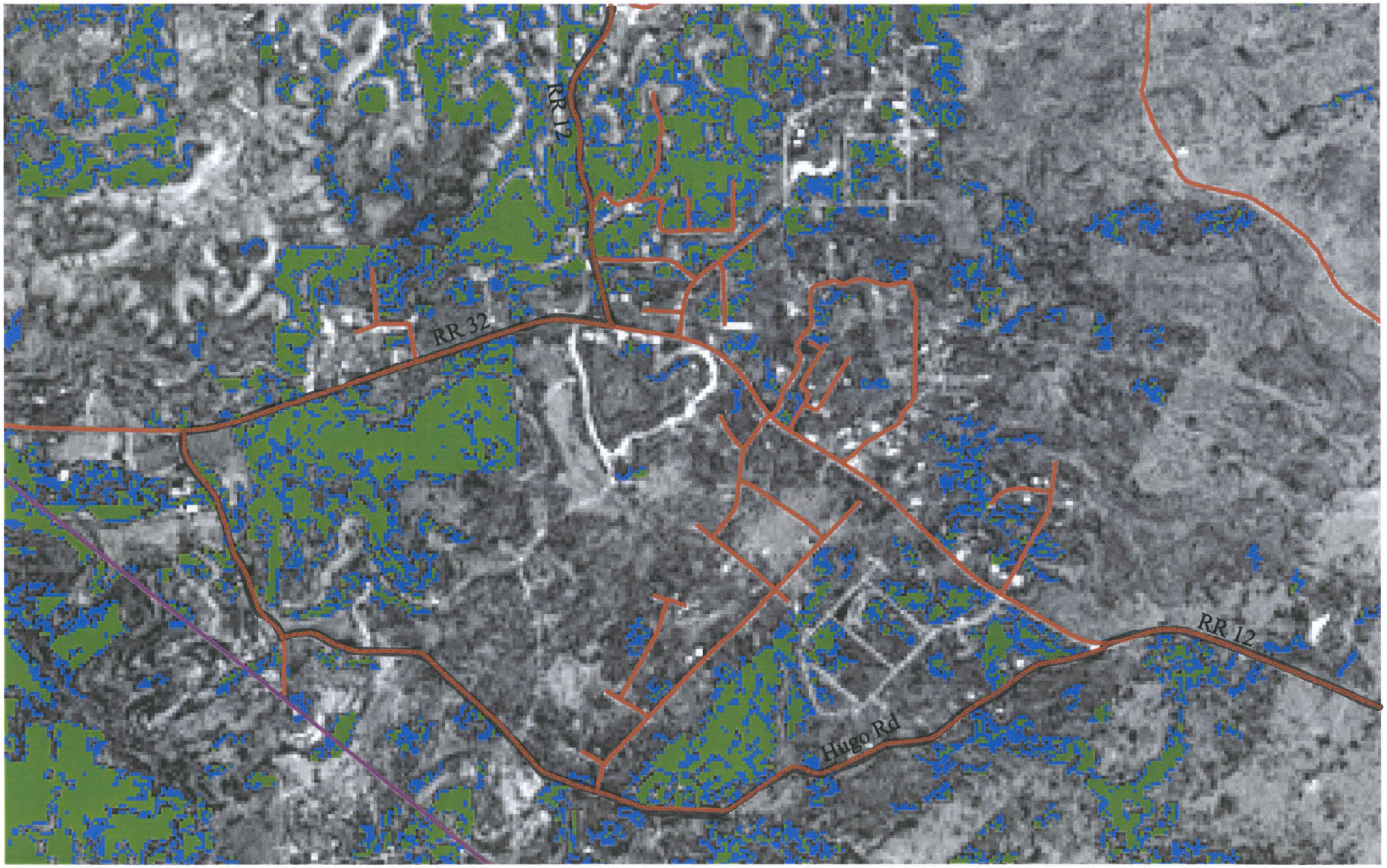
ENLARGEMENTS OF THE ROUTE TRAVELED DURING THE FIELD SURVEY



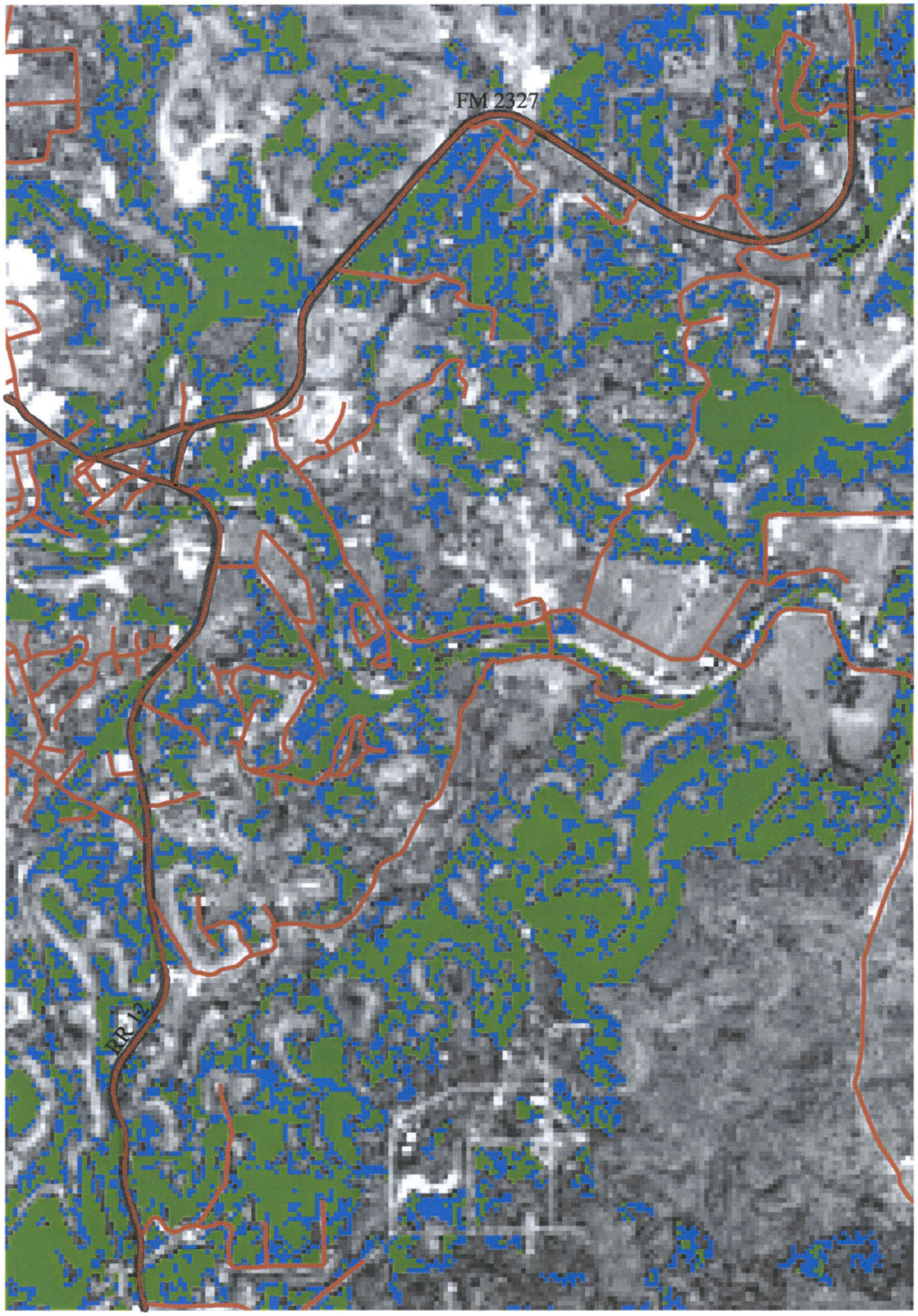
Appendix 1-A. Enlargements of the route traveled during field survey.


Deertrail Dr
Merrywood Ln
Lime Kiln Rd
Hilliard Rd
Lime Kiln Rd
Post Rd

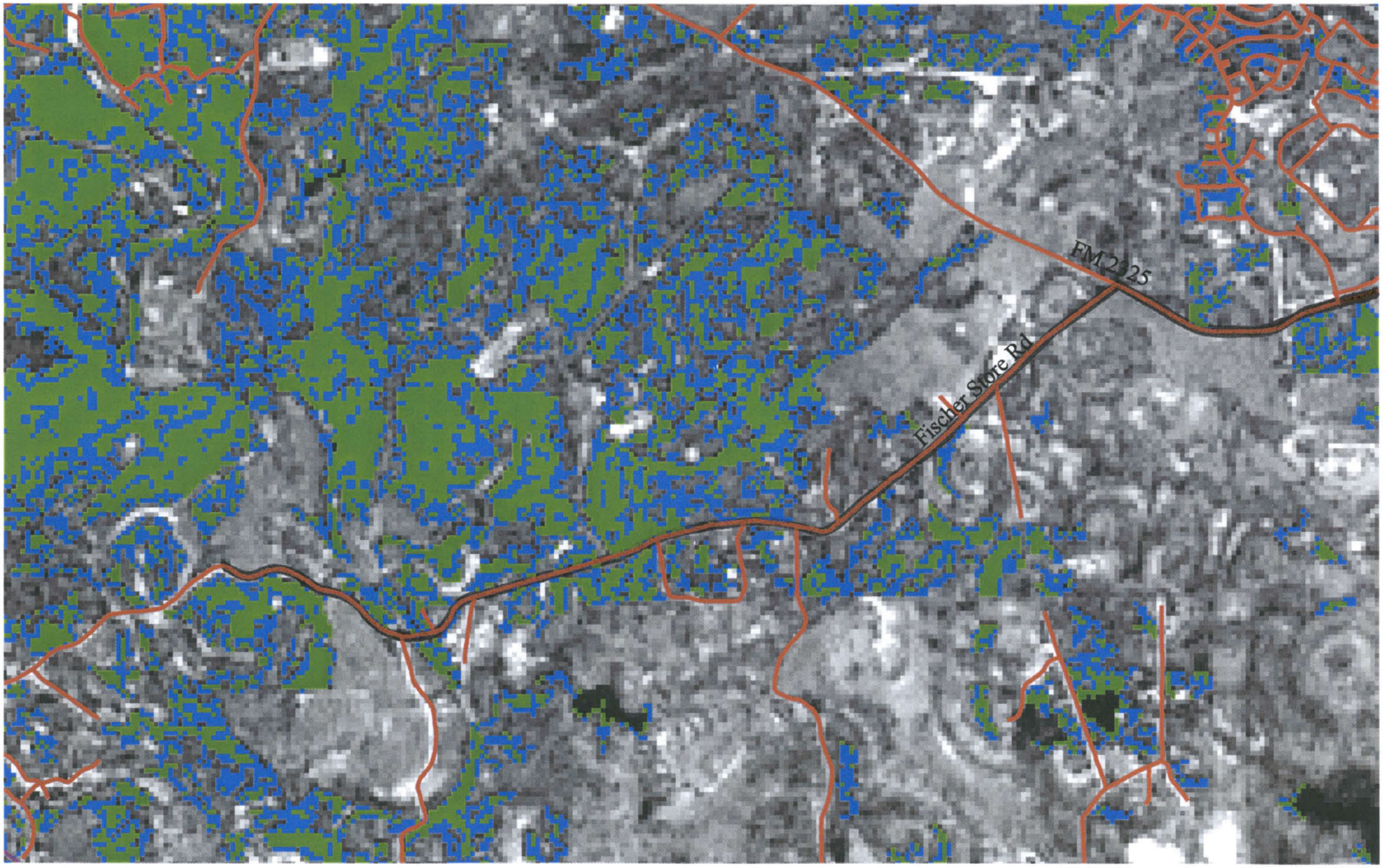
Appendix 1-B.



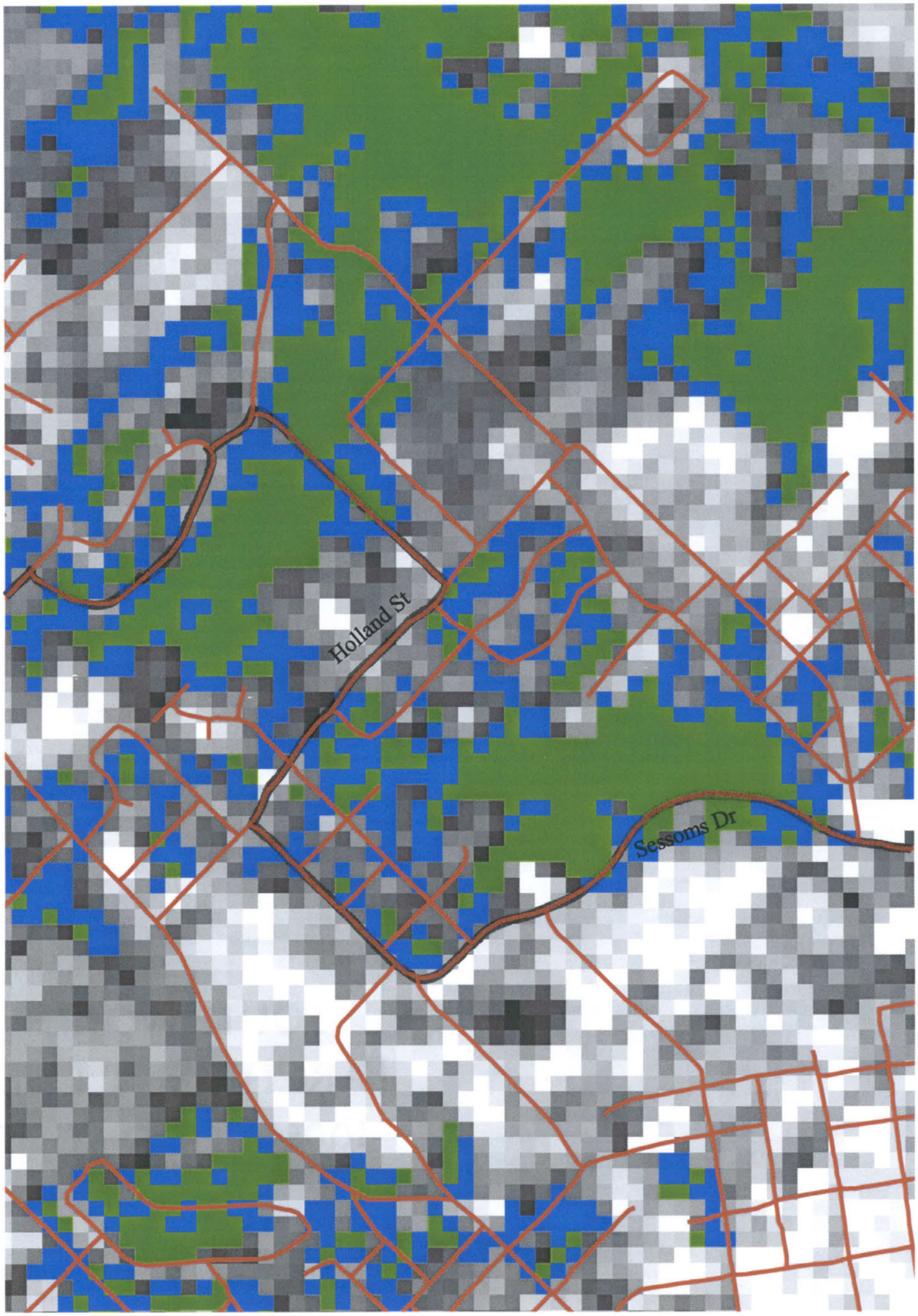
Appendix 1-C



Appendix 1-D



Appendix 1-E



Appendix 1-F

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