

A GEOSPATIAL TOOL FOR WILDFIRE THREAT ANALYSIS IN CENTRAL TEXAS

Bruce Allan Hunter, B.A., M.S.

Dissertation Prepared for the Degree of

DOCTOR OF PHILOSOPHY

UNIVERSITY OF NORTH TEXAS

August 2005

APPROVED:

Samuel F. Atkinson, Major Professor  
Miguel Acevedo, Committee Member  
Kenneth L. Dickson, Committee Member  
Paul F. Hudak, Committee Member  
William T. Waller, Committee Member  
Thomas LaPoint, Program Coordinator  
Art Govan, Chair of the Department of Biology  
Sandra L. Terrell, Dean of the Robert B.  
Toulouse School of Graduate Studies

Hunter, Bruce Allan, A geospatial tool for assessing potential wildland fire risk in central Texas. Doctor of Philosophy (Environmental Science), August 2005, 141 pp., 10 tables, 47 illustrations, 114 references.

Wildland fires in the United States are not always confined to wilderness areas. The growth of population centers and housing developments in wilderness areas has blurred the boundaries between rural and urban. This merger of human development and natural landscape is known in the wildland fire community as the wildland urban interface or WUI, and it is within this interface that many wildland fires increasingly occur. As wildland fire intrusions in the WUI increase so too does the need for tools to assess potential impact to valuable assets contained within the interface. This study presents a methodology that combines real-time weather data, a wildland fire behavior model, satellite remote sensing and geospatial data in a geographic information system to assess potential risk to human developments and natural resources within the Austin metropolitan area and surrounding ten counties of central, Texas. The methodology uses readily available digital databases and satellite images within Texas, in combination with an industry standard fire behavior model to assist emergency and natural resource managers assess potential impacts from wildland fire. Results of the study will promote prevention of WUI fire disasters, facilitate watershed and habitat protection, and help direct efforts in post wildland fire mitigation and restoration.

Copyright 2005

by

Bruce Allan Hunter

## ACKNOWLEDGEMENTS

I would like to acknowledge the guidance of Rich Gray, Regional Fire Coordinator, and Karen Kilgore, Urban Wildland Interface Specialist, Texas Forest Service, Bastrop Region, and the assistance of Christine Thies, GIS Analyst, City of Austin Fire Department.

I also appreciate the encouragement, patience and support of my major professor, Dr. Sam Atkinson, and committee members for this effort. My love of education and teaching is shared and supported by my wife, without whom this research would not have been possible.

## TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS .....	iii
LIST OF TABLES .....	iv
LIST OF ILLUSTRATIONS .....	vii
CHAPTER	
1 INTRODUCTION .....	1
1.1 Wildland Fire .....	1
1.2 Statement of Problem .....	2
1.3 Wildland Fire Versus Wildfire .....	2
1.4 Catastrophic Wildfire Impacts .....	4
1.5 Wildfire-Urban Interface .....	6
1.6 Wildfire in the WUI .....	7
1.7 Wildfire Impacts on Natural Environments .....	8
1.8 Understanding Wildland Fire Behavior .....	9
1.9 Fire Behavior Models .....	10
1.10 Objectives of this Research .....	11
1.11 Tasks Conducted to Achieve the Goals .....	12
2 LITERATURE REVIEW .....	14
2.1 Background to Study .....	14
2.2 Recent WUI Fires .....	16
2.3 Environmental Impacts of Wildland Fire .....	19
2.3.1 Impacts on Soils .....	19
2.3.2 Impacts on Water Quality and Quantity .....	22
2.3.3 Wildfire Effects on Wildlife and Habitat .....	24
2.4 Wildland Fire Management .....	26
2.5 Definition of Terms Used in the Research .....	27
2.6 Communicating Threat .....	31
2.7 Wildland Fire Modeling .....	32
2.8 Fire Model Categories .....	34
2.9 GIS-Coupled Fire Models.....	36
2.10 Data Requirements for Wildland Fire Models .....	39
2.11 Techniques for Mapping Urban Areas .....	42
2.12 Scale and Resolution .....	42

3. METHODOLOGY .....	45
3.1 Study Area .....	45
3.2 Urban Land Cover .....	51
3.3 Model Concepts .....	53
3.4 Model Design and Construction .....	58
3.5 Data Collection.....	59
3.6 Remote Sensing Component .....	61
3.6.1 Land Cover Analysis .....	61
3.6.2 Fuel Model Classification .....	65
3.6.3 Classification Test .....	66
3.6.4 Image Registration .....	66
3.7 GIS Data Preparation .....	67
3.7.1 Road and Rail .....	68
3.7.2 Slope Analysis .....	69
3.7.3 Soil Data .....	71
3.7.4 Fire Station Locations .....	71
3.7.5 Real-Time Weather Data .....	74
3.7.6 Additional GIS Data .....	77
3.7.7 Fire Behavior Calculation .....	78
3.8 GIS Model Construction .....	81
3.8.1 Generalized Threat Map .....	81
3.8.2 Ignition Sources .....	82
3.8.3 Target Areas .....	83
3.8.4 Real-Time Weather Factor .....	84
4. RESULTS .....	87
4.1 Remote Sensing of the WUI.....	87
4.2 Threat Classes Using Static Threat .....	96
4.3 Natural Resource Features .....	110
4.4 Real-Time Weather Component.....	114
5. CONCLUSIONS .....	124
5.1 Comparison To Other Wildfire Threat Models .....	124
5.2 Fuel Model Classification .....	127
5.3 Model Testing .....	130
5.4 Natural Resource Impacts .....	130
5.5 Future Plans for the WFBM .....	131
REFERENCE LIST .....	131

## LIST OF TABLES

Table	Page
1.1 Characterization of Wildland Fire Models .....	35
3.1 Population Data for CAPCO, 1990 - 2000 .....	52
3.2 Housing Units in the CAPCO Region, 1990 – 2000 .....	52
3.3 City of Austin Fire Risk Model Variables and Weighting Scheme .....	55
3.4 Data Types and Sources .....	61
3.5 NRCS Report on Potential Damage to Soils from Wildfire .....	73
3.6 Example of RAWS Weather Data .....	77
3.7 Fire Behavior Output for Fuel Model 9 .....	80
4.1 Classification Error Matrix .....	98
4.2 Potential Damaged Soil Acreage .....	113

## LIST OF ILLUSTRATIONS

Figure	Page
3.1 Study Area in Central Texas .....	45
3.2 Ten Counties of the CAPCO Region .....	46
3.3 The Natural Regions of Texas .....	47
3.4 Natural Regions of the CAPCO .....	48
3.5 Subdivisions of the CAPCO Region .....	49
3.6 General Vegetation Types of the CAPCO .....	50
3.7 30-Mile Radius Around Austin, Texas .....	53
3.8 Wildland Fire Threat Model Design Components .....	58
3.9 Sequence of Steps in Model Development .....	60
3.10 Landsat 7 Images, Path and Row .....	62
3.11 Comparison of Landsat and IKONOS Pixel Size .....	64
3.12 400 ft. Buffer Around Named Roads .....	69
3.13 Elevation Range Across Study Area .....	70
3.14 Microsoft® Access Template for Soil Series Attribute Data .....	72
3.15 5-Mile Buffer from Fire Stations .....	74
3.16 Nine RAWS Stations Used for Fire Behavior Calculations .....	76
3.17 Illustration of BehavePlus 3.0.0 Demonstration Input Worksheet .....	81
3.18 Illustration of BehavePlus Output .....	81
3.19 GIS ModelBuilder Example of Rate-of-Spread Threat Calculation .....	87
4.1 Examples of Images Used for Classification .....	88



4.2	Comparisons of WUI in Landsat 7 and DOQQ .....	89
4.3	Comparison of WUI in IKONOS and DOQQ .....	89
4.4	Comparison of Landsat 7 and DOQQ in Tall Trees .....	90
4.5	Comparison of IKONOS and DOQQ in Tall Trees .....	91
4.6	Buffered Roads Delineating WUI .....	93
4.7	Detail of Buffer of Named Roads .....	94
4.8	Example of Unincorporated Areas Identified by Buffer Method .....	95
4.9	Fuel Model Classifications for CAPCO Study Area .....	96
4.10	Test Locations Used for Accuracy Assessment .....	98
4.11	Fuel Model Threat Classes .....	100
4.12	Slope Threat Classes .....	101
4.13	Detail of Slope Threat In Western Travis County .....	102
4.14	Threat from Roads and Railroad Corridors .....	103
4.15	Detail of Threat from Road and Railroad Corridors .....	104
4.16	Threat to WUI .....	106
4.17	Detail of WUI Threat Overlay .....	106
4.18	Threat Classes from Combined Static Features .....	108
4.19	Detail of Threat Classes for Static Features .....	109
4.20	Subwatersheds Included in Threat Analysis .....	111
4.21	Potential Soil Damage Levels from Wildland Fire .....	111
4.22	Detail of Threat to Soils in Subwatersheds .....	114
4.23	Potential Rate-of-Spread Under Specific Weather Conditions .....	116

4.24	Fireline Intensity Threat Under Specific Weather Conditions .....	118
4.25	Flame Length Threat Under Specific Weather Conditions .....	119
4.26	Probability of Ignition Under Specific Weather Conditions .....	121
4.27	Example of ROS Application .....	122
4.28	Example of Flame Length Application .....	123

## CHAPTER 1

### INTRODUCTION

#### 1.1 Wildland Fire

In late October and early November, 2003, southern California was the scene of wildfire devastation on a scale seldom seen in the United States. Statistics for the thirteen wildfires that occurred during the two-week period are unprecedented: 750,000 acres burned, 4,000 homes destroyed, billions of dollars in damage, 22 human deaths and 12,000 firefighters required to battle the blazes (Smith, 2003). Extensive news coverage alerted the American public to the awesome force of wildland fire, birthed, in this instance, within the wilderness of chaparral and sage on California hillsides and grown to destructive maturity in the trees of forests and houses of urban developments.

Since the 1940s, Americans have been warned of the dangers of what has traditionally been called forest fires through such popular figures as Smokey Bear and the animated Disney movie character, Bambi. Roadside signs and entrances to campgrounds reminded travelers that: "Only you can prevent forest fires". Several generations of Americans have grown up with the concept that fires occur in forests, campgrounds and wilderness reserves, natural areas that should be protected for the sake of trees and wildlife. In the past two decades, particularly in rapid urban growth areas such as in California, that there has been a growing danger of forest fires, now known as wildfire, impacting human residences and businesses (Carle, 2002).

## 1.2 Statement of the Problem

Wildfires occur regularly throughout the United States due to certain combinations of fuel types, weather conditions and ignition sources. The severity of impact on natural and human-made resources is typically a result of fire intensity; also a combination of fuels and weather. Information about fuel types and weather is available through numerous sources. Although fuel types remain fairly stable from year to year, fuel moisture levels change as a result of precipitation events, and wildfires increase or decrease as a result of humidity, temperature and wind speed.

This research sought to contribute to efforts to reduce the severity of detrimental effects from wildfire in a portion of the state of Texas. Through computer modeling, using satellite remote sensing and Geographic Information System software, a series of models were constructed that examined combinations of fuels, landscape and weather to produce mapped information about potential threats from wildfire. The purpose of the research is to identify portions of the study area that are under high threat from wildfire and by so doing, assist emergency and natural resource managers in directing preventive measures to reduce severe impacts. The specific goals and tasks of the research are presented at the end of this chapter.

## 1.3 Wildland Fire Versus Wildfire

Whereas the term forest fire is used in a generic sense for fires that occur in wilderness, there are many types of fuels that burn other than just forests. The fires that caused so much destruction in Southern California were primarily brush fires and

numerous fires in Florida occur in palmetto scrub, hardly a forest. As a result, the term forest fire is used among professional firefighters, emergency managers and fire researchers, collectively known as the fire community, as a description of a specific type of wildland fire in forests. The word wildfire is another description of fire, often found in print and news headlines and particularly in terms of fire disasters. The terms wildland fire and wildfire create some confusion among the public and even within the professional fire community.

The terms wildland fire and wildfire are often used interchangeably, even among fire professionals. Joseph Lowe, a twenty-year veteran of fire fighting, refers to combating fire in vegetation as wildland firefighting (Lowe, 2001). The United States Forest Service, as do many writers, describes wildland fire as that which takes place in wildland fuels; grass, shrub, timber litter or logging slash; whereas wildfire is “an unplanned wildland fire requiring suppression action” (NWCG, 1994). For the purposes of this document, the terms wildland fire and wildfire will be used to describe fire under different conditions.

Wildland fire is a generic term that describes fire that occurs in natural vegetation or non human-made environments, as opposed to structure fires or those occurring in urban settings. Forest fires, prairie fires, and prescribed burns are all examples of wildland fire. Wildland fires are frequently caused by natural means, such as lightning strikes in a forest, but just as frequently, or more so, wildland fires are caused by arson, human carelessness or intentional ignition as in prescribed fire.

The term wildland fire neither suggests levels of fire intensity nor causality. Low intensity wildland fires in natural areas, commonly occurring events in ecology, are often not extinguished but are allowed to burn so as to clear underlying brush, reduce fuels loads, and restore or alter habitats. Wildland fires deliberately ignited by land management agents are generally done so under a prescription, or burn control plan (Whelan, 1995). The intensity of a prescribed fire can range from low to high, depending upon the goal of the fire. Very hot, intense fires are sometimes prescribed to obtain specific ecological effects. Although high fire intensity is usually associated with wildfires, high intensity alone is not necessarily a qualifying factor.

A wildfire is unwanted fire that requires measures to control and suppress it whereas a prescribed fire is controlled fire promoted to meet management needs (Pyne et al., 1996). For example, a lightning strike that causes a fire that moves into treetops, expanding rapidly and threatening valuable natural and human resources, would typically be called a wildfire. A prescription fire, a form of wildland fire, that goes out of control becomes classified as a wildfire, and the approach to the fire usually changes from fire management to firefighting and suppression.

#### 1.4 Catastrophic Wildfire Impacts

Wildland fire has existed as an environmental presence ever since the components that support fire, fuel, oxygen and heat, became available in correct proportions. For more than 400 million years fire has played a vital role in the ecological processes of the planet, much in the same manner as drought, hurricanes, floods and

other forms of natural disasters. Wildland fire is a disturbance force that resets the clock of ecological succession, changing vegetation types and eliminating or creating habitats (Pyne, 2001). Wildfire, the high intensity subset of wildland fire, often devastates the vegetative cover of landscapes, creating radical changes in wildlife habitats, soil properties and water quality.

Catastrophic wildfires have great potential to harm people and local communities as well as natural resources. Smoke from fires, both prescribed and wildfire, in the vicinity of urban areas, cause increased levels of air pollution. High levels of fine particulates in smoke can produce deleterious impacts on the young and aged, and particularly those with respiratory problems. Smoke plumes are often the cause of evacuations or closings of health care facilities, schools and retirement centers (Core and Peterson, 2001).

Evacuations of large numbers of people are disruptive, dangerous and expensive. Losses in business revenues can be substantial and disruption of the daily activities of individuals can take an enormous psychological toll. Damage to property and homes cost individuals and the insurance industry millions (U.S.D.A., 2002). The danger to the lives of the public and to firefighters is of the greatest concern. In the decade 1994 – 2004, wildfires caused the death of 201 wildland firefighters and the injury of hundreds more (NIFC, 2005).

## 1.5 Wildfire-Urban Interface

Some of the most devastating impacts of wildfire in recent history have been located in the Wildland-Urban Interface (WUI) – the ecotone of human-made habitat and natural wilderness. There are various definitions of the wildland-urban interface, although all are not used nationally. Four examples are (Weatherford, 2002):

1. Interface condition: Structures abut wildland fuels. There is a clear line of demarcation between structures and wildland fuels along roads or back fences. Wildland fuels do not continue into the developed area.
2. Intermix condition: Structures are scattered throughout the wildland area. There is no clear line of demarcation; wildland fuels are continuous outside of and within the developed area.
3. Occluded condition: Structures abut an island of wildland fuels, normally within a city, such as a park or other open space. There is a clear line of demarcation between structures and wildland fuels along roads and fences.
4. Rural condition: Scattered small clusters of structures (such as ranches, farms, and resorts) are exposed to wildland fuels. There might be miles between clusters of development.

This study uses a definition suggested by Hermansen (2003): “a zone where human-made infrastructure is located in or adjacent to areas prone to wildfire.” The author suggests that the interface is a condition rather than a specific place; a condition



that is an intermix of the environmental factors of fuels, weather, landscape, and humans that place a community at risk from wildfire (Hermansen, 2003).

### 1.6 Wildfire In The WUI

The summer of 2002 witnessed the loss of hundreds of homes in urban and suburban communities in Colorado, New Mexico and California (Smith, 2003; Carle, 2002). Frequently WUI fires result in high numbers of destroyed homes because of a large, difficult to suppress fire front. WUI fires are different from structural fires, normally thought of in terms of large fire engines and urban fire departments, and typically involving a single structure. Wildland fuels, grasses, shrubs, and trees can rapidly carry fire from open areas into landscaped yards and then house to house; fire consuming shingles and siding and outpacing suppression capabilities of firefighters. Loss of residences from wildfire now occur with ever increasing frequency as housing developments push further into previously wild areas, surrounded by wildland fuels.

Additionally, cities are increasingly integrating "green space" or islands of wildland into the cityscape. Development surrounds these wildland areas, leaving them as public or private property managed for recreational purposes, habitat protection, for aesthetic reasons, or simply because they are too expensive to develop (Hermansen and Macie, 2002). These interface areas, consisting of wildland fuels and surrounded by development, are also a source of wildfire risk.

## 1.7 Wildfire Impacts On Natural Environments

Natural areas have always borne the brunt of wildland fire. Watersheds can be negatively impacted when they are "burned over", to the extent that soils are left exposed, desiccated and impermeable. Rainfall events following hot wildland fires commonly create accelerated soil erosion, causing topsoil loss, plumes or pulses of burn byproducts in receiving waters, and downstream sedimentation of aquatic habitats. Although wildland fires are part of the natural ecological process and are often viewed as rejuvenating, extreme wildfires, those with high temperatures and rapid spread, can have the opposite effect, leaving watersheds barren and eroded. Downstream receiving waters can be heavily impacted, causing loss of aquatic life and added great costs to treat water for human consumption (Clark, 1994).

Habitat critical to maintain the viability of threatened and endangered wildlife is another major concern of extreme wildfire. Although many creatures are able to avoid direct death by fire, it is not uncommon for critical nesting habitat, for birds particularly, to be lost. Species that depend upon certain vegetation types or landscape characteristics for breeding and rearing young can be severely impacted by loss of habitat (Anderson, 1995). Once again, wildland fire is a natural process, but devastating wildfire, common to areas with excessive fuel buildup, can clear major areas of a landscape, leaving little for nesting or protection purposes.

## 1.8 Understanding Wildland Fire Behavior

Due to the devastating effects some wildland fires have on natural and human-made environments, great effort is expended by state and federal agencies to prevent fires from happening; to rapidly suppress fires that pose a threat; and/or to mitigate damage caused to homes, wildlife habitat or watersheds. In order to properly deal with wildland fire it is imperative to understand fire behavior, how fire functions in different settings of fuels, landscape and weather.

Wildland fire has characteristics and behaviors that are relatively well known and understood, although the movement of fire across the landscape does not always fit a specific pattern (Whelan, 1995). Despite the element of uncertainty, wildland fire behavior can be broadly understood within the context of three interacting factors: fuel, topography and weather (NWCG, 1994).

One factor of the triangle consists of fuel. Wildland fuels, such as dry grass, resinous shrubs, leaf litter, or standing timber, provide the medium through which fire moves. Fuels can range from a dense, contiguous cover of a single vegetation type to a thin, patchy mosaic of various species. The heights and density of fuels can exhibit a wide range of values (Whelan, 1995). However, what is consistent is that without fuel there is nothing to burn, thus if fuel is removed, the fire behavior triangle is broken.

A second set of factors deals with topography and land surface; the shape and characteristics of the landscape that contribute to the behavior and movement of wildland fire (NWCG, 1994). Fire burns faster up steep slopes, caused by the preheating of fuels and updrafts or "chimney effect". Topography also includes aspect that is the

compass direction that slopes face. Vegetation growing on slopes is differentially affected by weather conditions depending upon the direction of the aspect. For example, vegetation on south facing slopes in the northern hemisphere is often dryer due to a constant exposure to sunlight, whereas vegetation on steep, northern slopes is shade grown and usually has higher moisture content. Vegetation moisture has a major impact on fire behavior.

The third set of factors is weather – the driving factor in fire behavior. Relative humidity (RH) is perhaps the single most important factor in wildland fire, for RH determines the moisture content of fuels. Dry fuels are more likely to burn than wet fuels; hot, dry days cause dry fuels and so increase the potential for wildfire. Wind is the carrier of fire. Light winds have little impact on wildland fire whereas strong winds feed the fire with oxygen and push fire out ahead of it, causing the rapid movement of wildfires over great distances (Whelan, 1995).

### 1.9 Fire Behavior Models

Fire behavior models help provide the fire community with an understanding of the movement and intensity of flaming fuels, providing various tools for predicting location and severity of wildfires. Models range in scale from small to large geographic area and in complexity, from paper nomographs and charts in firefighter handbooks (NWCG, 1998) to complex mathematical research models for flame height and ecological effects (Johnson and Miyanishi, 2001). Since wildland fire behavior factors

are location specific – fuels, topography and weather – the fire behavior factors are ideal for integration into models using remote sensing and GIS (Sampson et al., 2000).

A common application for remote sensing imagery is to identify areas of interest such as housing developments or critical habitats based upon specific vegetation types. Fuels, in the forms of grasslands, shrublands and forests, can be categorized and mapped using remote sensing. Fuel moisture is determined by satellite images, as demonstrated by the use of imagery for crop inventory and health during drought conditions. Digital topographic data are a keystone of GIS, allowing the mapping of slope and aspect across a landscape (Sampson et al., 2000).

Mapping of weather is conducted on a continuous basis, as seen on round-the-clock television channels. Whereas the factors of topography remain relatively constant, and fuel types change very slowly, if at all, weather conditions change almost continuously. In order for a fire behavior model to reflect current conditions, wind speed, direction and relative humidity must be introduced on a real-time basis. By combining all three sets of multidimensional fire behavior factors, facilitated by a GIS, the direction of fire movement, fuels consumed and to be consumed, and the ferocity with which they burn can be modeled and mapped.

### 1.10 Objectives Of This Research

There are two primary goals for this study and multiple tasks necessary to accomplish the goals:

1. Develop methodology to identify potential risk from wildfire to the Wildland Urban Interface in ten counties of central Texas. The purpose is first and foremost to aid in the protection of human health and life from wildfire. A secondary purpose, but one of great economic importance, is the protection and mitigation of wildfire impacts on homes and businesses within the WUI.
2. To identify potential risk to natural resources within the study area. Urban populations within the area depend upon watershed protection for good drinking water quality and quantity. The model evaluates the proximity of soils that, if denuded of vegetation by intense wildfire, potentially contribute high sediment loads to waterways and reservoirs as a result of rapid erosion. Numerous wildlife species depend upon certain vegetation types specific to the area for habitat; radical vegetation changes as a result of wildfire can have profound effects upon the viability of the species. Identification of natural areas at high risk from wildfire facilitates habitat protection and wildfire damage mitigation.

#### 1.11 Tasks Conducted To Achieve The Goals

1. Digital geodatabases (databases tied to geographic locations through internal coordinates) were assembled from various sources for the ten-county study area.
2. Multiple satellite images from two different space platforms and at different scales were obtained and analyzed to identify wildland fuel types over the ten-county study area. A comparison of the usefulness of fine and coarser scale spatial and spectral

resolution imagery for fuel identification was conducted. Also, the usefulness of using satellite imagery for demarcating wildland urban interface was examined.

3. A methodology for mapping wildland urban interface areas was examined for use in identifying both potential wildfire ignition areas and built-up areas at risk from fire.
4. Areas within the ten-county study area that have inadequate coverage from emergency wildfire response services were identified.
5. Real-time weather data was integrated into the model enabling emergency managers to determine wildfire threat analyses based upon current conditions.

To achieve the above objectives, the research integrates existing data sources describing fuels, topography and natural and human-made resources, with an industry standard wildland fire behavior model and geographic information system (GIS) software. The results of the integration of digital data, a fire behavior model, and a GIS model is an easily reproducible methodology to develop a series of maps, in near real-time, that display potential threats from wildfire to human-made and natural resources.

## CHAPTER 2

### LITERATURE REVIEW

#### 2.1 Background to Study

There are numerous reasons given for the large numbers of highly destructive wildland fires that have been occurring over the past few decades. The most widely used explanation is that wildland fire suppression, as dictated by U.S. Forest Service policy since the early nineteenth hundreds, has allowed for a build up of fuels that, when ignited, promotes larger and hotter fires (Carle, 2002). Coupled with increased fuel loading is what appears to be increasing summer temperatures, more severe droughts, lower snow pack and earlier snow melt. Warmer temperatures and increased vegetation growth due to higher carbon dioxide levels are perhaps causing more frequent and severe fires, particularly in the western United States (McKenzie et al., 2004).

There is ample evidence to suggest that increased fuel loadings, higher summer temperatures and severe droughts are primary factors in the higher incidence and intensity of wildland fire, but it is the frequency and intensity of wildland fires that is unusual, not the occurrence. What the general public often misunderstands is that wildland fire is a natural occurring impact in ecosystems, similar to floods, hurricanes, or tornados. Educational campaigns against fire have obscured the reality that wildfire is a natural function that actually purges landscapes of invasive species, thins tree stocks to healthy levels, and recycles nutrients into the soil. Wildfire replenishes and maintains healthy ecosystems and needs to remain in the cycle of nature. With several generations of Americans raised on the media image of fearful young deer fleeing



before the ravages of wildfire or Smokey Bear reminding us that “even little fires kill little trees” (Carle, 2002; Pyne, 1995), it is not surprising that fires have been suppressed and fuels have increased to dangerous levels.

Ironically, if fire had remained solely in “wild lands” it is unlikely that there would be as much national attention as is now focused on wildland fire issues. As wilderness areas have become progressively less wild, dotted with the homes and cabins of exurbanites who demand protection for their property similar to that they had in cities, wildfire has now gained as much public attention as hurricanes and floods that impact populated areas.

Approximately one hundred years ago, in the early days of the U.S. Forest Service, wildland fire suppression became a credo for forest professionals who were concerned with protecting stocks of timber vital to a growing U.S. economy. Today, protection of timber supplies remain a major concern, but the majority of news broadcasts focus not on fires burning in remote areas of the west but rather on conflagrations that threaten or engulf homes, a direct economic impact and loss to humans. What seems to be wildland fire moving into urban areas is in reality human habitation rapidly invading wildland fire areas, housing growth driven by a steadily growing U.S. population whose desire is to live in the natural settings on the fringe of urban benefits (Pyne, 1995).

This urban fringe, known in the fire community as the Wildland-Urban Interface (WUI), is an area that has become the focus of great attention by such groups as urban planners, emergency personnel, insurance companies, and politicians. The interface is

frequently a source of conflict between housing developers and environmentalists. From a developer's point of view, the "edge of town" is often both aesthetically pleasing and economically rewarding, encouraging development of expensive houses in country settings. In the past decade in the western U.S., 38% of new home construction has occurred adjacent to or intermixed with the WUI (FEMA, 2002). From an environmental perspective, the urban interface is a continually expanding front intruding into wild space, displacing indigenous species as their natural habitats are changed or lost.

The driving factor behind wildland-urban interface issues is primarily population growth and changing demographics. Population growth in the United States is primarily in urban areas; currently over 80% of the U.S. population is urban. Continually increasing urban populations and recent low mortgage interest rates has increased the demand for new housing developments and pushed urban areas into wildlands, expanding the wildland-urban interface. Nationwide, between 1992 and 1997, approximately 16 million acres of rural land were converted to urban purposes (Cordell and Macie, 2002).

## 2.2 Recent WUI Fires

As mentioned in the Introduction, the fires of southern California in October of 2003 were perhaps the most poignant example in recent U.S. history of the devastation of fire in the urban interface. The previous summer, 2002, was one of the worst overall wildfire seasons in modern history. Fires in the front range of Colorado exemplified the danger and costs to urban areas. Having experienced three years of less than normal precipitation, Colorado wildland was prime for a season of devastating fire, the most

serious of which was the Hayman Fire in the Colorado Springs vicinity, burning 138,000 acres (Graham, 2003).

During the year, wildfires raged throughout western states as well as along the eastern seaboard and the northeast; an unusual experience for that part of the country. By June, 2002, the National Interagency Fire Center had reported that wildfire had consumed 420,000 acres in Alaska, 490,000 acres in the west, 390,000 acres in the south and 79,000 acres in the Northeast (NIFC, 2004). All told, more than 5.9 million acres burned in the United States, causing the evacuation of tens if thousands of residents from over 200 communities and the destruction of more than 2,300 homes (White House, 2002).

May, 2000, was devastating for the communities of Los Alamos and White Rock in north central New Mexico. What began as a prescribed fire, in an attempt to reduce heavy fuel loads and the fire threat to the Los Alamos National Labs (LANL), became a destructive inferno that forced the evacuation of 18,000 residents, consumed 45,000 acres and destroyed 400 homes and other structures within Los Alamos and the neighboring community of White Rock (Carle, 2002; Wolf, 2003).

The LANL facility sits atop a series of mesas surrounded and interspersed by ponderosa pines and mountain grasses. An earlier vegetation survey calculated as many as 2,000 pines per acre in some areas of the forest in comparison to areas with 25 to 80 pines per acre where low-intensity fires had historically burned (Carle, 2002). Prescribed fire was chosen as the optional method to reduce fuels to more manageable levels. Sporadic winds and critical mistakes changed the fire from prescribed to a

wildfire. A series of mistakes were the cause of the breakout wildfire that wreaked havoc in this urban interface.

Prior to 2000, the largest economic loss from wildfire in the United States, and certainly in California history, took place in October, 1991, in the Oakland and Berkley hills. The wildfire that swept out of the hills to the east of the cities killed 25 people, injured 150, and destroyed 2,499 houses and 437 apartments and condominiums (Carle, 2002). Damage was estimated at between \$1.5 to \$2 billion dollars, from a fire that burned only 1,500 acres (Gottschalk, 2002).

Upon investigation, the reasons for the intrusion of wildland fire into the urban realm of Oakland were fairly clear. Over time, housing developments had pushed into the chaparral covered ridges and canyons on the fringes of the city. Extensive planting of vegetation was often undertaken to “green” the developments, adding Eucalyptus and Monterey pine, superb fuels for wildfire, to the highly combustible chaparral (Gottschalk, 2002).

Wildfire destruction is not limited to the western states. Following a period of very hot temperatures and lack of rainfall, Texas experienced a high number of severe wildfires during the month of February, 1996. Angelena County, in the southeast of the state, experienced a burn of 2,500 acres; Houston area fire departments fought 467 grass fires in a three-week period, a high rate compared to the 1,100 fires fought during the previous year. Fifteen structures were destroyed in Denton County that month. The largest fire that month was located near Poolville in Parker County to the northwest of Fort Worth. By the time it was extinguished it had burned 45 homes and

23,000 acres (CNN, 1996). Following years were also severe. By July, 1998, more than 6,800 fires had occurred in Texas since the beginning of the year, consuming 288,500 acres (FEMA, 1998). A headline in CNN.com in 2000 declared "Texas takes the lead in number of U.S. wildfires" (CNN, 2000).

## 2.3 Environmental Impacts of Wildland Fire

Wildland fire has an ecological effect similar to natural disasters such as droughts, floods, hurricanes and other physical disturbances because of the direct impact it makes on the landscape and organisms (Whelan, 1995). Severe impacts to vegetation and soil characteristics influence the type and condition of vegetative regrowth, and thus wildlife habitat, following a fire. Wildfire is similar to overgrazing, common in the western states, in its impact on vegetation and landscape (Whelan, 2000). Highly erodible soils, denuded of vegetation, wash away in heavy rains, choking streams and degrading water quality; the impacts felt long distances from the wildfire.

### 2.3.1 Impacts on Soils

The impact of wildland fire on soils is varied; some researchers record negative impacts and others somewhat positive effects (Clark, 1994). However, much attention is paid to damage caused to soils for they result in post-fire contributions to erosion, changes in water runoff quality and quantity, and major effects on plant regrowth. A commonly recorded impact upon soils following wildfires, particularly in resinous vegetation types such as chaparral and juniper, is hydrophobicity – burned soils become

water repellent. The surface of the burned soil loses organics and becomes sealed to water infiltration. The extent of hydrophobicity depends upon the temperature of fire which is a consequence of fuel loading, fuel moisture content, fuel distribution, rate of combustion, soil texture, moisture and resin content of the fuels (Clark, 1994). Shrub communities are more prone to hydrophobicity particularly where coarse-textured, sandy, low moisture soils (Wright and Bailey, 1982). Vegetation cover loss, root damage and changes in rainfall infiltration contribute to changes in water runoff and water quality.

Increased erosion is a common result of wildfire. Numerous research studies have documented an increase in runoff and erosion following wildfires (Miller, et al., 2003). Large increases in erosion losses have been recorded in forests following wildfire, the magnitude of the loss highly correlated with the intensity of the fire; increases in soil erosion have also been recorded in grasslands (MacDonald, et al., 2000). The impact of fire on erosional processes can be attributed to several factors. The primary factor is the removal of vegetation eliminates cover that serves to intercept raindrops, thus increasing rainsplash and movement of soil particles. High intensity fires consume humus, removing it as an important component of soil binding, and making certain soil texture types more erosion prone. Erosion is also accelerated by rapid rates of runoff. Soils denuded of vegetation lack the ability to slow down runoff, and hydrophobic soils cause increased and faster runoff. This increased runoff can cause accelerated erosion in channels and streams (Miller, et al., 2003; MacDonald, et al., 2000; Clark, 1994).

High erosion rates may not appear for several years after a high intensity burn. Vegetation that has been top-killed (the destruction of above-ground biomass) can maintain soil stability until the root system begins to decay (Clark, 1994). This is not necessarily the norm, however, since different plant species react to fire in different manners. Many plants experience top-kill but the root mass remains viable and vegetative regeneration occurs from sprouts at ground level. Although soil is a good insulator, protecting root and underground bud tissue from elevated temperatures, very hot wildfire, the time of year of a burn, or frequent return of fire can kill even fire tolerant plants (Whelan, 1995), thus exposing soil to potential erosion.

Post-fire erosional processes are similar to those resulting from agriculture and are a combination of soil and topographic properties. Potential for water erosion following burning is a function of rainfall intensity, slope characteristics of the land, surface soil texture and erodibility, intensity of the fire (similar to crop removal in agriculture), and use of the land after a fire (Scifres and Hamilton, 1993; Whelan, 1995; Wischmeier and Smith, 1962). Post-fire erosion rates in southern California have been reported as high as 150 tons per acre with extreme rates of as high as 165 tons per acre on slopes of 40 – 80% in Arizona (Clark, 1994). These rates far exceed the more common rates of 23 –52 tons/acre found on granitic, sandstone and shale-derived soils (Wright and Bailey, 1982). On limestone derived soils in central Texas soil losses of 7 to 10 tons/acre over a 2.5-year period were recorded for slopes of 45% to 53% (Wright and Bailey, 1982). Generally, four years are required for stabilization of slopes

with natural shrub vegetation but some reports suggest that as long as 10 years are needed to return to pre-fire conditions.

On limestone-derived soils in central Texas, Wright and Bailey (1982) found that juniper burns could significantly affect runoff and erosion. On moderate slopes of 15 to 20%, erosional losses of 0.1 to 1.1 tons/acre were recorded whereas on steeper slopes of 45 to 53%, losses of 6 to 8 tons/acre occurred. This condition continued until cover (live vegetation and litter) reached about 70%. In comparison, burned grasslands experienced considerably lower erosion rates except on sandy soils. Erosion in forested areas is usually related to the intensity of wildfire. High intensity burns that remove litter and duff are more likely to cause higher erosion rates, particularly in relation to high slopes and sandy soils (Wright and Bailey, 1982).

### 2.3.2 Impacts on Water Quality and Quantity

As mentioned in the above section, intense wildfire can change soil infiltration rates, increase runoff and create changes in water quality and quantity. Infiltration rates of undisturbed soils are typically high in forested areas or grasslands with high duff and litter cover. Removal of duff and litter reduces the moisture holding-capacity of the soil, as well as exposing the soil to erosion (Weldan 1995). Typically, higher runoff is seen after fires that convert brush shrublands to grasslands. Vegetation types and associated soils have been shown to be key factors in water yield following burns (Wright and Bailey, 1982). Researchers found runoff increases of up to 29% following fires in the Rio Grande basin of New Mexico. Higher runoff quantities were observed



following fire in the Ashe juniper zone of central Texas; they declined steadily to pre-burn water yields after three years (Wright and Bailey, 1982).

Increases in surface runoff exacerbate erosion and add to sediment loading of in watersheds and streams. The effects of runoff are less apparent on low slopes than on steep slopes due to lower water velocity (Wischmeier and Smith, 1978). Research found that moderate slopes exhibited a 10-fold increase in erosion and a 100-fold increase on steep slopes in the first six months after burning (Clark, 1994).

Water quality in post-fire runoff can be highly variable depending upon fire intensity, vegetative cover, soil characteristics, topography, and rainfall amount. Gently rolling grasslands are less likely to exhibit water quality changes than forest or shrubland on steep slopes. In areas that experience increased post-fire runoff, the impact can be enormous. For example, following the Buffalo Creek Fire of 1996 in Colorado, the Strontia Springs Reservoir supplying Denver with water was heavily impacted. Rivers of ash flowed from burned slopes, filling the reservoir to the extent that it had to be drained and dredged. Water treatment plant filtering screens were plugged and hydroelectric plant turbines were heavily damaged (Wolf, 2003). Physical impacts on water bodies include increased turbidity, elevated temperatures (primarily from removal of vegetative and solar heating), change in pH, and increased nutrient loading (Clark, 1994).

Pyne, et al. (1996), suggest that the chemical impacts on aquatic habitats after fire are ambiguous and very site specific; erosion problems are specific to certain fire regimes rather than inherent to all fires. Nutrient increases, specifically organic carbon

and nitrogen, typically increase with increased runoff after a fire, most likely bound to detritus and sediment. However, studies suggest that nutrient flux falls well within natural range of variation and the increase shows no significant habitat deterioration (Pyne, 1996). The impact of fire on the water regime is more physical than chemical. Removal of vegetation from riparian areas add to increased solar heating of streams, increased runoff causes stream bank scour and rapid channel changes (Pyne, 1996), and sediment deposition can bury aquatic habitat.

### 2.3.3 Wildfire Effects on Wildlife and Habitat

As with so many aspects of wildland fire, the relationship of fire and wildlife habitats is complex and ambiguous. Wildland fire is a natural phenomenon but that does not mean that it is benign on its impact on wildlife; its effects can be both advantageous and destructive depending upon animal and plant species, breeding season, time of year of burn, intensity of fire, extent of burn, and many other factors (Anderson, 1995). For purposes of this study, deleterious effects of wildfire were examined.

Although many wildlife species are dependent upon a specific set of vegetative conditions, they tend to select habitat on the basis of structure rather than plant species composition (Whelan, 1995). Species that are structure dependent are broadly adaptable in behavior and can adjust to changes in post-burn conditions (Anderson, 1995). There are, however, numerous species that are vegetative species specific. Not

infrequently, species that are vegetation specific are already listed as Threatened and Endangered due to changes or loss of their particular habitat type.

Detrimental impacts from wildfire can include loss or change of habitat as well as direct mortality on individuals. A major change in habitat is loss of cover for purposes of travel, elimination of nesting and protective cover for rearing of young, and protection from predators. Another major impact from removal of vegetation is loss of food stock. Herbivores can experience loss of forage for short through extended periods depending upon fire severity, vegetation dynamics and post-fire weather conditions, although increased herbaceous production is common after burning occurs, promoting increased populations of certain species (Whelan, 1995). Population numbers among certain species decline in post-fire conditions due to lower nutrition, higher predation of eggs and young and emigration (Clark, 1994).

Direct mortality of wildlife is frequent with factors such as high rate of spread, fire intensity, and occurrence during nesting season. Individuals that cannot move out of the path of oncoming fire are likely to die unless they are able to take refuge in underground sites. Numerous invertebrates, amphibians, reptiles and mammals can survive burnover by remaining in deep burrows or slow burning brush piles (Wright and Bailey, 1982; Whelan, 1995).

The effects of wildfire can also detrimentally impact aquatic wildlife. Though there is seldom direct mortality from fire, changes in stream habitat and water quality parameters directly impact fish and invertebrates. Common post-fire impacts include burial of spawning sites from increased sedimentation, decrease in dissolved oxygen

and change in food-web from increased nutrient loading to the system (Spencer, et al., 2003), and increased water temperature through loss of shading vegetation (Wright and Bailey, 1982; Clark, 1995).

## 2.4 Wildland Fire Management

Developed in 2000 by the USDA Forest Service and the Department of the Interior, the National Fire Plan (NFP) is designed to reduce the risks of wildland fire to communities and the environment (NFP, 2004; U.S. Congress, 2002; USDA, 2002). The NFP represents an effort to strategically coordinate and enhance resources to control, prevent and mitigate the spread of wildfire through collaborative, long term planning and action across the landscape of the United States.

“That plan (the NFP) is an historic document setting forth an agenda to aggressively manage wildland fires and reduce hazardous fuels, protect communities and restore ecosystems over the next decade. It came about because of the high level of growth in the wildland urban interface that is placing more citizens and property at the risk of wildland fire, the increasing ecosystem health problems across the landscape and an awareness of (sic) that past suppression has contributed to more severe wildfires,” (Rey, 2002).

As Wildland/Urban Interface issues become more prominent in public discussion, it is important to emphasize that natural resources remain an important focus for fire management agencies. The working group of the “Preparedness and Suppression” section of the Federal Wildland Fire Management Policy and Program and Program Review (USDA, 1995) produced protection priorities based upon the potential for

wildland fire to destroy human life, human property and natural resource values. The first priority is to protect human life. However, there is debate about placing greater importance on human property rather than on natural and cultural resources. Where natural and cultural resources are considered to be of higher value than lower value property, managers must have the ability to protect such natural resources (USDA, 1995).

Protection of valuable human and natural resources from wildland fire is an area of expertise that differs greatly from traditional urban fire protection. Control of fire within structures is based upon keeping fire contained within a specific area; the goal of wildland fire management is to keep fire out of areas, (Pyne, 1996). In order to keep fire out of WUI areas, or to provide rapid mitigation for fire impacted natural systems, a means of identifying wildland fire hazards and areas at risk is essential. Fire protection in the intermix is very complicated; legal and political responsibilities cross many jurisdictions, requiring federal, state and local governments and private landowners to coordinate management and mitigation plans. As mentioned previously, wildland fire prevention education has historically been geared toward forest fires with little attention given to the WUI. The Federal Wildland Fire Management Plan repeatedly mentions the need for methods to identify hazards and risks of wildland fire to urban communities and an education initiative to bridge the gap in understanding between home owners, natural resource managers, emergency personnel, developers, insurance companies and local government officials (USDA, 1995).

## 2.5 Definition of Terms used in the Research

The terminology and phraseology used in risk assessment is often confusing and inconsistent (Maund and Mackay, 1998). This is particularly true in wildland fire where the uses of "danger", "hazard", "threat" and "risk" are often associated with categories of fire models, as in a "fire hazard model" or "fire danger index." Without a clear understanding of the various uses of the words, comparison of results from various models are difficult and communication of the results to the public or emergency personnel can be misunderstood or misinterpreted (Bachman and Allgower, 2001). As part of this research an attempt will be made to use terms in a manner consistent with general use among agencies and researchers while adhering to more formal use within the risk assessment and risk management discipline.

"Fire danger" is widely used on public notices at park entrances and roadways to issue a warning of environmental conditions that may result in a wildland fire. Defined broadly, fire danger is "the sum of constant and variable danger factors affecting the inception, spread, and resistance to control, and subsequent fire damage; often expressed as an index," (Lowe, 2001). Using this definition of fire danger, a fire danger rating area is the "geographical area within which climate, fuel, and topography are relatively homogenous, hence fire danger can be assumed to be uniform," (Lowe, 2001). Fire "danger" models are commonly used to describe combinations of factors, in comparative format, that have potentially harmful effects to the public and the environment. However, Bachman and Allgower (2001) suggest that the term "danger"

is an abstract concept based on subjective perceptions of outcomes that are considered harmful and, as such, is a useless and obsolete term for wildland fire research.

Suter (1993) defines hazard as "a state that may result in an undesired event, the cause of risk." Following this definition, a hazard assessment or analysis is the "determination of the existence of a hazard," (Suter, 1993), as in the presence of hazardous or toxic materials; those materials that cause harm to an organism. The primary hazard in wildland fire typically pertains to fuel complexes. The National Wildfire Coordinating Group describes a wildland fire hazard as "a fuel complex defined by kind, arrangement, volume, condition, and location that forms a special threat of ignition and resistance to control," (Lowe, 2001). Examples of hazards in the wildland that contribute to wildfire include such fuel factors as tall, dense, dry grasses or large quantities of litter and logging slash, among others.

In public health and environmental issues, Graham and Wiener (1997) define risk as "the chance of an adverse outcome to human health, the quality of life or the quality of the environment." For wildland fire purposes "risk" is defined as "1) the chance of fire starting as determined by the presence and activity of causative agents or, 2) a causative agent," (Lowe, 2001). In the discipline of environmental risk assessment the term "risk" is defined as "the probability of a prescribed undesired effect," (Suter, 1993). An undesired event is a realization of a hazard. A wildland fire risk is therefore "the probability of a wildland fire occurring at a specific location and under specific circumstances, together with its expected outcome as defined by its impacts on the objects it affects," (Bachman and Allgower, 2001).

Probability appears to be the common description of risk, suggesting a quantitative approach to risk analysis. However, the term "risk" is regularly used in a non-quantitative manner. For example, we commonly hear news reports that our western forests are at high risk from wildfire, suggesting that other areas are obviously at lower risk levels. Although there are no quantitative values used in these news announcements, there is a general understanding among the public that destructive wildfire can occur in high risk areas. This use of the term risk is qualitative, rather than quantitative. Gerrard and Petts (1998) suggest that there are in fact two types of risk assessment: quantitative and qualitative. Quantitative risk assessment "relates to an activity or substance and attempts to quantify the probability of adverse effects due to exposure," whereas, in contrast, comparative risk assessment, a qualitative measure, is "a procedure used for ranking risk issues by their severity in order to prioritize and justify resource allocation," (Gerrard and Petts, 1998). The difficulty in wildland fire issues remains the inconsistent use of "risk" and "risk assessment."

To further complicate the matter, the term "threat" is also used to describe wildland fire situations. Webster's (1983) dictionary defines threat as "an indication of eminent danger, harm, evil, etc." A wildland fire research project from the state of South Australia uses the term "threat" as the combination of hazard, risk and value, where "hazard" is the "intensity at which a fire will burn once ignited", "risk" is "the potential for fire ignition", and "values" are the "value of natural and constructed assets which may be destroyed," (Planning SA, 1999).



For purposes of this research, terminology follows that adopted by the South Australian project. The term “risk” is used to describe the potential that a combination of events will result in devastating wildfire. Due to lack of historical wildfire ignition records within the state of Texas, risk has no probability factors associated with it but rather is a qualitative comparison. The term “hazard” is used to describe physical components that contribute to wildland fire; in particular fuel types, weather conditions, and landscape form. Hazard assessment also identifies and categorizes hazards in a qualitative manner. “Value” is identical to the use in the South Australian project: natural and constructed assets that may be destroyed by wildfire. Finally, the term “threat” is used to describe the results of combining risk, hazard and values components also described in the previous paragraph.

## 2.6 Communicating Threat

One of the obstacles in wildfire prevention and control is a lack of communication between emergency managers and the general public about fire hazards and threats (USDA, 1995). Public officials and emergency response personnel need means by which to analyze and assess hazards and identify risks in specific geographic location in order to help reduce the threat of fire to human and natural assets. Various type of wildland fire models have been devised that attempt to analyze the complex factors of weather, fuel types, resources, and landscape topology to predict fire behavior and impacts. A major challenge of wildland fire modeling is to communicate analyses results in a manner that is readily understandable by property owners, planners, elected officials

and others concerning potential impacts on ecosystems and wildland urban interfaces (USDA, 1995; Atkinson, 2000).

Wildland fire model outputs often take the form of maps showing relative degrees of hazard, risk or threat (Chuvieco, 2003; Atkinson, 2000). Maps are a very effective means of communicating to the public. Geographic Information Systems (GIS) technology facilitates the assembling of multiple layers of geographic and demographic data into a form that can be used to answer questions of place and time, the results of which are displayed in map format. Maps are available in paper format or, more recently and likely more widely in the future, in electronic format over the Internet. The public use maps on a regular basis, are familiar and comfortable with the visual interface and, for the most part, are able to more rapidly understand the information being conveyed than that presented in written form (O'Looney, 2000).

## 2.7 Wildland Fire Modeling

Over the past 25 years numerous computer-aided support systems have been designed and implemented to assist wildland fire management decision-making in the U.S. and internationally. Support systems typically are designed to target specific needs, such as predicting wildland fire growth in small, rural areas or mapping fire risks over broad landscapes. Models are used to simulate a variety of fire effects including management of prescribed fire, ecosystems impact, and risk assessment to resources (Andrews, 1998).

The effects of fire, for the most part, are well understood and predictable, allowing modelers to simulate fire behavior and to compare the consequences of fire scenarios. Certain models predict fire behavior in terms of direction and speed of movement, heat intensity and flame height (Allgöwer et al., 2003). Other models are used to compare the results of various prescribed burn plans designed to achieve specific ecological effects. The ecosystem dynamics of different vegetation types impacted by fire are better understood by the use of models (Reinhart et al, 2001).

The term model has several connotations and within the computer simulation environment there are numerous varieties. A majority of fire models are mathematical simulations describing aspects or characteristics of fire or fire effects. Fuel models are descriptors of fuel types and conditions and are used as input into fire models. Typically fire models are mathematical equations and fuel models are numeric classifications of input information needed as input into the equations (Andrews and Queen, 2001).

The word "model" is also often used in terms of spatial analysis and mapping. Spatial modeling technology depends on the use of GIS to integrate frequently disparate geospatial data into a manageable form from which simulations, projections and assessments can be determined. Although the term fire model is often used to describe a GIS-based map produced by overlay of coincidental information, fire models are not intrinsically GIS-based nor are GIS-based models strictly mathematical equation based. However, many fire models are a combination of equation-based fire effects simulations coupled with the spatial analysis and mapping capabilities of GIS (Reinhart et al, 2001; Andrews and Queen, 2001; Radke, 1995). GIS can provide a comparative

view of hazards, such as flammable fuels, areas that are at risk of ignition either from lightning or humans, and identification of resources that are in need of protection (ESRI, 2000).

In wildland fire management the term "model" is not only used to describe mathematical simulations, as in fire model, but also as a description of fuel types, as in a fuel model (Andrews and Queen, 2001). The Anderson Fuel Model, for example, consists of a list of 13 classes that describe various types of fuels ranging from grasses to timber slash (Anderson, 1982). Fuel models describe the physical characteristics of a vegetative community rather than specific species, since the same species may exhibit different fire behavior under different moisture conditions, compactness, vertical continuity, and such (Chuvieco et al, 2003). Fuel models serve as input into fire behavior models.

## 2.8 Fire Model Categories

Andrews and Queen (2001) propose a categorization of fire models into three broad classes: fire environment, fire characteristics and fire effects models. Fire environment models describe conditions that exist before a fire event and which contribute to the likelihood of a fire taking place. Components that contribute to the fire environment are the physical and chemical factors described by the fire behavior triangle - fuel, weather and topography (Table 1.1). Fire environment models use factors such as fuel types, humidity, wind speed, temperature, steepness and direction

Table 1.1 Characterizations of Wildland Fire Models

	Fire Environment	Fire Characteristics	Fire Effects	
			First Order	Secondary
<b>Timing and location of the results.</b>	Pre-fire conditions	Process that take place during the fire	Prompt and local effects.  Measurable within a few days after the fire.  Restricted almost totally to the burned area	Removed from the fire area.  Results occur after a longer time delay
<b>Modeled results and output</b>	Fuel type description  Fuel condition and moisture content  Weather – wind, temperature, humidity  Terrain – slope, elevation, aspect.	Ignition  Extinction  Fire state – flaming or smoldering  Flame dimensions – length, height, depth  Fire intensity  Rate of spread  Fuel consumption  Emissions – gaseous and particulate  Heat transfer above the surface  Heat transfer below the surface	Reduction in fuel loading  Exposure of mineral soil  Mortality or thermal injury to vegetation  Chemical and physical response of fire-heated soil  Local air quality	Erosion  Smoke transport and dispersion  Health effects due to air quality  Wildlife habitat change  Water quality change  Economic impact  Visual change of the landscape  Global climate change

(Andrews and Queen, 2001)

of slope to predict fire behavior. The results of fire environment models are often displayed in map format showing comparative fire hazards across a landscape. Fire characteristics models describe fire behavior. Flame height, rate of spread, heat released, smoke produced, fuel consumed, are all aspects of fire behavior which can be described and simulated by this class of models. Fire effects models simulate the physical, biological and ecological impacts of fire on the environment (NWCG, 1998) and can be classified as first order and secondary fire effects (Andrews and Queen, 2001). First order fire effects are those that are immediate or prompt, measurable within a few days of the fire event and restricted to the area burned. Secondary fire effects are those effects that take place some time after a fire event or at a distance from the burn location (Andrews and Queen, 2001).

## 2.9 GIS-Coupled Fire Models

Wildfire disasters often produce similar impacts as those of floods or hurricane disasters. Damage to structures, wildlife habitat, and changes to hydrologic regimes are common. Implicit in disaster research and mitigation is the need to aggregate information about social, economic, and political data with geographic or spatial locations (Dash, 1997). GIS is well suited for combining spatial and non-spatial data into an integrated system from which spatial analyses can be conducted. Disaster mitigation and preparedness depend upon advanced information management systems for collecting, storing, indexing, analyzing and disseminating essential data. By allowing emergency and resource managers to incorporate spatial analysis and modeling into

their decision making process, they are better able to plan for potential disasters, (Dash, 1997).

There are numerous examples of GIS-based wildfire models that address fire behavior and promote an improved understanding of wildland fire primary and secondary effects. Although the majority of fire models are currently mathematical simulations without a spatial or mapped component (Reinhardt et al, 2001; Albright and Meisner, 1999), effort is being made to couple them with GIS software (Green et al, 1996). Two fire model areas that readily lend themselves to GIS coupling are "fire environment" and "secondary effects." Work is proceeding on the more difficult area of fire growth simulation models in the "fire characteristics" category.

Pre-fire conditions, the components of "fire environment," are predominantly location based. Fire environment models attempt to address the question "where are fuels, weather conditions, and topography most likely to support wildfire?" Numerous researchers and agencies are conducting projects to catalogue and analyze landscapes for wildfire potential. A consortium of federal and state agencies recently released a GIS assessment of wildfire hazard along the Front Range of Colorado (CSFS, 2002). The model couples fire environment (fuels and topography) with probable ignition sources and structures prone to fire to determine the "values," in this case structures, that are potentially threatened by wildfire. This general type of threat assessment model has also been conducted for fire-prone areas in Idaho (Harkins, et al, 1999; Burton, et al, 1999), Alaska (Hay, 2000), South Australia (Planning SA, 1999), and British Columbia, Canada (Hawkes and Beck, 1999).

The majority of GIS-based fire environment models depend upon fuel identification using satellite remote sensed imagery. The term “fuel model” is used by the U.S. Forest Service to describe fuel types and vegetation densities used by numerous fire models and for fire behavior analysis. There are numerous fuel model classifications schemes; this project used the Fire Behavior Fuel Models developed specifically for estimating wildfire behavior and effects (Albini, 1976). Remote sensing analyses of vegetative land cover can serve as a basis for fuel model classifications. Commonly, researchers perform a classification procedure to meet general land cover identification needs, producing a raster file of land cover classes. Following the first classification procedure, the original land cover file is reclassified or aggregated into fuel classes that then serve as input into fire models (Menakis, et al., 2000). For example, landscape-scale evaluations, such as on the scale of Mexico, have been conducted using Advanced Very High Resolution Radiometer-Normalized Difference Vegetation Index (AVHRR-NDVI) satellite data to identify vegetation cover and drought conditions (Mora and Hernandez-Cardenas, 1999).

Some models combine weather conditions, coupling “fire characteristics” with topography and fuels. Many of these models are based upon Rothermel’s work on fire prediction and management (Rothermel, 1972 and 1983) and use raster-based GIS to combine landscape features with weather conditions to model the movement of fire across the landscape (Gocalves and Diogo, 1994; Liu and Chou, 1997; Englefield, et al, 2000).



To date, the most advanced wildfire model that couples “fire characteristics” and GIS is FARSITE (Finney and Andrews, 1999). This model simulates potential fires at various locations under a variety of conditions of fuel and weather. Using a combination of vector and raster GIS, maps are produced displaying fire growth upon a backdrop of landscape features such as cover and topography.

## 2.10 Data Requirements for Wildland Fire Models

Data requirements depend upon the model. Fire environment models that describe pre-fire conditions almost unanimously require land cover data, such as vegetative cover classified into fuel types, and elevation data that describe the terrain. Weather data are not a requisite of fire environment models but are commonly used, when available, to assess hazard. In addition, many models require the identification of both natural and human values that are potentially impacted by wildfire. Value identification requires information on human structures, soil characteristics, hydrological features, and wildlife habitat. Typical data sets used in model construction include political boundaries, watershed boundaries, digital elevation data (DEM), soils (both STATSGO and SURGO), vegetation, fire ignitions (from fire agencies or weather stations), threatened and endangered species, and population information from census services (Sampson and Neuenschwander, 2000).

To model potential risk of wildland fire to urban interface areas – human values - it is necessary to be able to distinguish “urban” from “natural” areas. Urban areas consist of a wide mix of materials: concrete, asphalt, shingles, grass, trees, water,

plastic, and soil. Urban materials are commonly arranged systematically in parks and recreations areas, housing developments, commercial complexes or transportation corridors. Visual characteristics of many of these arrangements and materials can be remotely sensed from aircraft or satellites (Cowen and Jensen, 1998). This imagery can be either machine processed, as in a raster-based computer analysis of digital satellite imagery, or as vector data, digitized from aerial photographs by a technician.

Although satellite remote sensing is commonly used to identify urban areas for input into GIS models, there remain numerous problems. High spatial variability within many urban areas, such as a mixture of land cover types – roofs, roads, manicured lawns, trees and shrubs – are a source of confusion for image interpretation. Urban scenes tend to be “noisy”, highly heterogeneous and difficult to differentiate into specific classification categories (Mesev and Longley, 1999).

The scale of the land cover files is dependent upon the recording medium. AVHRR imagery, with a spatial resolution of 1 Km. x 1 Km., is suitable for small geographic scale studies covering large areal extents. Larger geographic scale projects, with smaller areal extent, such as studies conducted in Idaho and Colorado (Sampson and Neuenschwander, 2000), use finer resolution imagery such as Landsat Thematic Mapper data.

Urban areas can be identified through several means for inclusion in a GIS. Beginning in the 1940s, land cover, including urban landscape, has been classified through interpretation of panchromatic, medium scale aerial photography (Lillisand and Kiefer, 1994). More recently, larger scale photography and satellite imagery have

become common sources for urban classification. Ancillary demographic data, such as census data and census data surfaces, have been coupled with remote sensing imagery to identify urban areas. Remote sensing applications for urban delineation rely on standard computer-based analysis and classification of raster cell reflected energy values. GIS-based methods typically incorporate visual interpretation and digitization of aerial photography by trained analysts (Epstein et al., 2002; USGS, 1986), thereby relying on the experience of the analysts rather than the computational capabilities of a computer.

Despite the increasing resolution of the sensors, there remain doubts about the ability of remote sensing to rapidly and accurately map and monitor urban areas. Coarse spatial resolution sensors are unable to distinguish building features, transportation surfaces, or vegetative differences. Second generation sensors are capable of identifying a broad urban category, such as distinguishing a built-up area from forest, rangeland or wetland, but again are too coarse for defining structures or transportation networks (Jensen, 2000). Higher resolution imagery can do just that but brings with it major problems. Many high-resolution images are panchromatic, eliminating the ability to conduct classification based upon multiple band analyses. Another important factor is that small pixels over large areas require massive storage space. Even though disk drives are becoming cheaper, processing of large digital files presents difficulties in data exchange and processing time (Donnay et al., 2001). Although structures may be readily visible in high-resolution multispectral imagery, color and texture of roof materials may vary to such a large degree, and numerous small

pixels are needed to encompass a building footprint, that it becomes difficult to classify structures.

### 2.11 Techniques for Mapping Urban Areas

Since the advent of remote sensing, extensive work has been conducted to identify urban landscapes for such purposes as urban planning, tax assessment, transportation studies, public utilities, parks and recreation, and emergency management (Jensen, 2002). Although conventional aerial photography remains the backbone for urban identification and change analyses, satellite remote sensing, particularly with the launch of recent higher resolution recording devices, has grown in importance (Masser, 2001; Donnay et al., 2001). Aerial photography is difficult to obtain with sufficient frequency, usually more expensive than digital satellite imagery for an equal area, and requires considerable time to classify using manual techniques. Satellite remote sensing can provide regular image acquisition, which is particularly useful for urban change analyses (Harris and Ventura, 1995), but, until recently, has suffered from issues of resolution.

### 2.12 Scale and Resolution

Scale is often used to describe geographic data, but it has a variety of meanings depending upon context and discipline. Within the spatial domain, scale can be used to describe map measurements (cartographic scale), the extent of a study area (geographic scale), the level at which actions exist and are observable (operational

scale), and the smallest measurement at which an object can be measured (resolution) (Cao and Lam, 1997). Resolution is used specifically within the remote sensing world to describe the smallest object that can be distinguished either in digital imagery or aerial photography.

Geospatial data are inherently scale dependent. Wildland fire models reflect a combination of scale terminologies, ranging from the areal extent of the study area to the identification of the smallest unit potentially impacted by wildfire. Satellite imagery, commonly used for land cover analyses, is defined by its spatial resolution or scale as well as its spectral and temporal resolution. Spatial resolution in digital imagery refers to the size of the pixels; cells that house digital values or measurements of electromagnetic energy reflected from land cover types and recorded by the satellite receiver.

Pixels, or spatial resolution, must be of appropriate size to record the smallest object required for the study. The spatial resolution has major effects on image classification accuracy. If an object is considerably larger than the image pixels, there are fewer pixels that fall on the boundary of the object, and thus it is possible to attain a higher level of classification accuracy. However, if pixels are considerably smaller than the object to be recorded, it is likely that each pixel within the object records different values, decreasing the spectral separability of classes, resulting in lower classification accuracy. The ideal pixel size is half the length and width of the object to be recorded, or  $\frac{1}{4}$  size of the area to be recorded (Cao and Lam, 1997).

An example of this concerns urban classification, specifically individual buildings. Multispectral Landsat Thematic Mapper (TM) imagery has a pixel size of 30 m. by 30 m., or approximately  $\frac{1}{4}$  acre in size. Houses are typically smaller than  $\frac{1}{4}$  acre in size, therefore TM imagery is not suitable for identifying individual houses. Each pixel might record reflectance values from the roof as well as from surrounding vegetation, producing confusion on the classification. A pixel size smaller than the area of the roof, ideally  $\frac{1}{4}$  the size of the total roof area, is more suitable for classifying the roof. There would possibly be four pixels recording roof values, avoiding the confusion of roof and vegetation reflectance values. Pixel sizes considerably smaller than the roof area could record variances in roof colors or structure, and therefore create confusion in classification. Thus the optimum size is a pixel size  $\frac{1}{4}$  the size of the roof area.

## CHAPTER 3

### METHODOLOGY

#### 3.1 Study Area

The study area for this research consists of the ten counties of the Capital Area Council of Governments, or CAPCO, located approximately in the center of the state of Texas (Figure 3.1). The study area is referred to as the CAPCO throughout the remainder of this paper.

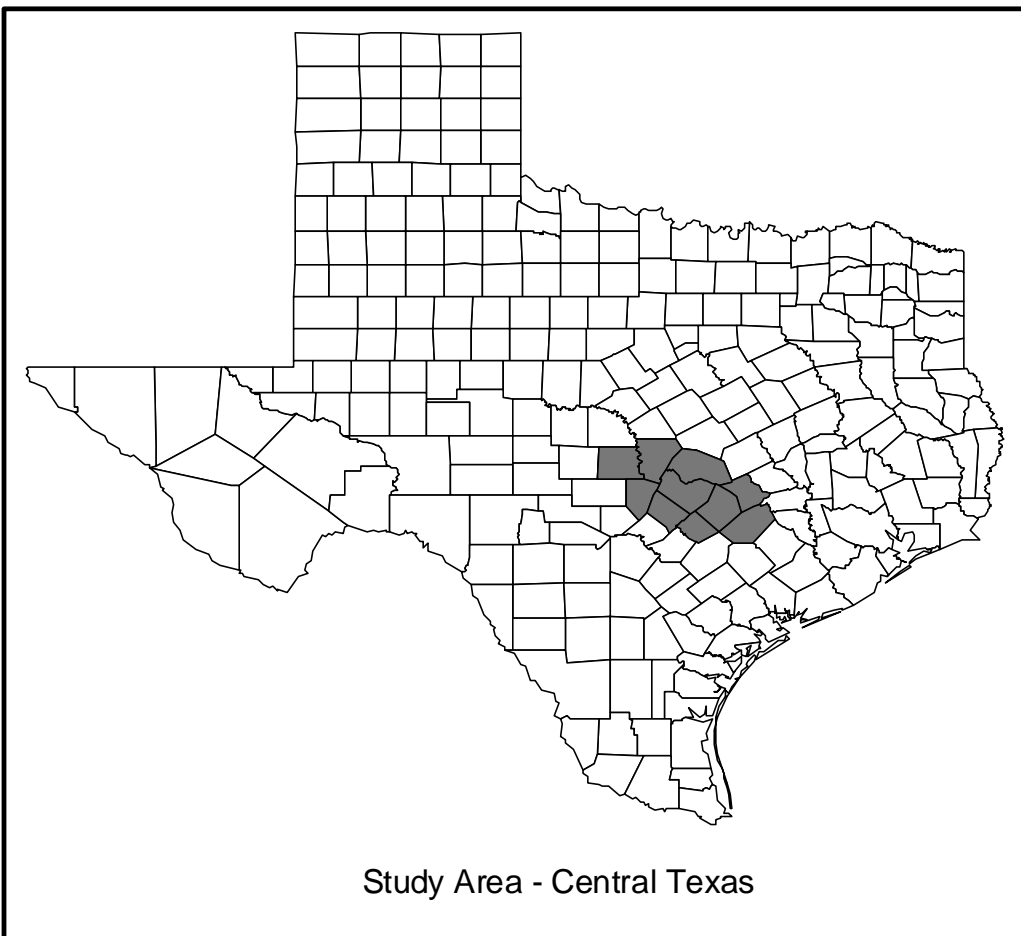


Figure 3.1 Study Area in Central Texas  
Source: ESRI, Inc. Data and Maps

Centered on the city of Austin, the ten counties of the CAPCO are Bastrop, Blanco, Burnet, Caldwell, Fayette, Hays, Lee, Llano, Travis and Williamson. The study area straddles U.S. Interstate 35; a transportation corridor that transects the region from north to south into eastern and western sections (Figure 3.2).

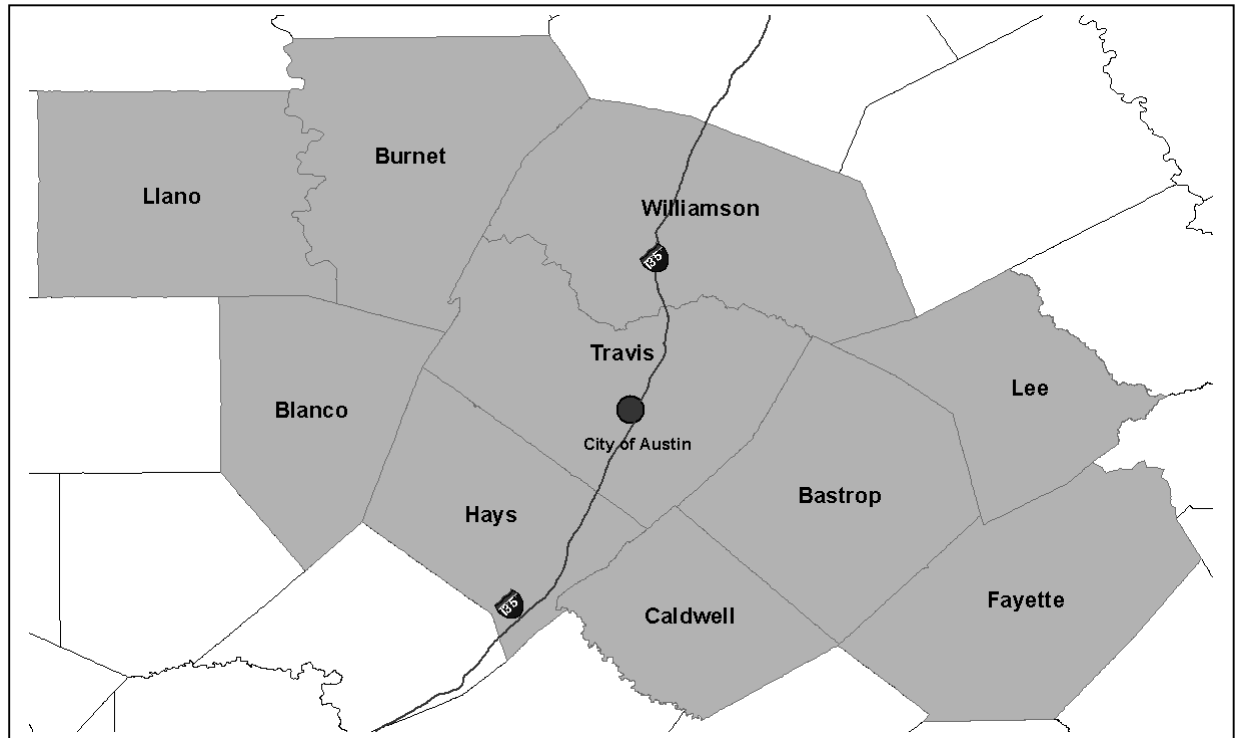


Figure 3.2 Ten Counties of the CAPCO Region  
Source: ESRI, Inc. Data and Maps

The CAPCO region is located within four broad “natural regions” as defined by the Texas Parks and Wildlife Department (TPWD, 2004): the Blackland Prairies and Oak Woods and Prairies to the east and the Edwards Plateau and the Llano Uplift to the west (Figures 3.3 and 3.4). The Blackland Prairie is characterized by gently rolling topography and thick, dark clays covered by grasslands and shrublands that stretch from the Texas Oklahoma border in the north to just south of the CAPCO region.



Running parallel with the Blackland Prairies is the savannah-like Oak Woods and Prairies, characterized by gently rolling patchy grasslands interspersed with large areas of deciduous trees (TPWD, 2004).

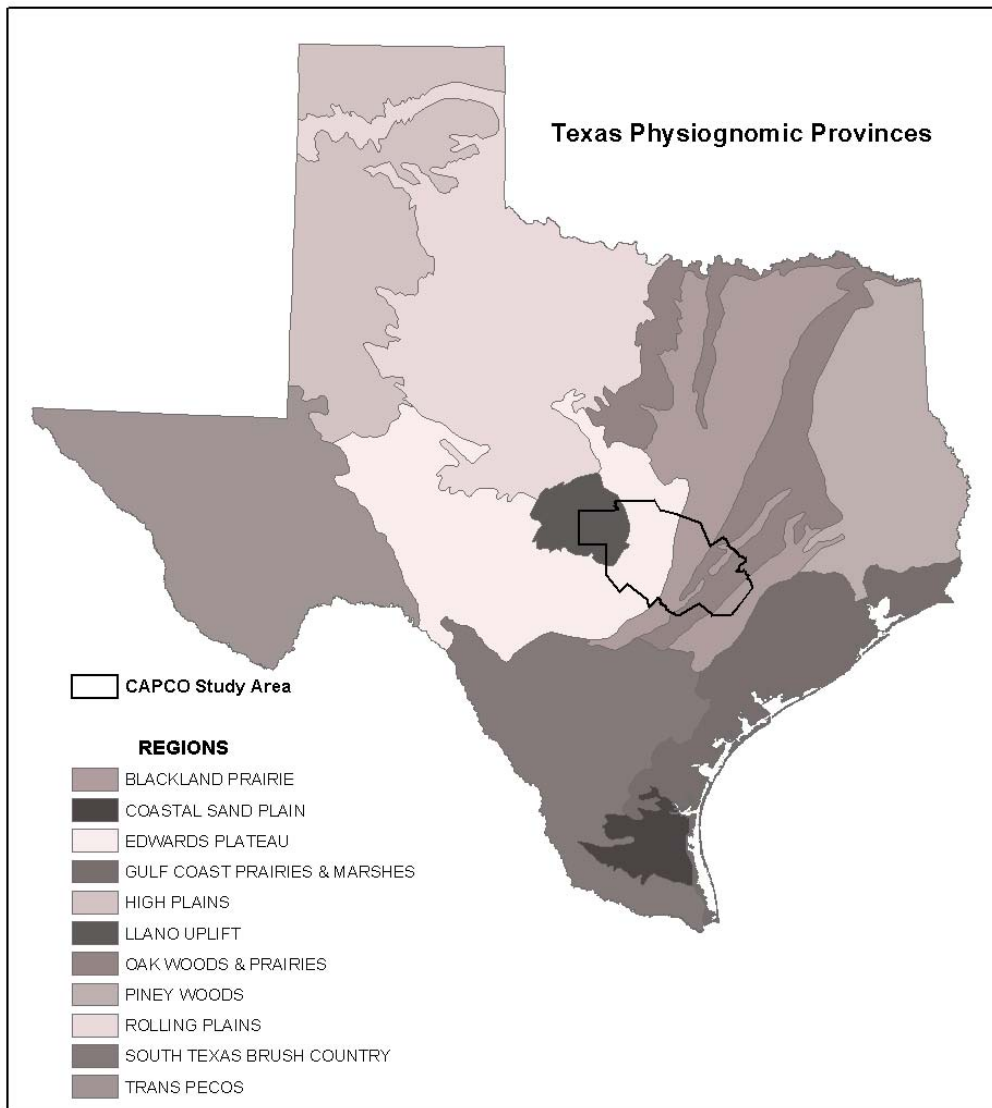


Figure 3.3 The Natural Regions of Texas (TPWD, 2004)

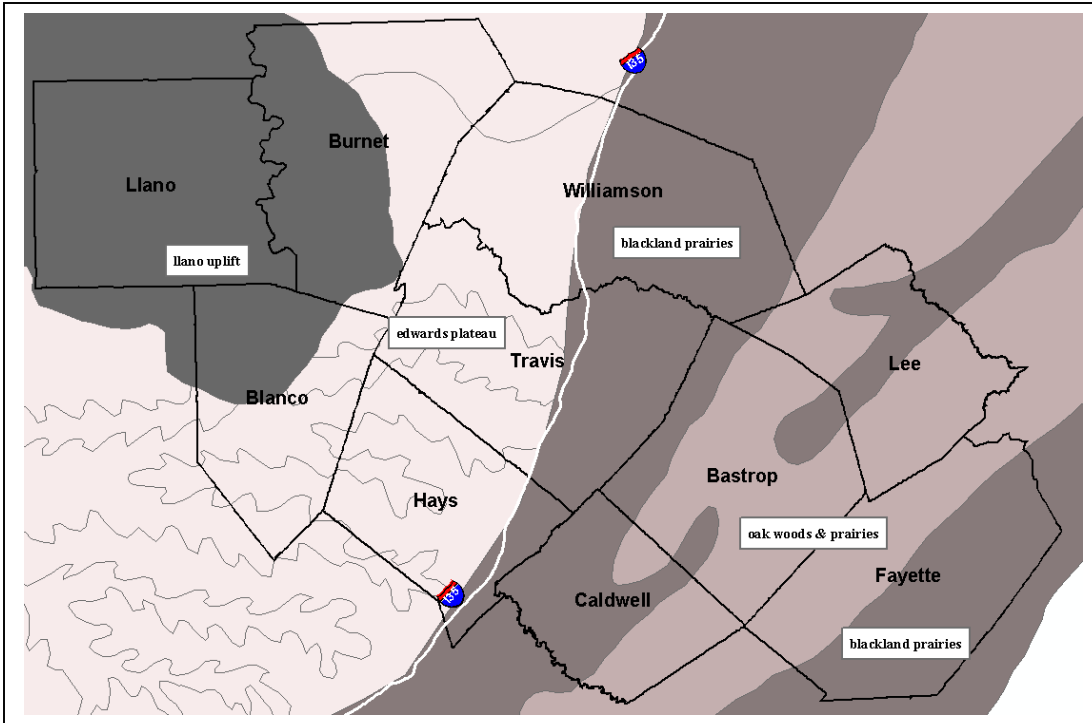


Figure 3.4 Natural Regions of the CAPCO (TPWD, 2004)

To the west of I-35 the land rises onto the Edwards Plateau. The plateau elevation ranges from 100 to over 3,000 feet and is dissected by several rivers systems, creating a rough landscape. This elevated area is characterized as a scrub forest association, dominated by Ashe juniper, Texas oak, mesquite and live oak. The plateau is transected west to east by numerous hills and canyons, known as the Balcones Canyonlands and further subdivided into the Lampasas Cut Plain in the northern portions of Burnett and Williamson Counties (Figure 3.5). To the west of the Edwards Plateau is the Llano Uplift, a highly eroded volcanic plug with elevations that range from 825 to 2,2250 feet above sea level (TPWD, 2004). Common vegetation types in the Llano are oak and oak-hickory woodlands along with scattered mesquite savanna.

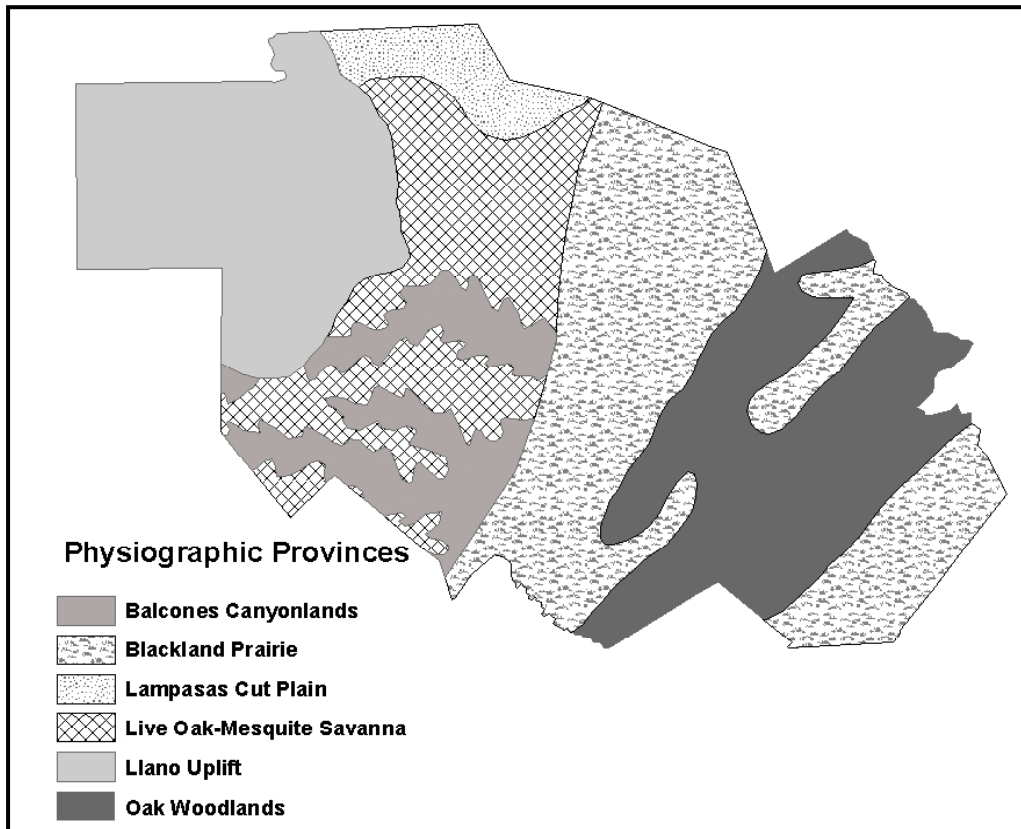


Figure 3.5 Subdivisions of the CAPCO Region (TPWD, 2004)

The following are descriptions of the general vegetation types of the CAPCO (McMahan, 1984) (Figure 3.6).

Grassland: Herbs (grasses, forbs, and grasslike plants) dominant; woody vegetation lacking or nearly so (generally 10 percent or less woody canopy coverage).

Forest: Deciduous or evergreen trees dominant; mostly greater than 30 feet tall with closed crowns or nearly so (71 to 100 percent canopy cover); midstory generally apparent except in managed monoculture.

Woods: Woody plants mostly nine to 30 feet tall with closed crowns or nearly so (71 to 100 percent canopy cover); midstory usually lacking.

Crops - Includes cultivated cover crops or row crops used for the purpose of producing food and/or fiber for either man or animals.

Parks - Woody plants mostly equal to or greater than nine feet tall generally dominant and growing as clusters, or as scattered individuals within contiguous grass or forbs (11 to 70 percent woody canopy cover overall).

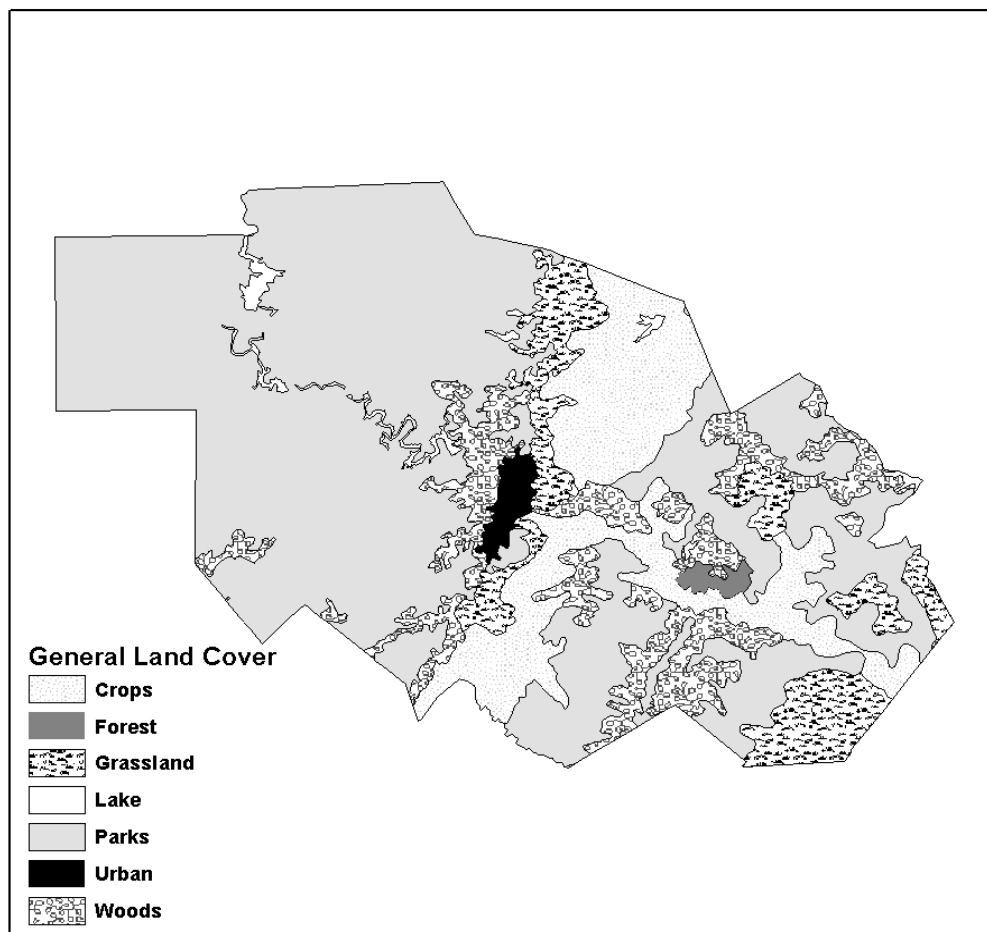


Figure 3.6. General Vegetation Types of the CAPCO (McMahan, 1984)

### 3.2 Urban Land Cover

Portions of the CAPCO are highly urbanized, particularly Travis and Williamson counties. The City of Austin is the capital of the State of Texas and has a population of 656,562 (U.S. Census, 2000). The next largest cities are Round Rock and Georgetown, with populations of 61,136 and 28,339 respectively. Travis County has 23 municipalities or incorporated areas and Williamson County has 16. The total population of the CAPCO region is 1,346,833 in 2000 (Table 3.1), (U.S. Census, 2000).

The majority of the counties has experienced greater than 40% growth in population in the decade 1990 to 2000 (Table 3.1). Population growth within the counties has resulted in an increase in housing units, with growth as high as 36,000 homes, a 65% change, in Williamson County (Table 3.2). This housing growth is particularly true for suburban areas within commuting range of Austin and the larger urban areas north along the I-35 corridor.

A major effect of large population growth in central Texas is typical of many other U.S. metropolitan areas. As property values increase in the central urban areas, people move further into the hinterland, seeking more affordable housing. Over the past decade, the City of Austin proper population grew by 190,914, whereas the incorporated populations within 30 miles of the center of Austin (Figure 3.7) grew by 128,592, or 67% of that of Austin. Much of this growth has taken place in small towns and communities, but numerous developments have sprung up within previously "natural areas;" fields, range, brush and forested area. Housing in these suburban

developments is often low-density, with large lots and extensive natural vegetation.

This suburban growth is the Wildland Urban Interface.

Table 3.1. Population Data for CAPCO, 1990 - 2000 (US Census, 2000).

County Name	1990 Census	2000 Census	Change	Percent Change	1990 Population Density (per sq. mile)	2000 Population Density (per sq. mile)
<b>Bastrop</b>	38,263	57,733	19,470	50.9%	42.7	64.4
<b>Blanco</b>	5,972	8,418	2,446	41.0%	8.4	11.8
<b>Burnet</b>	22,677	34,147	11,470	50.6%	22.2	33.4
<b>Caldwell</b>	26,392	32,194	5,802	22.0%	48.3	58.9
<b>Fayette</b>	20,095	21,804	1,709	8.5%	20.9	22.7
<b>Hays</b>	65,614	97,589	31,975	48.7%	96.6	143.7
<b>Lee</b>	12,854	15,657	2,803	21.8%	20.3	24.7
<b>Llano</b>	11,631	17,044	5,413	46.5%	12.1	17.7
<b>Travis</b>	576,407	812,280	235,873	40.9%	563.2	793.5
<b>Williamson</b>	139,551	249,967	110,416	79.1%	123.4	220.4

Table 3.2 Housing Units in the CAPCO Region, 1990 - 2000 (US Census, 2000)

County Name	1990	2000	Change – 1990-2000	Percent Change
<b>Bastrop</b>	16,301	22,254	5,953	36.5%
<b>Blanco</b>	3,135	4,031	896	28.6%
<b>Burnet</b>	12,801	15,933	3,132	24.5%
<b>Caldwell</b>	10,123	11,901	1,778	17.6%
<b>Fayette</b>	10,756	11,113	357	3.3%
<b>Hays</b>	25,247	35,643	10,396	41.2%
<b>Lee</b>	5,773	6,851	1,078	18.7%
<b>Llano</b>	9,773	11,829	2,056	21.0%
<b>Travis</b>	264,173	335,881	71,708	27.1%
<b>Williamson</b>	54,466	90,325	35,859	65.8%

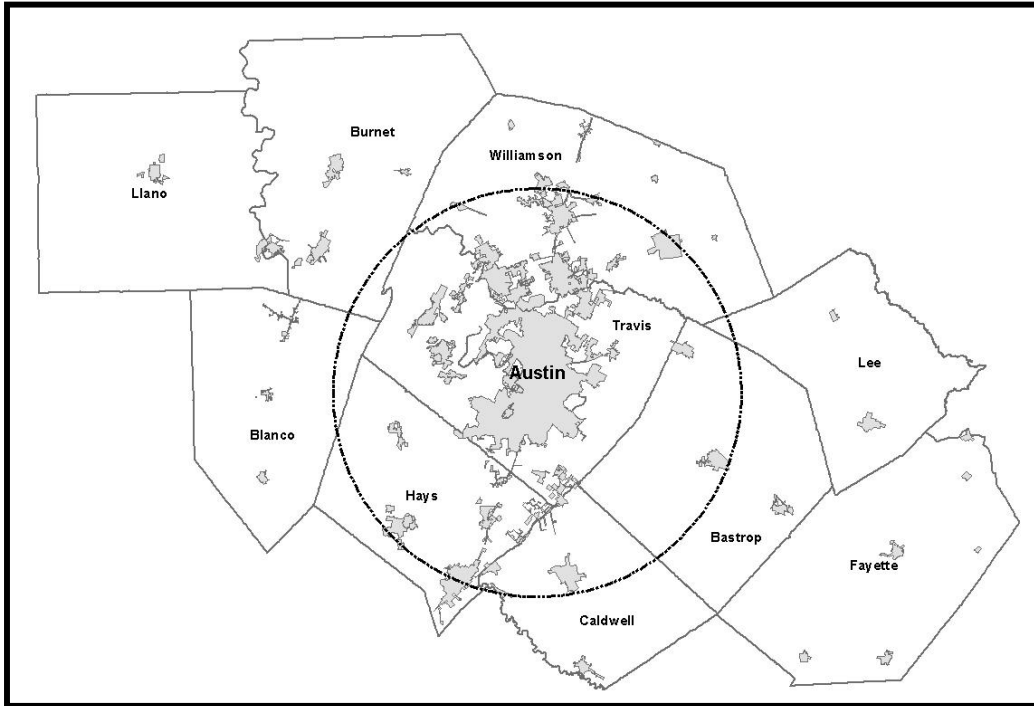


Figure 3.7 30-Mile Radius Around Austin, Texas  
Source: ESRI, Inc. Data and Maps

### 3.3 Model Concepts

In 2002, the City of Austin Fire Department received a grant from the Federal Emergency Management Agency (FEMA) to evaluate the western portion of the City of Austin and Travis County for potential risk from wildland fire. After reviewing wildland fire risk assessment projects from eight U.S. cities, Fire Chief Kevin Baum decided that GIS was the most appropriate vehicle by which to construct an assessment model. The result was the "Urban-Wildland Interface Risk Model for the West Austin / Travis County Study Area," a GIS-based model developed by Kevin Baum, Christine Thies, and Karen Kilgore (Baum et al, 2003).

The conceptual framework for the model was initially constructed with input from WUI experts from the Texas Forest Service, City of Austin Fire Department, U.S. Forest Service, the Texas Nature Conservancy, and others (Baum et al, 2003). The consensus of the participants was that the elements of risk for wildland fire consist of three major variables: spatial, human and temporal. Each variable is comprised of multiple types of information, weighted according to importance of input.

The spatial variable determines the potential to burn and consists of topography and fuels data. Topography, specifically slope and aspect, contribute to fire behavior. Fuels on steep slopes typically burn faster than lower slopes. South facing slopes are often dryer than north aspects, an important factor in fuel moisture. Fuel types, as specified by the Anderson Fuel Model classification scheme, drive flammability, speed of travel, and heat intensity. Grasses, or fine fuels, burn rapidly with high rate of spread as opposed to heavy, woody fuels that burn slower but with greater heat release.

The temporal variable defines the potential for ignition and fire reaction intensity. Weather is the driving factor in the temporal variable, with four input factors: Keetch-Byram Drought Index (KDBI), Energy Release Component (ERC), ignition component, and the 1000 hr. dry fuel model. The weather component for the model is the mean value for each input factor computed over a 28 day-day cycle.

The human variable reflects potential consequences of a wildland fire on human assets. The variable relies on information from four factors: combustible materials used in construction, emergency response times, defensible space around combustible structures, and access to water supply (Table 3.3).



Table 3.3 City of Austin Fire Risk Model Variables and Weighting Scheme (Baum et al, 2003)

Category of Variables Temporal	Category of Variables Spatial	Category of Variables Human
Potential for Ignition Fire Reaction Intensity	Potential to Burn	Potential Consequences
Current and Historical Climate Data (NFDRS Outputs)	Existing Fuel and Topographic Data	Existing Data on "Assets" and Human Values
Tv = Mean Temporal fluctuations in climate by 28-day cycle:  Tv1 = KDBI .....11% (Long term moisture cycle)  Tv2 = ERC/Burn Index (reaction intensity).....49%  Tv3 = Ignition Component (fuel ignitability) .....15%  Tv4 = 1000 hr Dead Fuel Moisture (drought cycle) .....25%	Sv = Fuels and Topo modeling by remote imagery and field research:  Sv1 = % Slope .....36% (fuel arrangement vis. products of combustion)  Sv2 = Aspect .....17% (mesic vs. zeric fuels)  Sv3 = Anderson Fuel Model .....47% (Models 1,2,4,6,9)	Hv = Human Vulnerability by GIS spatial analysis and field research:  Hv1 = Combustible construction .....35%  Hv2 = Mean response time .....20% < 5 minutes 6 – 15 minutes > 16 minutes  Hv3 = Mean distance of defensible space .....25%  Hv4 = Water supply within 1000 ft. (Yes/No).....20%
380 Total Points	420 Total Points	200 Total Points

Input data for the Austin model included vector data in six types: fire hydrants, defensible space around homes, response time from fire stations, home construction materials, fuels, and average monthly weather. Topography data were used to produce raster files for slope and aspect. The model was conducted in raster format, so all vector files were converted into raster files for combination in an overlay analysis. Modeling was conducted in ESRI, Inc. ArcView™ 3.2 software using the Model Builder extension.

A map for the western portions of the City of Austin and Travis County was produced showing wildfire risk to structures based upon the input variables and the weighting scheme. Although the Austin model produced results at a fine spatial scale based upon a sophisticated mix of input variables and weights, the difficulty with the model is that vegetation/fuels required hand digitizing from orthophotogrammetric images, structure materials were recorded for blocks of houses based upon field work by structural firefighters, and fire hydrant locations were mapped through field work. The model required extensive fieldwork and many hours of labor by individuals, thus it was expensive and time consuming to create.

Another shortcoming of the Austin model is the weather component. The model calculates potential risk based upon current and historical monthly weather records for moisture levels and ignitability of fuels. The model determines that the highest risk for the study area is during the months of July and August, months that are typically hot and dry (Baum et al., 2003). However, many of the destructive wildfires that have occurred in Texas in the past decade have been during the winter months when fuels are senescent and dry, windy cold fronts are common.

The Oklahoma Fire Danger Model is a model that uses real-time automated weather data coupled with AVHRR satellite data to compute potential fire danger for the whole state of Oklahoma on an hourly basis. The model has been in operation since 1996 and has been able to identify areas of the state that have been under high fire danger warnings due to hot, dry weather conditions. All models have limitations. Although this particular model is very suitable for statewide application and is

constructed to automatically run using real-time weather data, the very nature of the spatial extent of the data imposes limitations on a more local scale. AVHRR satellite imagery has a spatial resolution of 1 Km x 1 Km, thus the fire danger is a “broad-brush” approach. The model, not unlike most other fire danger models, is only based upon surface fuel models and does not apply to crown fires. The slope input is limited to 0-25% and thus the model is unable to identify steep terrain that might contribute to dangerous fire conditions. The model is designed for predominant vegetation fuel models over a 1-km square grid with low slopes (OCS, 2004; Carlson, 2005).

The methodology of this current project attempts to overcome some of the shortcomings of the Austin and Oklahoma models. In order to extend the model over a 10-county area, it is impractical and cost prohibitive to use numerous individuals to conduct fieldwork and hand digitizing of fuels. Also, the new model attempts to integrate current weather so that it is dynamic and calculates current threat potential.

This research project is not intended to replace the Austin model but rather to extend the concept of threat identification over a larger area than Austin, in real-time mode using methodology that is cost effective and easier to replicate. The Oklahoma model, which uses real-time weather data and satellite imagery, is a template for the new model. The new model, however, strives to determine threat on a finer scale and with greater application to WUI and local natural resources.

### 3.4 Model Design and Construction

Methodology for this research within the CAPCO study area concentrates on four major categories: Fire Behavior, Ignition Source, Threat Targets, and Emergency Response. The Fire Behavior component is comprised of three subcomponents: Fuel Models, Topography, and Weather (Figure 3.8). All of the components are based upon geospatial data containing attribute information about specific locations within the CAPCO.

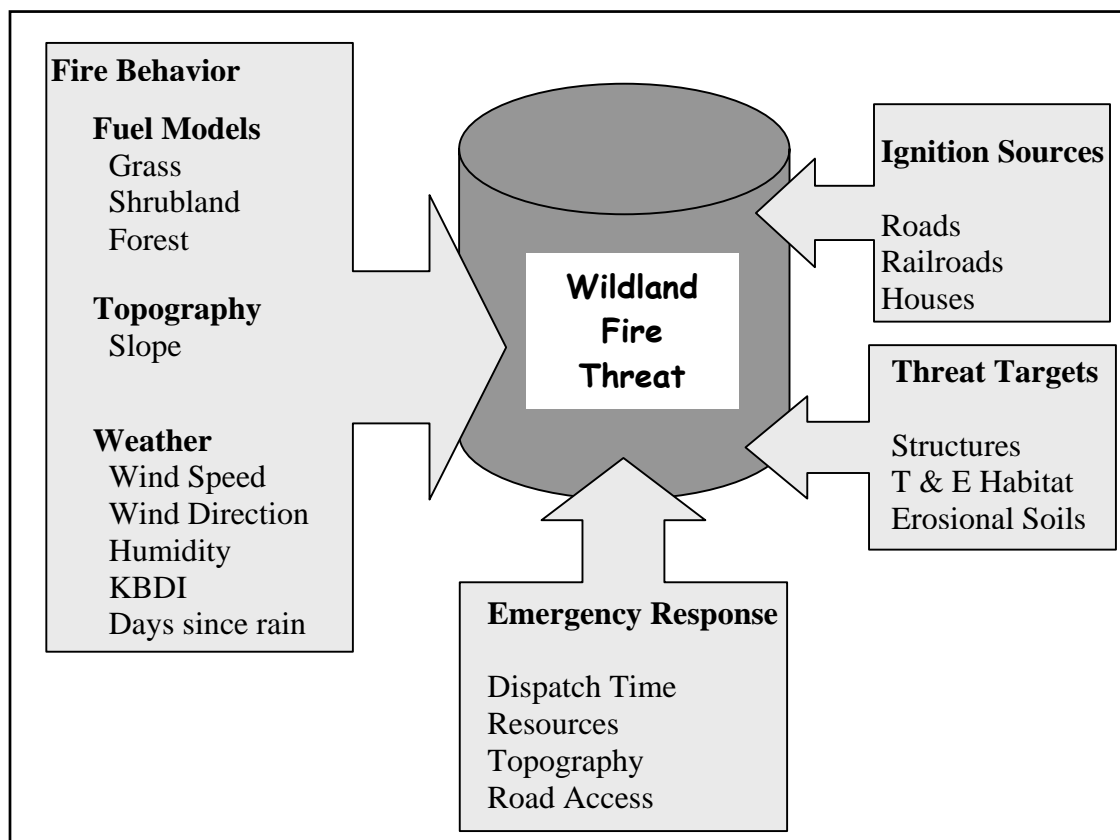


Figure 3.8 Wildland Fire Threat Model Design Components

Details of the methods of construction of the threat model follow the flow chart in Figure 3.9: data collection, remote sensing of satellite imagery to determine land cover, preparation of base GIS data, calculation of potential fire behavior based upon real-time weather, interpolation of fire behavior, integration of fire behavior and GIS layers, model output.

### 3.5 Data Collection

Data were obtained from a series of sources, the majority of which were available on the Internet from the Capitol Area Council of Governments (CAPCO, 2004) and the Texas Natural Resources Information System (TNRIS, 2004). The following table (Table 3.4) lists data types and sources.

GIS data used by municipalities and counties are typically projected in State Plane Coordinate System (SPCS), North American Datum 1983 (NAD83) and units in feet. The majority of the GIS layers for the project were obtained from CAPCO and thus the SPCS projection format was chosen as the standard for the project. All other geospatial files, such as imagery, DEM and fire station location, were converted into SPCS format after initial processing.

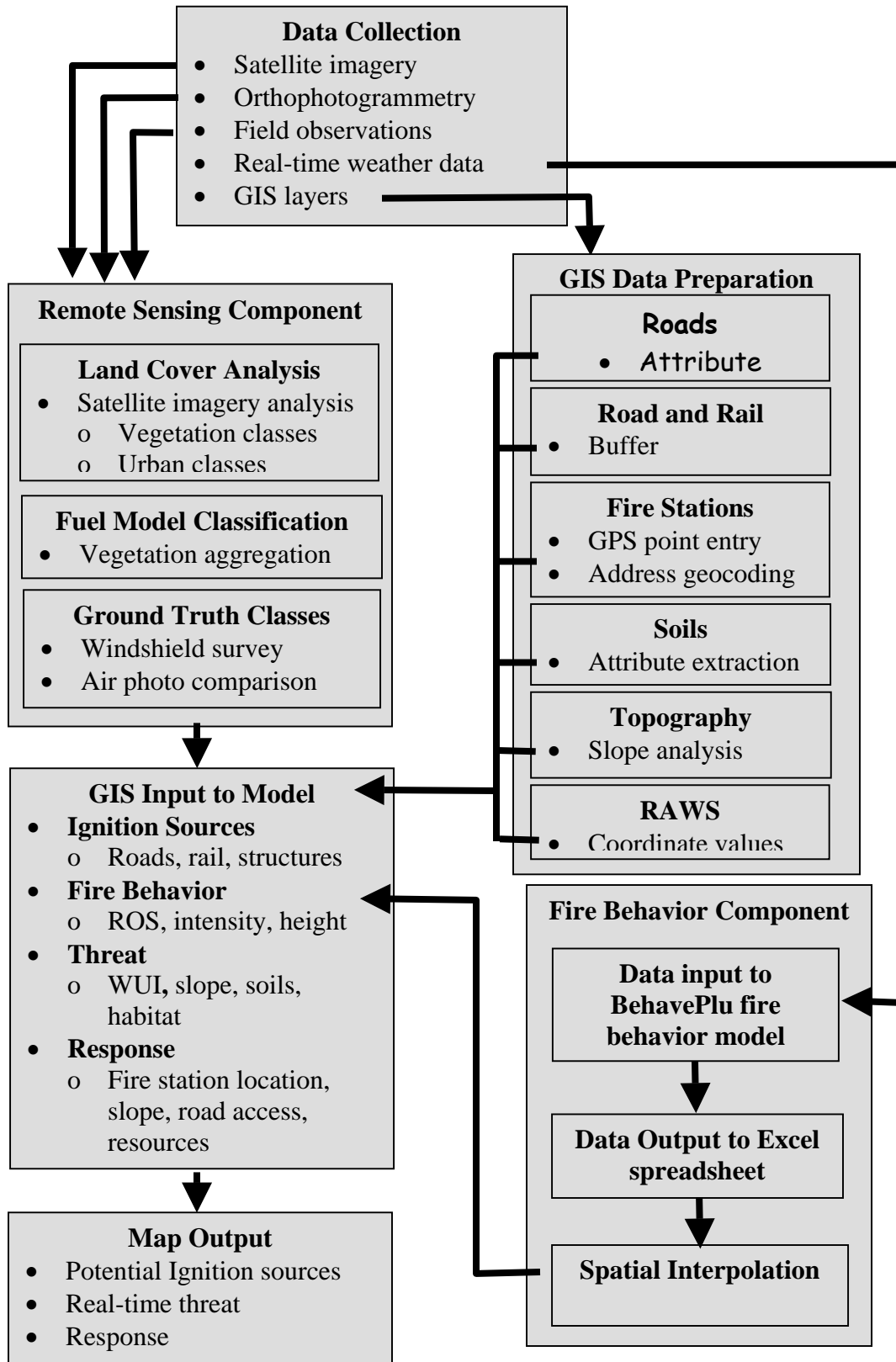


Figure 3.9 Sequence of Steps in Model Development

Table 3.4 Data Types and Sources

Data	Format notes	Date	Source
Landsat 7 ETM+ Imagery	NLAPS 30M x 30M Res.	2001	TNRIS – CSR/Univ. of Texas
IKONOS Satellite Imagery	GeoTIF 4M x4M Res.	2003	Space Imaging, Inc.
DOQQ - Photography	Mr. SID 2 ft. Res.	2003	CAPCO GIS Data Center
GAP Analysis land cover classes	ESRI Grid 90M x 90M Res.	1993	U.S.G.S. -Texas Tech Univ. GAP Analysis
Ground truth data	Field notes	2003	Texas Forest Service, Bastrop
Digital Elevation Model	DEM 30M x 30M Res.		U.S. Geological Survey
Topographic Quad Maps	GeoTIF 1:24,000	1970s	U.S. Geological Survey
Streams and Reservoirs	ESRI Shapefile		TNRIS - STRATMAP
Roads	ESRI Shapefile		CAPCO GIS Data Center
Railroads	ESRI Shapefile		CAPCO GIS Data Center
City boundaries	ESRI Shapefile		CAPCO GIS Data Center
County boundaries	ESRI Shapefile		CAPCO GIS Data Center
EMS Boundaries	ESRI Shapefile		CAPCO GIS Data Center
Soils	ESRI Shapefile		U.S.D.A.- N.R.C.S.
Census	ESRI Shapefile	2000	U.S. Bureau of the Census
Watersheds	ESRI Shapefile	2004	City of Austin, Texas
KBDI & NFDRS	Map from Website	Real-time	SSL/Texas A&M University
Weather data	Text from Website	Real-time	RAWS/TICC/TX A&M Univ.
T&E and Rare Species			Texas Parks and Wildlife
Fire Stations	GPS and addresses	2004	Texas Forest Service

### 3.6 Remote Sensing Component

#### 3.6.1 Land Cover Analysis

The fire behavior input to the threat model is comprised of three major components: fuels, topography and weather. Fuels are based upon vegetation classes identified through land cover analysis using remote sensing techniques and satellite imagery. Land cover analysis was conducted using NASA Landsat Enhanced Thematic Mapper (ETM) 7+ and IKONOS (Space Imaging, Inc.) satellite imagery. Aerial orthophotogrammetry was used to check land cover classes and for imagery

registration. Landsat imagery was obtained in National Land Archive Production System (NLAPS) Terrain Correction (Level 1G), which includes radiometric and geometric correction (USGS, 2005).

The long axis of the study area is oriented in an east/west direction along a single Landsat grid Row 39. However, the width of the study area required three ETM satellite image paths: 26, 27 and 28 (Figure 3.10). A total of seven ETM images were used; multiple dates were obtained for the three paths. Multiple dates allowed for image processing with "leaf-on" and "leaf-off" to improve vegetation and urban classification. Deciduous vegetation is more readily classified during the growing season (leaf-on) when it has canopy cover. Urban signatures are generally more obvious during winter months (leaf-off) when constructed materials can be seen more easily.

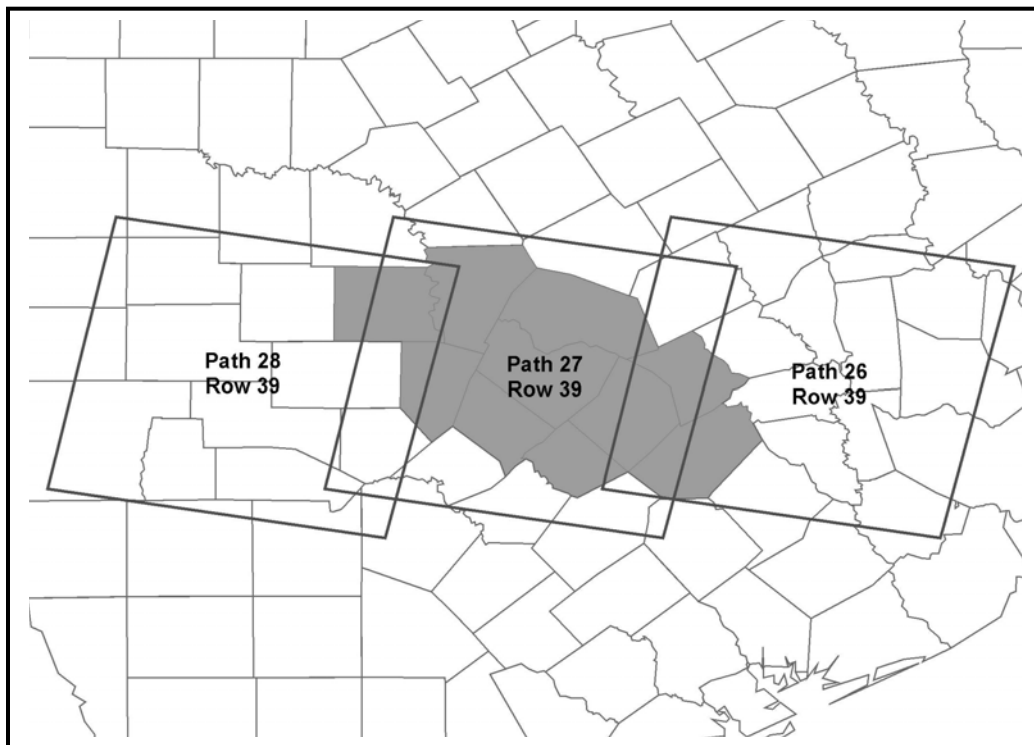


Figure 3.10 Landsat 7 Images Path and Row



The Landsat 7 ETM imagery consists of eight bands: bands 1-5 and 7 at 30-meter resolution, band 6 at 60 meters and band 8, a panchromatic band, at 15 meters. For this project, only bands 1 – 5, three visible bands and two near infrared, were used. One of the advantages of using Landsat is that the range provided by five spectral bands provide greater information for signature separation and land cover classification (Jensen, 1996). The spectral resolution advantage is somewhat offset by the moderate spatial resolution at 30 meters. The smallest area on the ground that can be captured by Landsat 7 is approximately  $\frac{1}{4}$  acre in size, a limitation when identifying urban features.

IKONOS satellite imagery was chosen for comparison of classification suitability because of its high spatial resolution at 4 meter. The data consist of 3 spectral bands: two visible (green and red) and one near-infra red. The finer spatial resolution image is more suitable than Landsat imagery for capturing urban features but the narrow spectral range is limiting for land cover class separation. A 30-meter Landsat pixel is generally far larger than the footprint of an average building. An IKONOS pixel, on the other hand, at 4 meters square, can easily fit within the expanse of a roof or driveway. This smaller IKONOS spatial resolution permits several pixels to record urban features such as rooftops and parking lots (Kuo et al., 2001). Figure 3.11 offers a comparison of pixel sizes in relation to a roof of a structure.

Unsupervised classifications were performed on the Landsat and IKONOS imagery. The initial unsupervised classification of the raw, 5-band data Landsat images assigned all pixels to one of 25 classes. The remote sensing software, ERDAS Imagine

(Leica, 2004), performs an unsupervised classification using the ISODATA algorithm, an iterative process that uses the minimal spectral distance between values in the 5 bands to create clusters of values. The iterative process repeats until the specified number of iterations is complete, in this case 6 times, or a maximum percentage of unchanged pixels has been reached between two iterations (Leica, 2004).

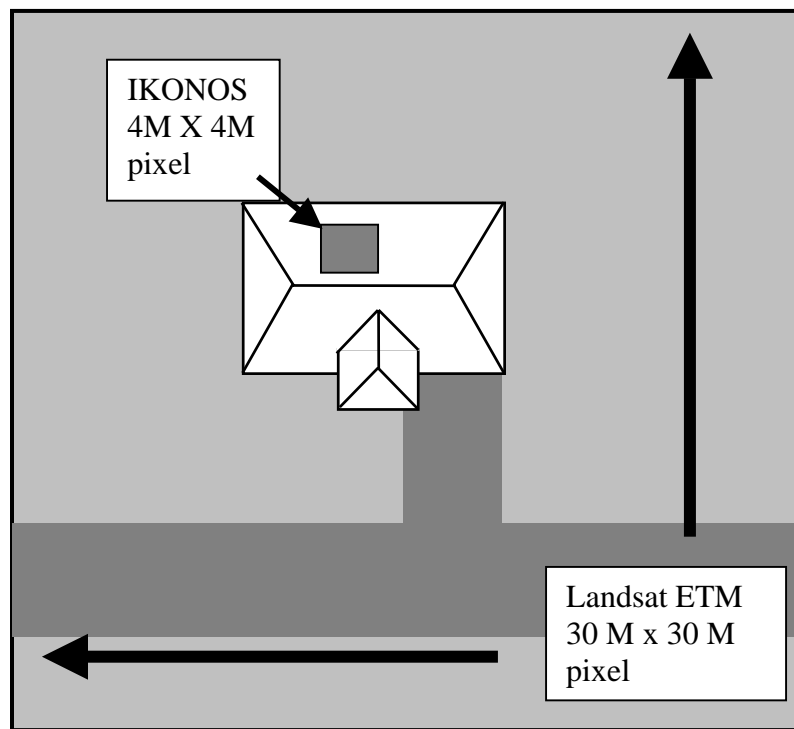


Figure 3.11 Comparison of Landsat and IKONOS Pixel Size.

The advantage of using an unsupervised technique is twofold. The first advantage pertains to the low number of classes needed to identify fuel models, water and impervious areas representing urban development. The second advantage is that this classification method is relatively easy to perform and can be reproduced using shareware remote sensing software and little training. One of the goals of this project is

to create methodology that can be easily reproduced by personnel with minimal training and inexpensive or free software, such as Multispec (Landgrebe and Biehl, 2004).

### 3.6.2 Fuel Model Classification

Once the unsupervised classification was performed, the 25 classes were assigned to one of six classes: water, Fuel Model 1 (Grasses), Fuel Model 4 (Shrub), Fuel Model 6 (Shrub), Fuel Model 10 (Forest Litter), Impervious. For purposes of this project, the Impervious class served as a surrogate for urban areas due to the large area of rooftops, parking lots and roads associated with development. The Impervious class also included bare surfaces such as might be found in agricultural fields during certain times of the year or bare soil in new urban developments. Bare and impervious land cover types do not function as fuels in the model but can be included in the "Target" category for fire threat.

An additional unsupervised classification using 100 classes was performed on all Landsat images in an attempt to further the division of vegetation types into fuel models. The 100-class unsupervised images were reclassified into 6 classes as above. Reclassification of the unsupervised images was performed by visually comparing locations within the classified images to the same locations within digital orthophotography obtained from the CAPCO GIS department. The scale of the Landsat images and the orthophotographs were mismatched (30 meter resolution vs. 2 foot resolution) but the greater detail of the aerial imagery allowed for excellent identification of vegetative cover and thus translation into fuel models. A total of 704

images, representing 176 USGS quad sheets of orthophotography, were downloaded for use in classification, however only a small number of quads were actually used. Quads were chosen from across the study area to represent the different vegetation covers that exist on an east to west gradient as seen in Figure 3.6.

### 3.6.3 Classification Test

Fuel model classification accuracy was tested through comparison with orthophotography, land cover information collected by the Texas Forest Service, and fieldwork. A total of 100 points were compared using within five USGS quad sheets scattered across the study area. Land cover information collected for a Texas Forest Service study conducted in Bastrop State Park (Kilgore, 2004) was used to compare classification in that area. Also, fieldwork and windshield surveys were conducted with Texas Forest Service personnel to confirm fuel model definitions and land cover classifications (Kilgore, 2004).

Urban classification results for Landsat and IKONOS satellites were also compared to orthophotography. Urban land cover was lumped with bare soils, concrete and asphalt surfaces due to the generally high spectral reflectance values of the surface materials.

### 3.6.4. Image Registration

Landsat and IKONOS imagery were originally obtained in UTM NAD83 coordinate system in units of meters. Elevation and soils data were obtained in Geographic

coordinates, NAD83. All GIS obtained from the CAPCO GIS center were in State Plane Coordinate System (SPCS), NAD83, with units of feet. This is typically the standard coordinate system for county and municipal GIS projects within the state of Texas. Since the majority of the initial layers were in SPCS and it was expected that the results fire model layers would be delivered for county and municipal use, the imagery, elevation and soils data, RAWS and fire station locations were all converted to SPCS.

All of the satellite imagery was obtained in Level 1G correction that, in relatively flat topography as the study area, demonstrated very good registration when overlaid onto the digital orthophotography (DOQQ). Shorelines and rivers were specifically checked, as the clear distinction between land and water show up clearly in DOQQs and satellite imagery alike and permit good comparison of registration. A series of checks were made for DOQQs throughout the study area and the registration was determined to be very adequate, particularly considering the difference in resolution (2 feet vs. 30 meter pixels).

### 3.7 GIS Data Preparation

Many of the data layers acquired from the CAPCO GIS Center and federal government sites required little alteration, except for attribute extraction, for use in the methodology. Streams, lakes, and county boundaries were used in the downloaded format. Roads, railroads, municipal boundaries, soils, digital elevation model (DEM), fire stations, and Remote Automated Weather Station (RAWS) data required modification before use.

### 3.7.1 Road and Rail

Humans are the source of the majority of wildland fires in the eastern half of Texas. The Texas Forest Service reports that 94% of ignitions within Texas are caused by human action (Weaver, 2005). Fires are typically caused by cigarettes thrown from vehicles, hot catalytic converters on cars stopped on the shoulders of roads, sparks from the wheels of railroad cars, trash burning in yards, air conditioning units, and arson. Ignition sources from roadways, rail lines and houses are therefore typically located within proximity of transportation lines. For this study, a buffer of 200 feet was created around all named roads extracted from road layers and within the same distance of rail lines (Figure 3.12). The 400-foot buffer on each side represents approximately a 2-acre depth. The buffer represents both an area of possible ignition and the most likely area that structures are found – the potential target of wildfire.

Road buffers were merged together by dissolving common boundaries to create large areas where roads were located within 400 feet of each other. In addition, island polygons smaller than 20 acres outside of the buffer zone were merged with the buffer (Figure 3.12). The reasoning behind this step was that small areas surrounded by roads are highly influenced by the roads and are therefore likely to be an ignition source or a target area.

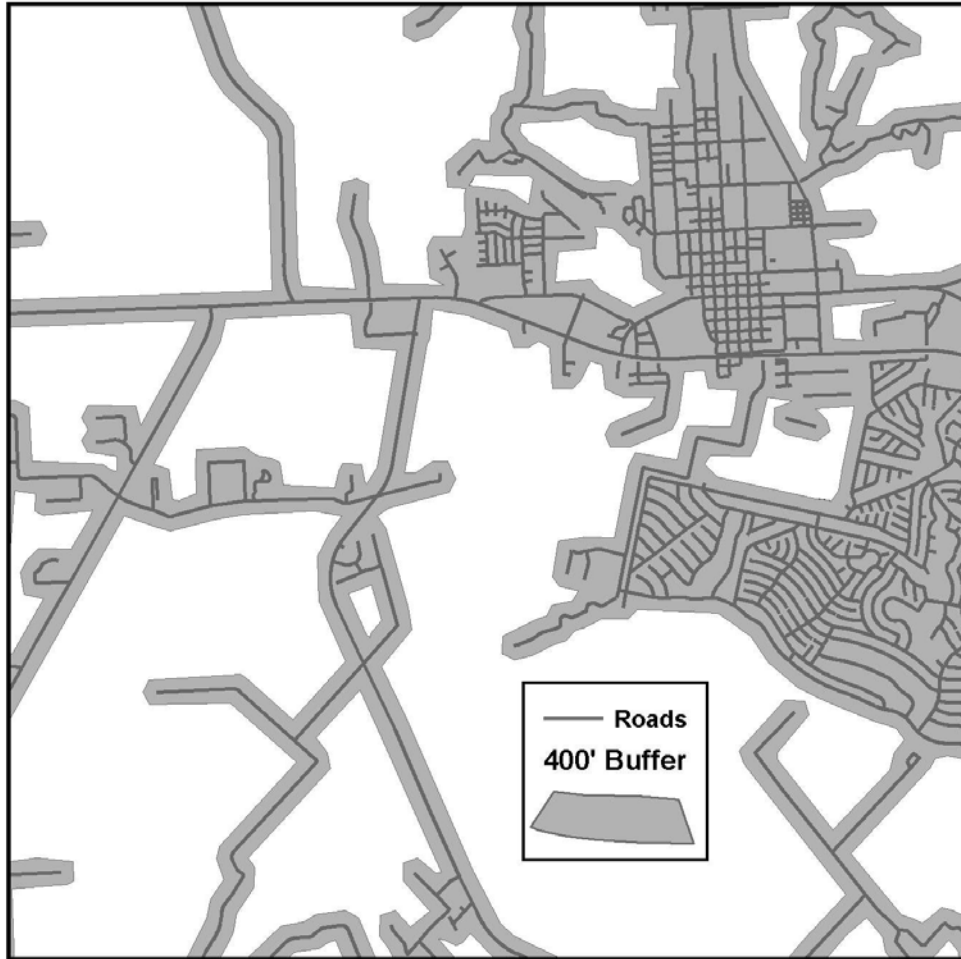


Figure 3.12 400 ft. Buffer Around Named Roads

### 3.7.2 Slope Analysis

Slope analysis was conducted using raster elevation data from U.S.G.S. National Elevation Dataset (NED) for the study area. The NED is a seamless elevation format for the whole of the continental U.S. and consists of merged 1:24,000 scale U.S.G.S. Digital Elevation quad sheets. The majority of the coverage for the CAPCO study area consists of 10-meter (1/3 arc second) cells, but the southern portion of Bastrop County and

Fayette County consist of 30- meter (1 arc second) cells (USGS\_SDDS, 2005). The elevation ranges from 42 meters in the southeast of the CAPCO to 674 meters in the far west (Figure 3.13).

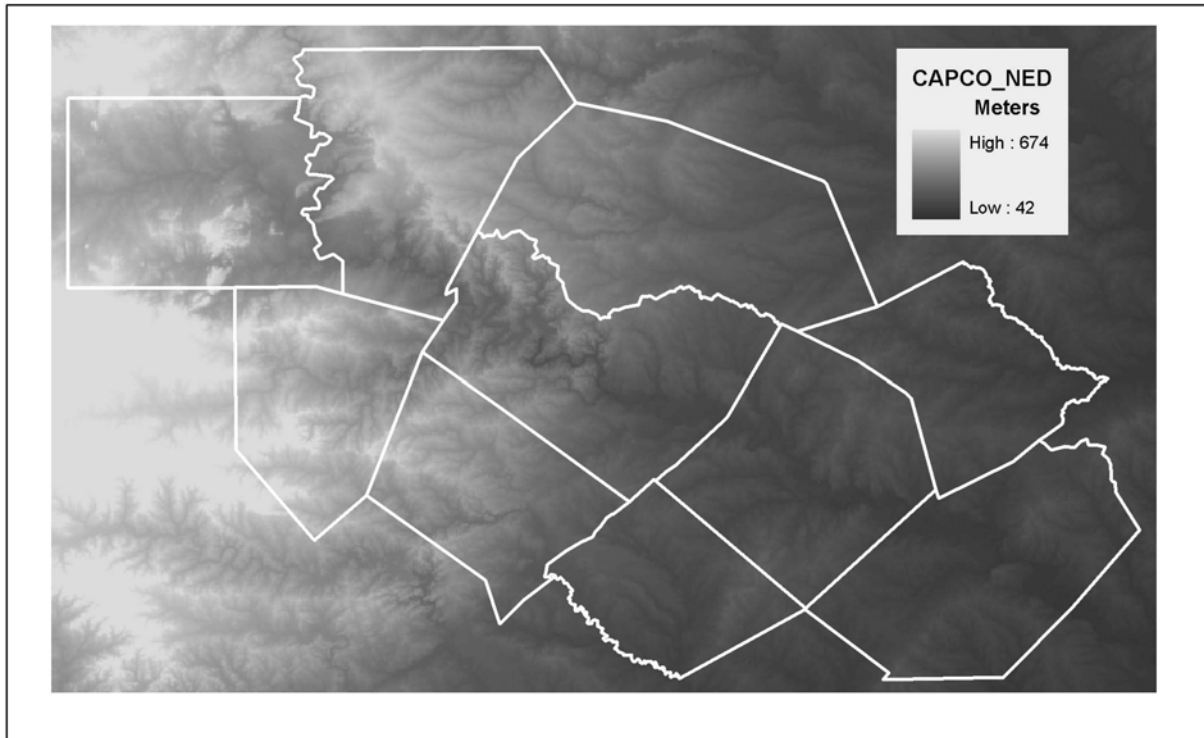


Figure 3.13 Elevation Range Across Study Area

The slope for each raster cell was calculated using the SLOPE function in the Spatial Analyst extension of ESRI, Inc. ArcGIS™ 9.0 software. The output slope values were reclassified into six classes: 0%, 1-25%, 26-40%, 41-55%, 56-75%, and > 75%. This slope classification scheme follows the slope classes used in the National Fire Danger Rating System (NFDRS) calculator in use by numerous federal and state fire agencies (Bradshaw and McCormick, 2000). The six classes were further aggregated into three qualitative categories, low, moderate and high, for use in the GIS model.



### 3.7.3 Soil Data

Digital soil series data for the ten county study area were obtained from the U.S.D.A. Natural Resources Conservation Services (NRCS) National Muir database website (NRCS, 2004). Download files contain ArcGIS™ shapefiles of soil series polygons for each county plus a Microsoft Access database of ancillary data pertaining to individual soil types. An Access template provides an interface to extract attribute data for soil types and generate reports. For example, the template allowed the extraction of information on "Damage by Fire and Seedling Mortality on Forest land" for soil types within Bastrop County (Figure 3.14). The report displayed potential fire damage levels for all soil types selected (Table 3.5).

Information concerning potential fire damage, potential erosion hazard on off-road and off-trail soils, and soil erosion K factor was extracted for each soil type within the CAPCO. These attributes were added to the soils shapefiles for integration into the GIS analysis.

### 3.7.4 Fire Station Locations

In an effort to determine emergency response coverage from paid and volunteer fire departments throughout the study area, a shapefile of locations was created using longitude and latitude coordinates collected by Global Positioning System (GPS) receivers and address geocoding from U.S. Postal Service addresses. Bastrop and Fredericksburg Texas Forest Service Regional Fire Coordinators provided location information concerning fire stations. (Kilgore; Hamrick, 2004).

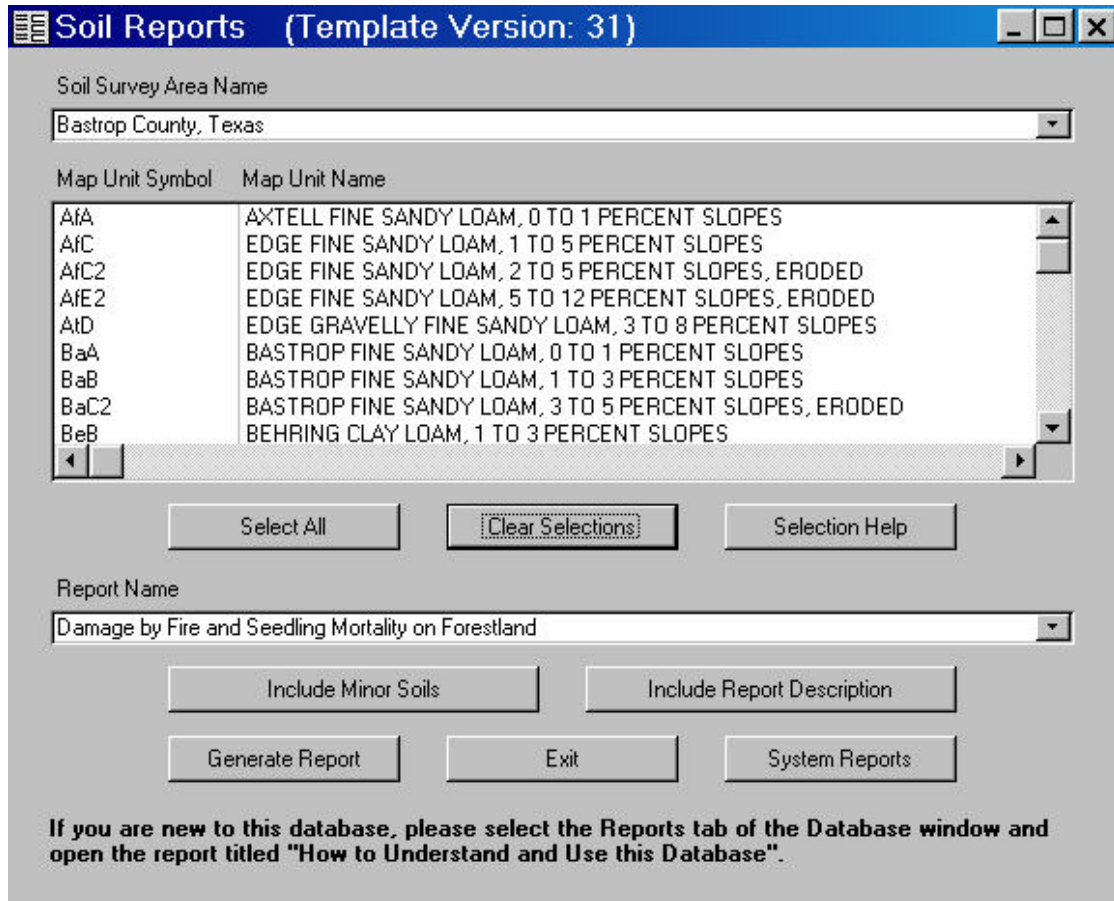


Figure 3.14 Microsoft Access Template for Soil Series Attribute Data

Five-mile buffers were created around each one of the fire station locations and overlapping buffers dissolved. The 5-mile distance is greater than the 2½-mile radius from fire stations used by Insurance Services Office (ISO) for calculating insurance rates for homeowners (Gray, 2005). This distance was chosen as a surrogate for response time by road for volunteer fire services. Gaps between buffers represent areas lacking rapid initial response and readily available water supply (Figure 3.15).

## Damage by Fire and Seedling Mortality on Forestland

Bastrop County, Texas

[The information in this table indicates the dominant soil condition but does not eliminate the need for onsite investigation. The numbers in the value columns range from 0.01 to 1.00. The larger the value, the greater the potential limitation. The table shows only the top five limitations for any given soil. The soil may have additional limitations]

Map symbol and soil name	Pct. of map unit	Potential for damage to soil by fire		Potential for seedling mortality	
		Rating class and limiting features	Value	Rating class and limiting features	Value
AfA: Axtell	95	Moderate Texture/coarse fragments	0.50	Low	
AfC: Edge	95	Moderate Texture/coarse fragments	0.50	Low	
AfC2: Edge	95	Moderate Texture/coarse fragments	0.50	Low	
AfE2: Edge	95	Moderate Texture/coarse fragments	0.50	Low	

Table 3.5 Microsoft® Access Report on Potential Damage to Soils from Wildfire

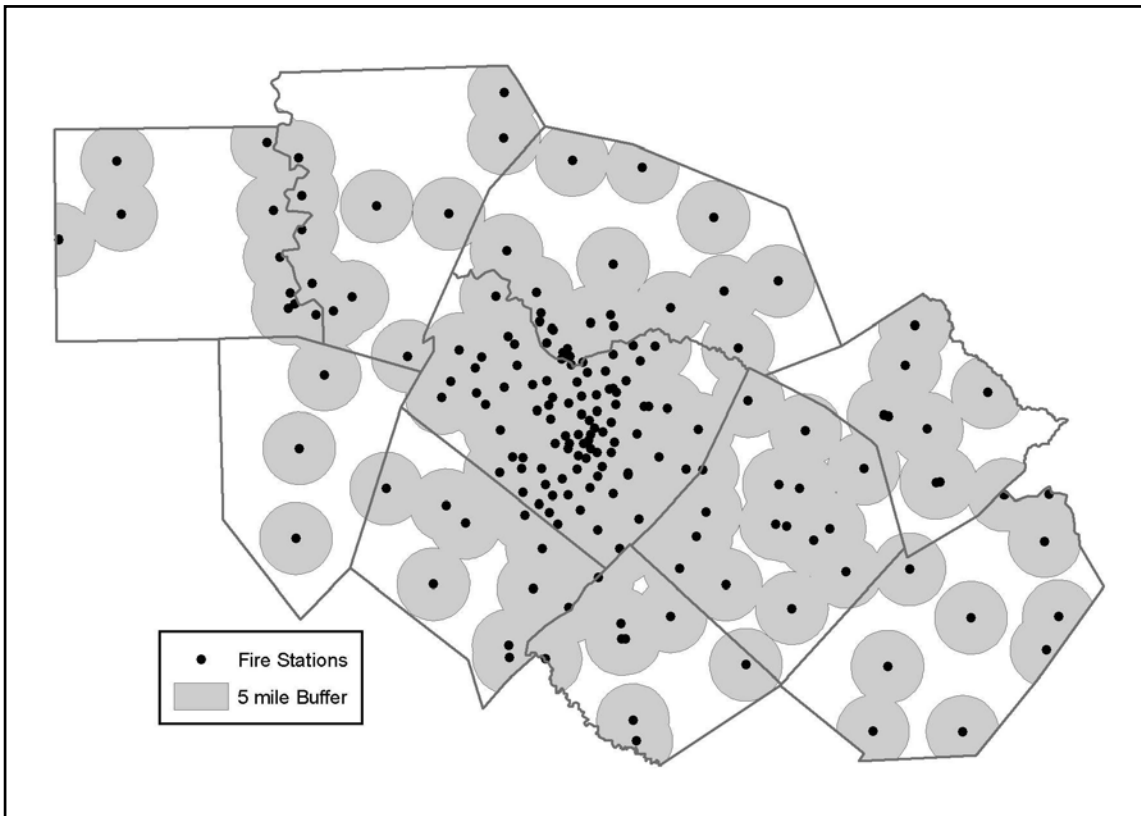


Figure 3.15 5-mile Buffer from Fire Stations

### 3.7.5 Real-Time Weather Data

One of the major goals of this methodology was to use real-time weather to calculate potential wildland fire behavior and threat. There is a multitude of weather stations within the study area that collect weather data on a continuous basis. Natural resource agencies, such as U.S. Fish and Wildlife Service and the U.S. and Texas Forest Services rely on their own weather collection stations to for use in wildland fire planning. These stations are called Remote Automated Weathers Stations (RAWS) and they are interagency devices distributed across the United States and the study area.

They are typically placed in locations where they can monitor fire danger. Information gathered from RAWS is forwarded to Boise, Idaho, via the GOES satellite and then on to several other computer systems for monitoring and analysis.

Although weather data are continuously available, real-time download of information is strictly controlled and monitored and is made available through managed agreement. However, the data are available in readable format from a number of Web sites. Data for this project were obtained from a portal maintained by the Texas Interagency Coordinating Council housed at Texas A&M University (TICC, 2005). Weather readings were collected from nine sites (Figure 3.16) for a specific hour and recorded in a spreadsheet for integration into a fire behavior calculator (Table 3.6 is an example of a RAWS web page).

The location of each RAWS station is recorded in longitude, latitude coordinates on the web accessible site (Table 3.7). The location coordinates for all nine sites were recorded in ascii format and used to create a point GIS shapefile from which weather interpolation could be made, as detailed in the section 3.7.7.

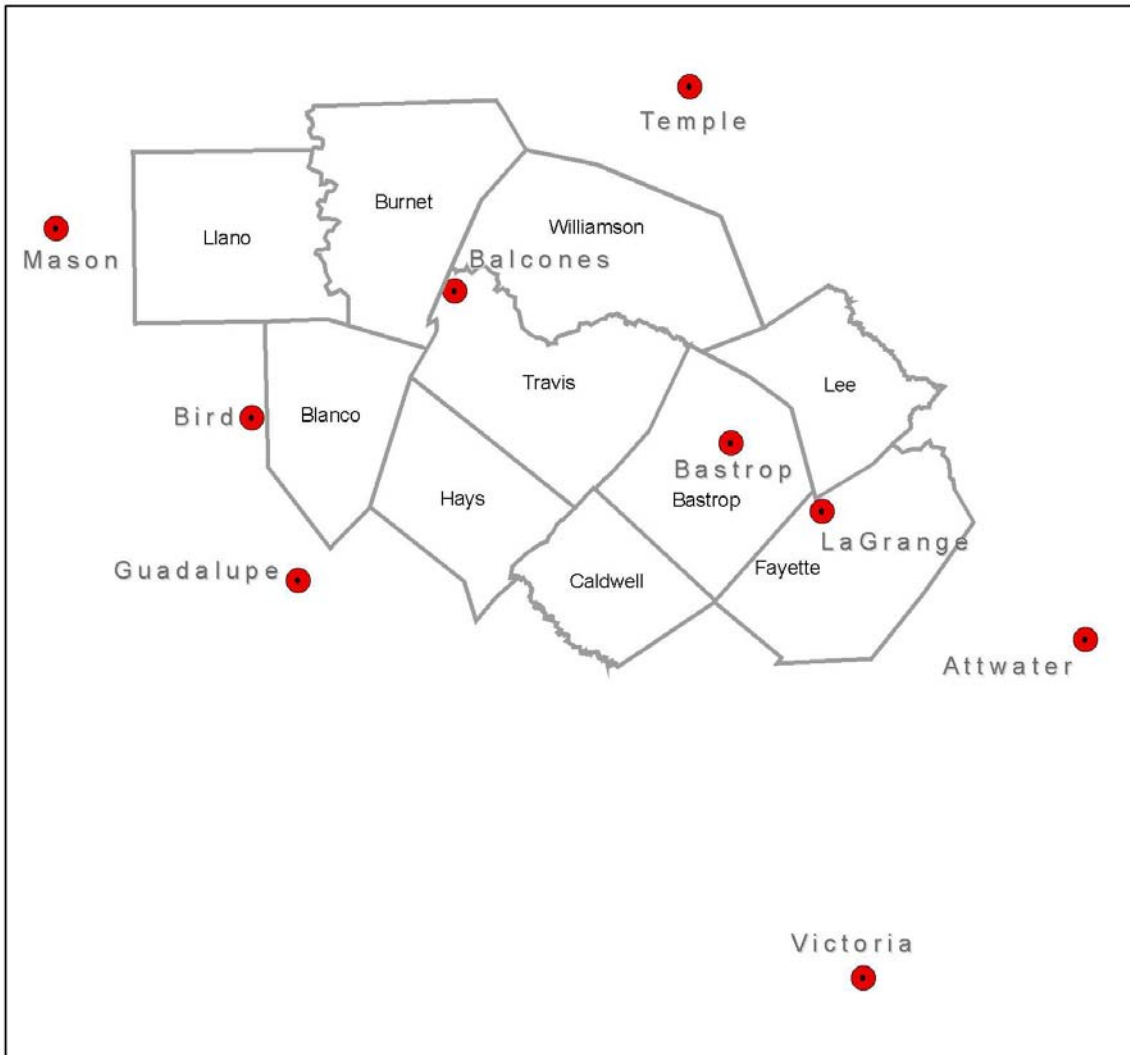


Figure 3.16 Nine RAWS stations Used for Fire Behavior Calculations

Table 3.6 Example of RAWS Weather Data

```

Network Message: none.

Station          GOES ID Elev  Lat    Long
=====
TX BALCONES     3265958A 1035   30:33:58 98:02:20

                Dew
                Day/Time  Tmp Pt  Wind  Pcpn Rh  Fuel  Peak  Bat  Fuel
                =====  =====
                Day/Time  Tmp Pt  Wind  Pcpn Rh  Temp  Wind Volt Moist
=====
TX BALCONES     21/0349Z  63/ 62/2000/ 3.29 RH 97 FT 61/ 22G03 12.5 FM 22 SR 0
TX BALCONES     21/0249Z  64/ 62/1601/ 3.29 RH 96 FT 62/ 21G03 12.5 FM 21 SR 0
TX BALCONES     21/0149Z  65/ 62/1801/ 3.29 RH 92 FT 64/ 22G06 12.5 FM 18 SR 4
TX BALCONES     21/0049Z  68/ 64/1903/ 3.29 RH 88 FT 68/ 20G10 12.5 FM 15 SR 74
TX BALCONES     20/2349Z  70/ 65/2006/ 3.29 RH 85 FT 74/ 22G13 12.6 FM 16 SR 205
TX BALCONES     20/2249Z  71/ 65/2006/ 3.29 RH 83 FT 74/ 20G11 12.6 FM 17 SR 170
TX BALCONES     20/2149Z  69/ 64/2106/ 3.29 RH 87 FT 70/ 22G11 12.5 FM 19 SR 120
TX BALCONES     20/2049Z  68/ 64/2105/ 3.29 RH 89 FT 68/ 22G10 12.5 FM 23 SR 82
TX BALCONES     20/1949Z  68/ 65/2103/ 3.29 RH 92 FT 68/ 26G09 12.5 FM 25 SR 101
TX BALCONES     20/1849Z  68/ 64/2405/ 3.29 RH 90 FT 67/ 24G10 12.5 FM 25 SR 200
TX BALCONES     20/1749Z  66/ 64/2106/ 3.29 RH 96 FT 67/ 21G12 12.5 FM 25 SR 149
TX BALCONES     20/1649Z  65/ 64/1905/ 3.29 RH 97 FT 66/ 22G08 12.5 FM 25 SR 97
TX BALCONES     20/1549Z  64/ 63/2104/ 3.29 RH 98 FT 65/ 18G06 12.5 FM 25 SR 87
TX BALCONES     20/1449Z  63/ 62/1902/ 3.28 RH 98 FT 63/ 22G04 12.5 FM 26 SR 5
TX BALCONES     20/1349Z  63/ 62/2303/ 3.27 RH 98 FT 63/ 25G05 12.5 FM 26 SR 0
TX BALCONES     20/1249Z  63/ 62/2103/ 3.27 RH 97 FT 62/ 19G06 12.5 FM 26 SR 0
TX BALCONES     20/1149Z  63/ 61/1804/ 3.27 RH 96 FT 62/ 23G10 12.5 FM 25 SR 0
TX BALCONES     20/1049Z  64/ 62/1704/ 3.27 RH 95 FT 62/ 18G11 12.5 FM 25 SR 0
TX BALCONES     20/0949Z  64/ 62/1705/ 3.27 RH 94 FT 63/ 14G12 12.5 FM 25 SR 0
TX BALCONES     20/0849Z  63/ 61/1404/ 3.27 RH 96 FT 62/ 18G11 12.5 FM 25 SR 0
TX BALCONES     20/0749Z  63/ 61/1506/ 3.27 RH 95 FT 62/ 16G12 12.5 FM 25 SR 0
TX BALCONES     20/0649Z  63/ 61/1505/ 3.27 RH 95 FT 62/ 24G13 12.5 FM 25 SR 0
TX BALCONES     20/0549Z  63/ 61/1506/ 3.27 RH 96 FT 62/ 22G11 12.5 FM 25 SR 0
TX BALCONES     20/0449Z  62/ 61/1405/ 3.27 RH 97 FT 62/ 14G15 12.5 FM 25 SR 0
TX BALCONES     20/0349Z  62/ 61/1304/ 3.26 RH 98 FT 62/ 11G08 12.5 FM 25 SR 0
TX BALCONES     20/0249Z  61/ 60/1502/ 3.25 RH 99 FT 61/ 12G06 12.5 FM 25 SR 0
TX BALCONES     20/0149Z  61/ 60/1002/ 3.24 RH 99 FT 60/ 11G05 12.5 FM 25 SR 1
TX BALCONES     20/0049Z  61/ 60/1303/ 3.24 RH 99 FT 61/ 10G06 12.5 FM 25 SR 30
TX BALCONES     19/2349Z  60/ 59/1502/ 3.24 RH 99 FT 61/ 19G04 12.5 FM 25 SR 28
TX BALCONES     19/2249Z  61/ 60/1402/ 3.23 RH 97 FT 61/ 10G05 12.5 FM 25 SR 99

=====
Disclaimer: the National Weather Service does not own or operate any
RAWS site. The data passes through this system from Bureau of Land
Management computer systems. Some of the sites are periodically moved,
especially those called portable or those with a q after the longitude.
Location information and weather data might be incorrect. No quality
control is done on the data or the location information. Use with
caution and at your own risk.
=====

```

### 3.7.6 Additional GIS Data

Six additional GIS layers were used in the study: streams, lakes, municipal boundaries, county boundaries and watersheds. All but the watershed layers were

obtained from the CAPCO GIS. The watershed layer represents subwatersheds within portions of Bastrop, Caldwell, Hays, Travis and Williamson counties. The layer was obtained from the Watershed Protection Development Review in the City of Austin. The purpose for integrating the layer was to identify watersheds in which might be found high erosion rates following vegetation loss from wildland fire. Watersheds that contain highly erodible soils, high slope landscapes and fuels that burn extremely hot are more likely to experience faster runoff and high erosion rates with intense rains that sometimes follow wildland fire. Identification of critical watersheds allows for erosion mitigation preparation.

### 3.7.7 Fire Behavior Calculation

The BehavePlus Fire Modeling System, Version 3.0.0, wildland fire behavior calculator (Andrews, et al., 2004) was used to calculate fire behavior based upon interactions of weather and wildland fuels. Data were input into the model using an interactive worksheet that allows direct entry of variables, a drop-down of preset choices or a range of values. The worksheet was formatted for the following data input: type of wildland fuel, dead and live fuel moisture, mid-flame wind speed (the wind speed measured at mid-flame height), slope, air temperature, shading from the sun and slope (Figure 3.17). The slope value of 0% was for all fire behaviors calculations. The GIS component of the methodology factors in the slope, eliminating the need in BehavePlus and making the fire behavior calculations more simple to calculate.



Output variables for the worksheet included maximum estimated Surface Rate of Spread of fire (in chain/hour where 1 chain = 66 feet), Fireline Intensity (in Btu/ft/sec), Flame Length (in ft), and Probability of Ignition (Figures 3.18). The following define the output variables (NWCG, 1996):

**RATE OF SPREAD:** The relative activity of a fire in extending its horizontal dimensions. It is expressed as rate of increase of the total perimeter of the fire, as rate of forward spread of the fire front, or as rate of increase in area, depending on the intended use of the information. Usually it is expressed in chains or acres per hour for a specific period in the fire's history.

**FIRELINE INTENSITY:** The product of the available heat of combustion per unit of ground and the rate of spread of the fire, interpreted as the heat released per unit of time for each unit length of fire edge. The primary unit is Btu per second per foot (Btu/sec/ft) of fire front.

**FLAME LENGTH:** The distance between the flame tip and the midpoint of the flame depth at the base of the flame (generally the ground surface), an indicator of fire intensity.

**PROBABILITY OF IGNITION:** The chance that a firebrand will cause an ignition when it lands on receptive fuels.

Output values from BehavePlus are presented in tabular format as illustrated in Figure 3.18. Values were transcribed from the tabular output into the spreadsheet. This method is cumbersome, at best, but served the purpose of the methodology and the time availability to prepare the GIS output. Sections of the spreadsheet for each of the four fuel models were exported as DBF IV files containing RAWS station ID, Rate of Spread, Fireline Intensity, Flame Length, Probability of Ignition, Relative Humidity, Wind Speed and Direction. An example of the spreadsheet is given in Table 3.8

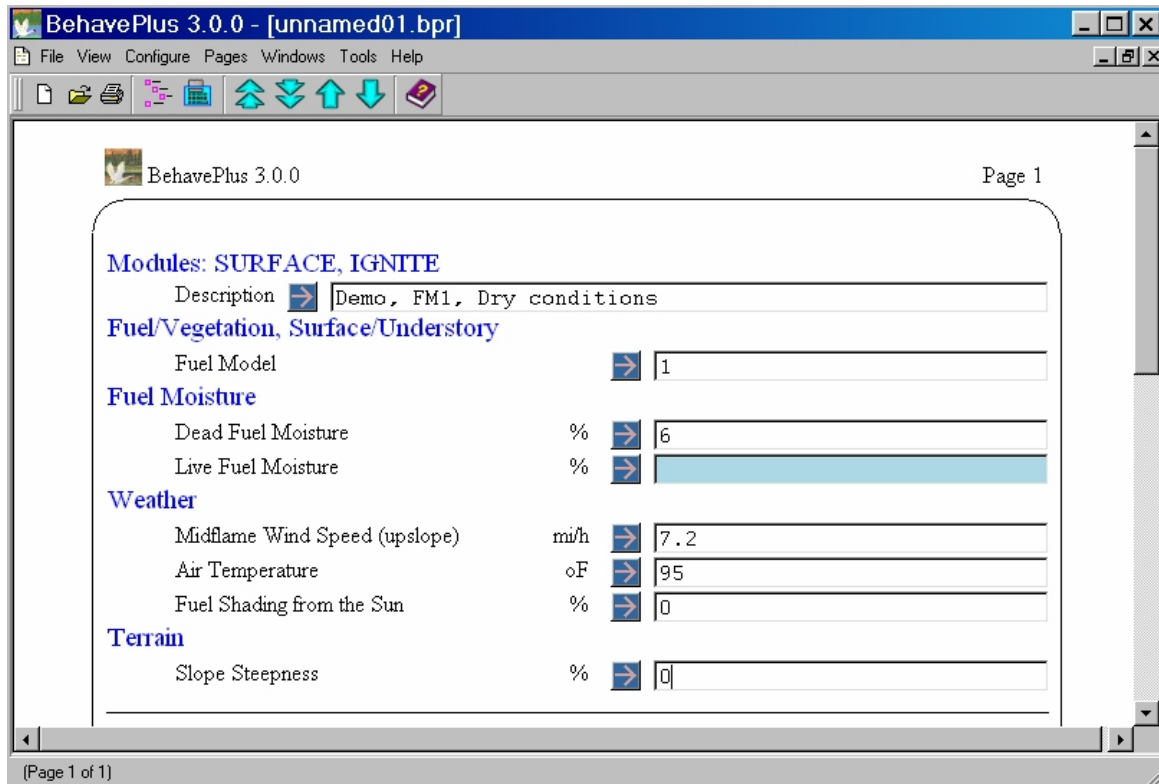


Figure 3.17 BehavePlus 3.0.0 Demonstration Input Worksheet

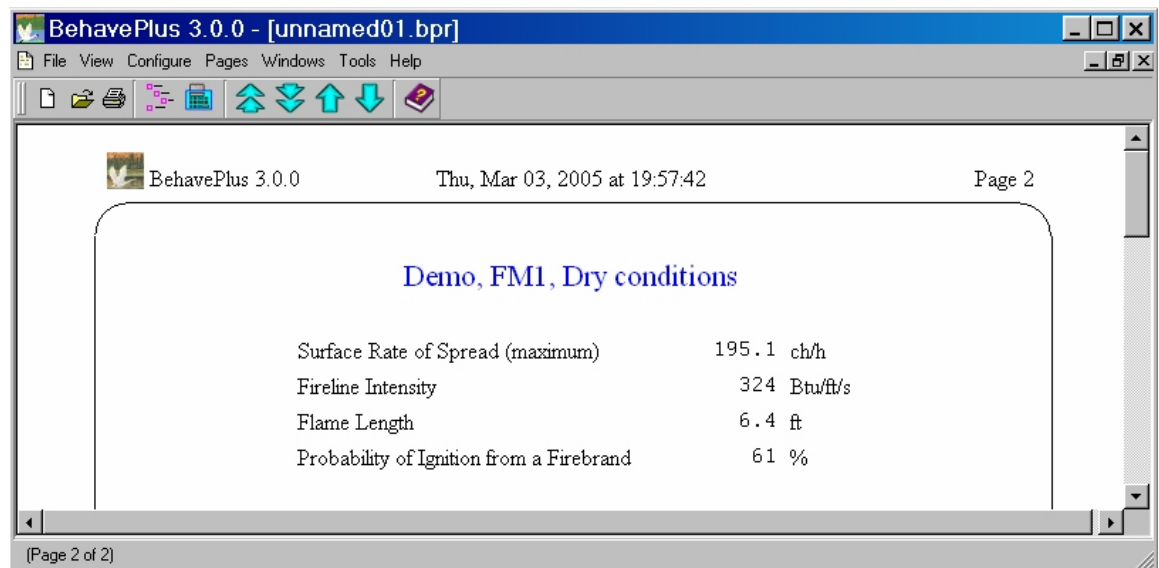


Figure 3.18 Illustration of BehavePlus Output.

Table 3.8 Fire Behavior Output for Fuel Model 9

52	Fuel Model 9 - Litter: Wind Adjustment Factor 0.3									
53	Station	MWS	WS/FM	ROS	ROS-Code	Fire-Int	FI-Code	Flm-Lgth	FL-Code	
54	Mason	6	6 / 6	15	1		1	4	1	
55	Bird	5	5 / 6	12	1		1	3	1	
56	Guadalupe	3	3 / 7	6	1		1	2	1	
57	Balcones	4	4 / 6	6	1		1	3	1	
58	Temple	4	4 / 5	10	1		1	3	1	
59	Bastrop	3	3 / 7	6	1		1	2	1	
60	LaGrange	3	3 / 8	4	1		1	2	1	
61	Attwater	3	3 / 8	5	1		1	5	2	
62	Victoria	4	4 / 10		1		1		1	
63										
64	Probability of Ignition from Firebrand									
65	Station	Tmp / FM	% Ignit	Rh	WS	Wdir				
66	Mason	84 / 6	48	35	18	340				
67	Bird	83 / 6		33	14	320				
68	Guadalupe	87 / 7		36	9	340				
69	Balcones	86 / 6		34	11	310				
70	Temple	85 / 5		30	13	330				
71	Bastrop	88 / 7		32	9	320				
72	LaGrange	85 / 8		32	8	340				
73	Attwater	78 / 8		31	10	160				
74	Victoria	92 / 10		42	12	170				
75										

### 3.8 GIS Model Construction

#### 3.8.1 Generalized threat map

The first GIS overlay addressed generalized potential threat to the study due to the influence of fuel models and slope. The land cover results from the Landsat imagery were reclassified into one of seven categories starting with class one: Water, Bare, Crop, Fuel Model 1, Fuel Model 9, Fuel Model 6, and Fuel Model 4. Classes 3 through 7 represent an increasing threat from wildfire as fire behavior characteristics increase in Rate of Spread, Intensity and Flame Length. Since this first overlay concerned potential threat without a weather input, a simple ranking of the fuels was adequate.

The slope of the landscape poses an added threat. Not only does slope increase fire behavior, higher slopes are more difficult for emergency crews to fight fires, thus there is greater danger to both personnel and structures. Following the guidelines of the National Fire Danger Rating System (NFDRS) Calculator (Demming et al., 1977), the slopes were categorized into six classes: 0%, 1%-25%, 26%-40%, 41%-55%, 56%-75% and >75%. As in the fuels input, although high slopes increase fire behavior, for this overlay the slopes were given a simple ranked order.

The land cover/fuel model grid was overlain with the slope grid to produce a new grid output in which each output cell was a combination of fuel type and slope. The output grid cells potentially ranged in value from 1100 (water with 0% slope) to 4600 (FM4 on >75% slope). The higher output cell values represent higher threat based upon fuel model type and slope.

### 3.8.2 Ignition sources

The second overlay step examined the influence of potential ignition sources and included the grid output from fuels and slopes plus the grid layer of buffered roads and railroad. The roads and railroad layers represent the areas most likely to be a source of ignition from human activities. The road buffer was recoded to 0 for outside the buffer and 10 for inside the buffer. The railroad layer was recoded to 0 for outside and 20 for inside. The combination of the two layers produced an output grid with three values: 10 – road buffer, 20 – railroad buffer and 30 - combination of both buffers. If roads and

rail are the most likely sources of ignition, then class 30 represents the highest ranking of likely ignition areas.

### 3.8.3 Target areas

In order to identify high potential risk of wildfire to the human component of the methodology, the road buffer layer was used as a surrogate for developed areas. The majority of human structures were assumed to lie within 2 acres of a paved road, thus the target area was identified as the 400 ft. buffer around the road layer. A value of 2 was assigned to areas outside the buffer and a value of 9 within the buffer. The purpose of this classification scheme will be demonstrated shortly.

As part of the threat to human component, potential response from emergency fire personnel and equipment was factored in. The GIS layer of 5-mile buffers around fire stations was overlaid with the road buffer layer. The response layer was classified as 1 for inside the buffer and 3 for outside the 5-mile buffer. The classification scheme allows the following results:

		Road Buffer	
		Outside - 2	Inside - 6
Response Buffer	Inside - 1	3	7
	Outside - 3	5	9

In this overlay scheme, a point outside of a road buffer is less likely to be ignited through human factors and is also less likely to have human-made structures that are

threatened by fire. If a wildland fire is located outside of a 5-mile response buffer and outside a road buffer, although it is more difficult to respond to the fire in a rapid manner, the likelihood of damage to a structure is not as great. This area would have a value of 3 in the overlay. On the other end of the scale, a value of 9 represents an area that is likely to be ignited by human factors, is also likely to have human-made structures and is outside the 5-mile response buffer, so will experience a much slower response from emergency personnel.

#### 3.8.4 Real-Time Weather Factor

The overlays in section 3.8.3 demonstrate areas that can experience high potential threat from wildfire based upon the relatively static factors of fuel model types, topographic conditions, sources of ignition, location of development and distance of emergency response. This final section of the GIS analysis factors in real-time weather data and resultant potential fire behavior. For an area as large as the CAPCO region, weather conditions can vary over both space and time. For example, a cold front can impact counties in the northwest region of the CAPCO causing extreme fire behavior while at the same time counties in the southeast remain under the influence of humid, Gulf breezes with low fire behavior potential. Real time weather data gathered from nine weather stations across the study area was used to calculate potential fire behavior, the results of which were interpolated across ten counties through a krigging process.

Fire behavior data for each of the four fuel models were saved as individual database files in a directory. A series of GIS steps were then performed on the fire behavior data in order to integrate and display the information across the study area. The basic steps within the GIS software included krigging (at a 1000 meter interval), convert the floating point grid file to integer values, resample the grid cells from 1000 to 100 meters, mask the interpolated data by the respective fuel model, and reclassify the resulting data to a threat level. Threat levels maps were generated for rate of spread (in mile per hour), fire line intensity (in Btus/ft/s), and flame lane (in feet). In addition to the threat maps, maps were generated displaying Relative Humidity and Probability of Ignition based upon real-time weather data.

One of the goals of this project was to develop methodology that can be readily reproduced in a field office by emergency management personnel. To do so, ModelBuilder within ArcInfo 9 (ESRI, Inc.) was used to create an automated process for the GIS from the point that the fire behavior database is generated to the creation of the threat layers for mapping. There are 27 steps and 33 data components for each of the 4 fuel models, making for a very complex path without data automation. With the automated steps, the total processing time from database to threat map for one component, such as rate of spread, was approximately 8 minutes on a 3 GHz computer. Development of a threat map without benefit of automation would certainly take far longer and be far more vulnerable to data entry error. An example of the automation steps for rate-of-spread is demonstrated in Figure 3.19.

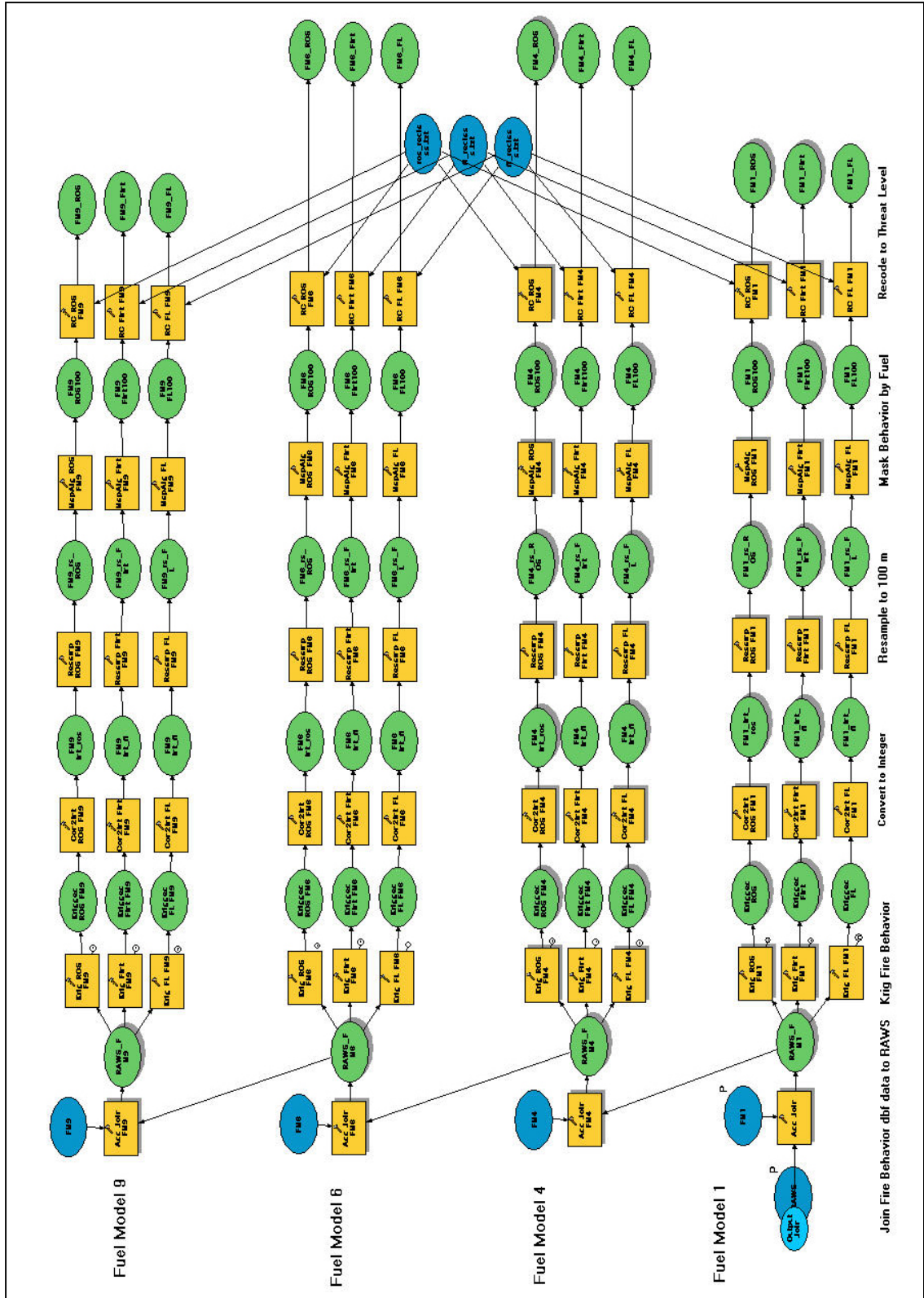


Figure 3.19 GIS ModelBuilder Example for Rate-of-Spread Threat Calculation



## CHAPTER 5

### RESULTS

The results chapter of this research addresses four different aspects of wildland fire threat: 1) identification of wildland/urban interface; 2) threat based upon relatively static land features such as fuels and topography; 3) soils and important watersheds potentially impacted by loss of cover due to wildland fire; and 4) threat analyses based upon real-time weather and resultant fire behavior.

#### 4.1 Remote Sensing of the WUI

Figure 4.1 is an example of the three types of imagery that were used to attempt to identify wildland/urban interface: Landsat 7 (30 meter resolution), IKONOS (4 meter resolution) and DOQQ (2 meter resolution). An unsupervised classification to 100 classes was used to attempt to identify human-made structures that makeup the WUI. The classified image was linked geographically to the high resolution DOQQ and buildings and roads were identified in both images. Pixels in the classified image were given a color of orange to easily distinguish them from background features. A visual qualitative comparison of sample sites was conducted throughout the study area to determine the ability of Landsat 7 to capture the WUI.

In portions of the study area where vegetation is generally lower or equal in height to structures the imagery appeared to do a relatively good job of



Figure 4.1 Examples of Images Used for Classification

distinguishing the interface. For example, a housing development south of Lake Travis, west of the City of Austin, displayed a similar layout pattern to that of development within the high resolution DOQQ (Figure 4.2).

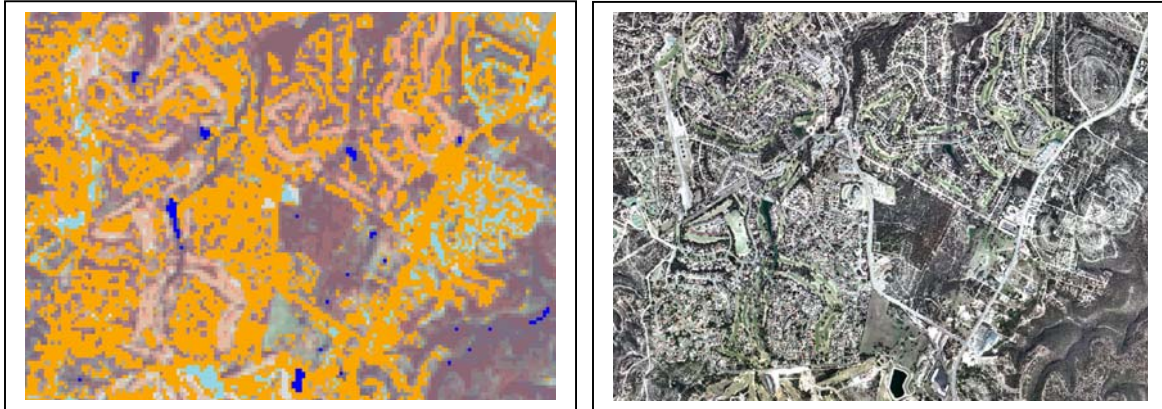


Figure 4.2 Comparisons of WUI in Landsat 7 and DOQQ.

Not surprisingly, the IKONOS imagery, at 4-meter resolution, performed much better than the Landsat 7 for WUI identification when compared to 2-meter DOQQ photography, as exhibited in Figure 4.3.

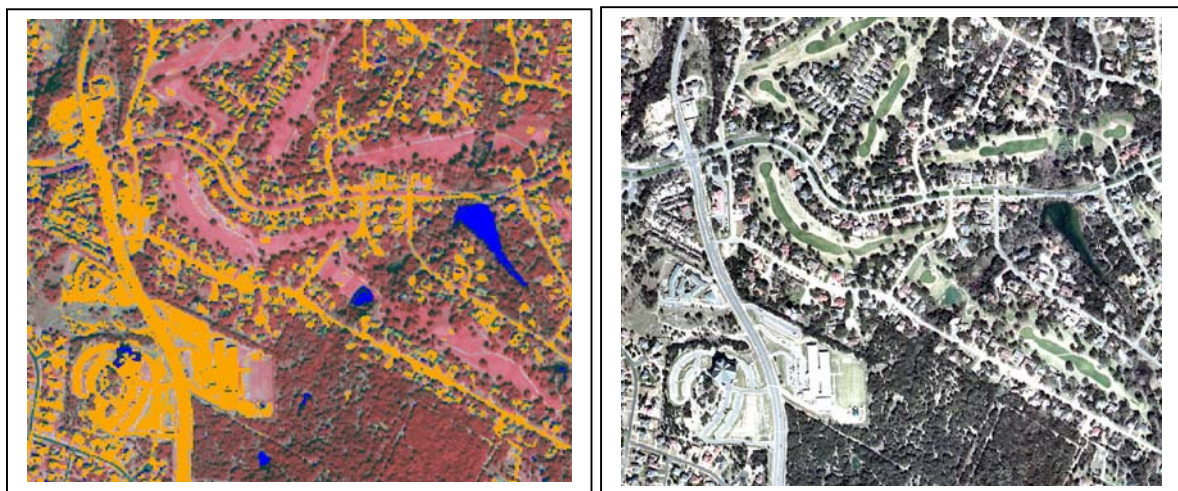


Figure 4.3 Comparison of WUI in IKONOS and DOQQ.

Although IKONOS and Landsat 7 performed relatively well in the lower vegetation areas of western Travis County, they were less than adequate for the eastern portion of the study area where trees are much taller and often partially or fully cover structures. An example is a development to the south east of Bastrop, in Bastrop County. According to the Texas Forest Service, Bastrop Regional Fire Coordinator, this development is a prime example of WUI which is under high potential threat due to proximity of vegetation. A community-based Firewise program has been underway in this development for several years to reduce fuel loads and reduce potential fire threat, but this is only one community among many similar that face similar conditions (Gray, 2004). An attempt to identify the WUI in this community with Landsat 7 was unsuccessful, as demonstrated in Figure 4.4

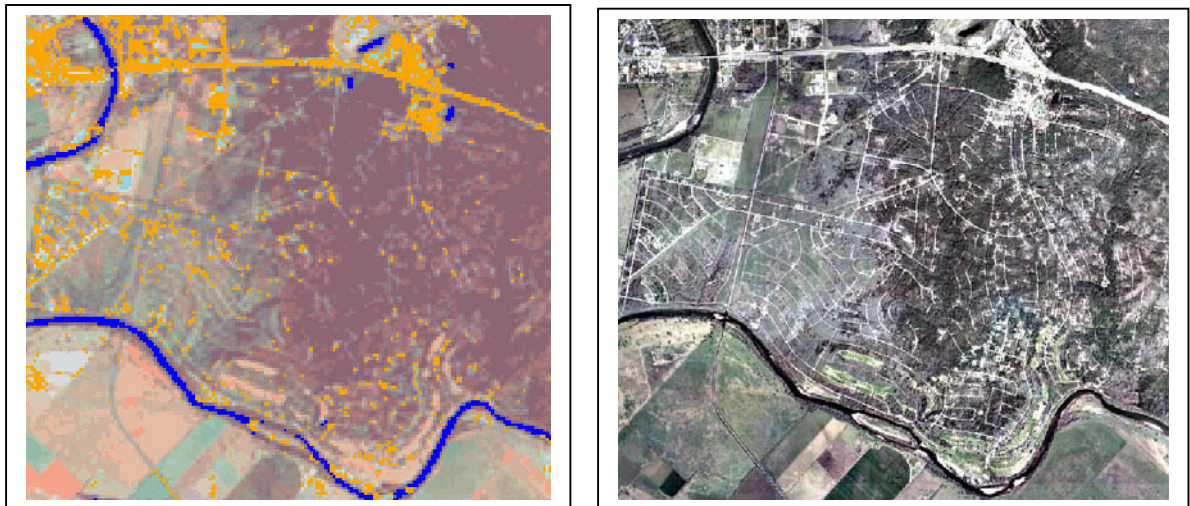


Figure 4.4 Comparison of Landsat 7 and DOQQ in Tall Trees.

As demonstrated in Travis County, the IKONOS imagery was able to distinguish far greater detail than the Landsat imagery for the heavily wooded area within Bastrop County, displaying very similar patterns to that of the DOQQ photography (Figure 4.5).

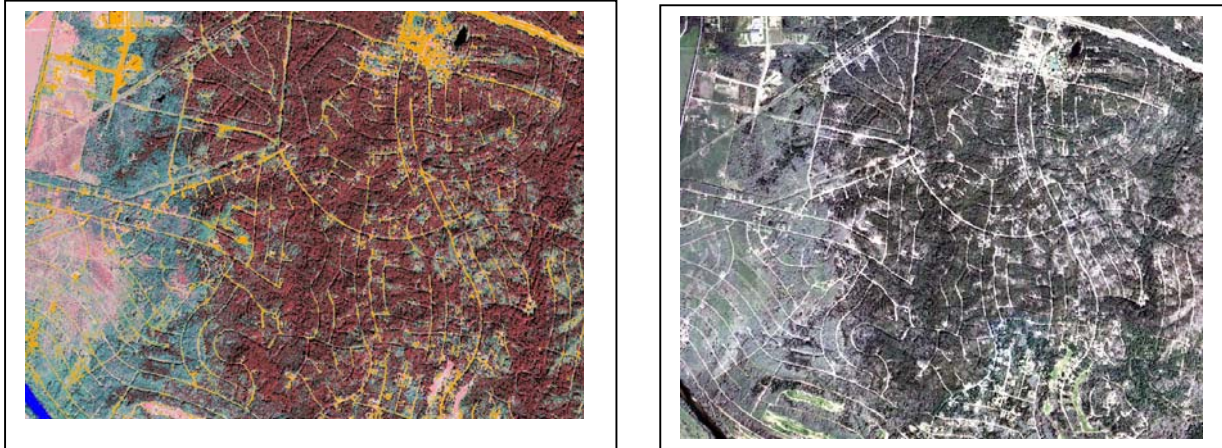


Figure 4.5 Comparisons of IKONOS and DOQQ in Tall Trees.

Classification of neither the Landsat 7 nor the IKONOS satellite imagery served as adequate means for delineating the Wildland Urban Interface. Tall vegetation that covered structures in eastern portions of the study area classified as vegetation rather than urban/developed, the result of which was an underestimation of the presence of WUI. Although roads and structures (roof surfaces) were easier to determine in many western portions of the study area where the vegetation was relatively low or sparse, visual comparison with DOQQs showed considerable areas of bare soils that classified incorrectly as roads or structures. The classification techniques served well to identify fuel models but not for developed areas.

One of the intentions of this project was to create methodology that can be easily reproduced by GIS technicians without requiring lengthy remote sensing processing. Another goal of the methodology is to readily update WUI information to reflect rapid growth around the urban areas of the central study area. The technique of buffering roads was determined to be a more effective method of identifying "potential" WUI. As in the satellite classification method, the buffer technique is not an accurate assessment of WUI presence but it creates a more conservative approach to identifying threat targets by overestimating potential locations. Areas within a 400 foot buffer (2 acres) either side of roads with address ranges, as provided by the CAPCO GIS department, are more likely to have structures than areas outside that space. The thought, in this case, is that it is better to estimate the presence of WUI for planning purposes than to miss structures that do exist, as is the concern with satellite classification.

One of the strengths of this buffering method is that Emergency Management Dispatch, such as 9-1-1 services and fire departments, have a mission to maintain an accurate and reliable 9-1-1 database (which depends on road maps and address ranges) on a day-to-day basis. New developments are expected to have 9-1-1 services as soon as they are occupied. Thus, by using county road data obtained appraisal and 9-1-1 districts (taxes and emergency response require rapid updates), the WUI layer within the model can remain relatively current.

An example of the buffering technique is displayed in Figures 4.6 and 4.7. Overlapping buffers were dissolved to create larger buffered areas, allowing for easy distinction between single roads and clusters, or developments. This method is effective in identifying developments in unincorporated areas of counties that are not defined by city or town boundaries (Figure 4.8).

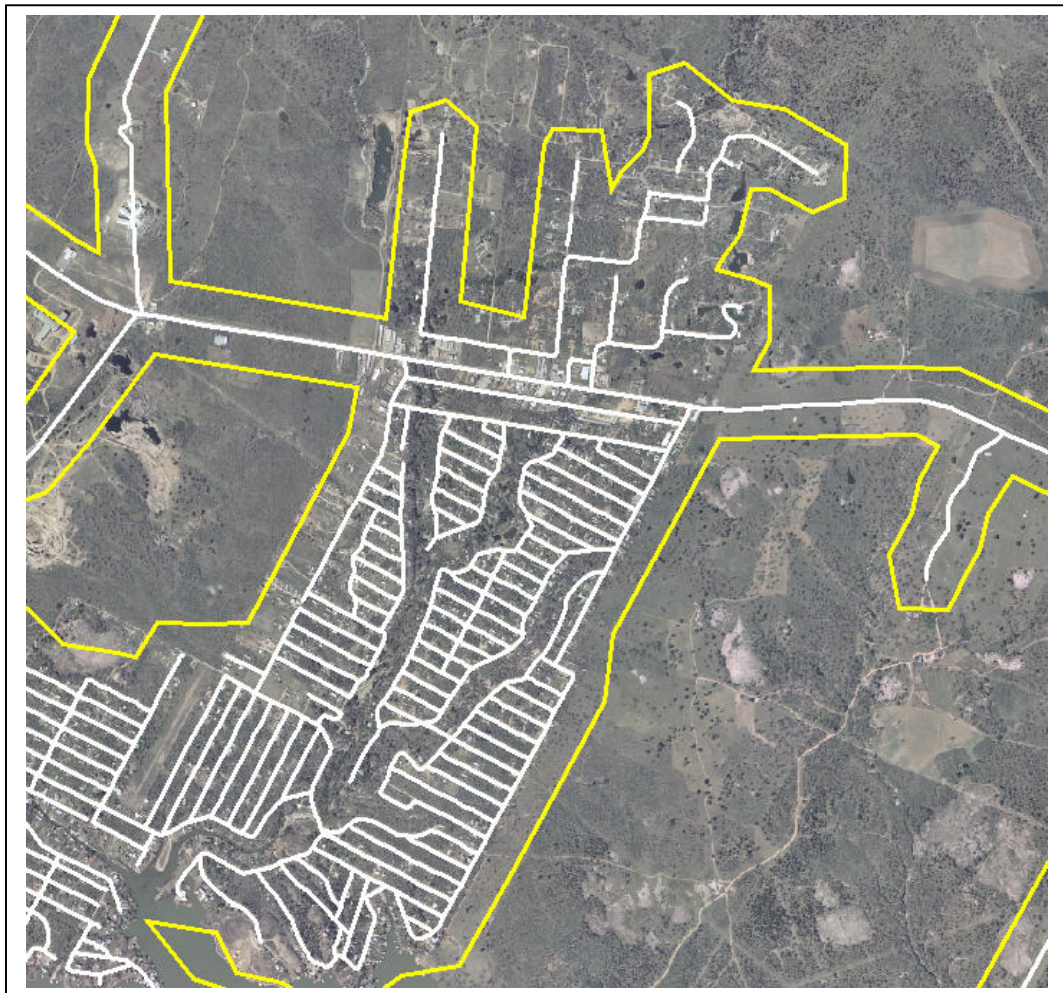


Figure 4.6 Buffered Roads Delineating WUI.

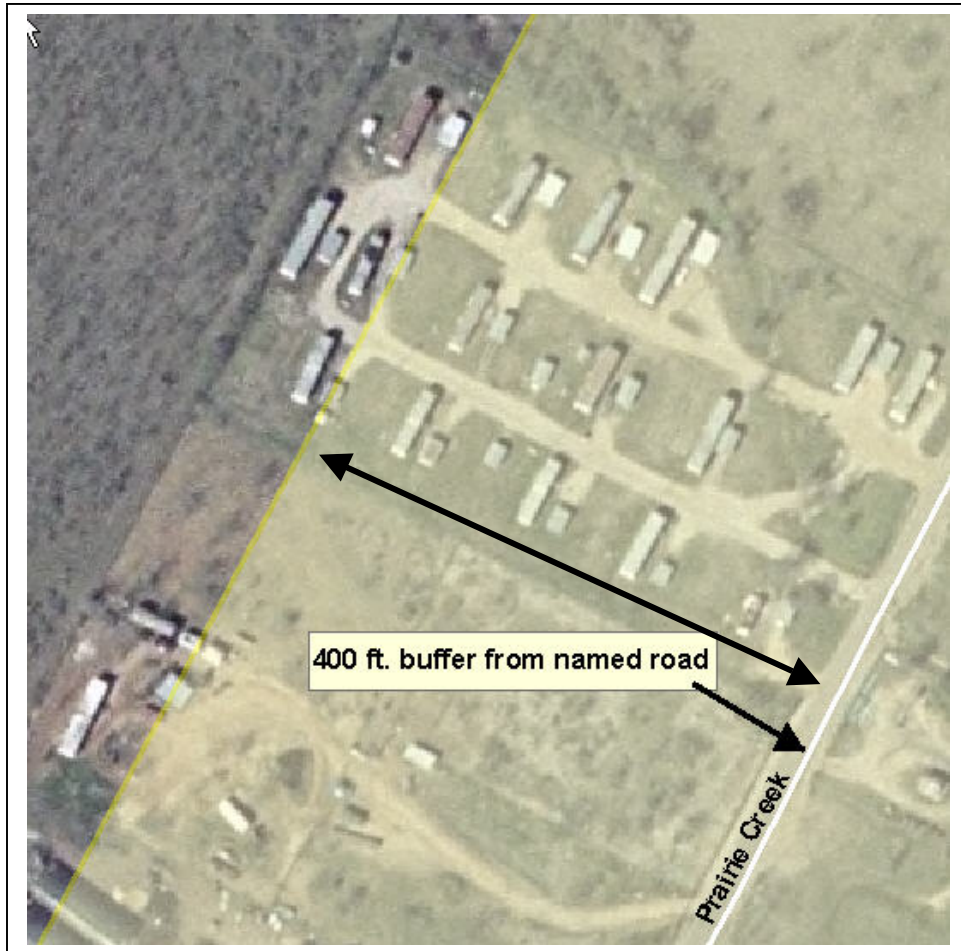


Figure 4.7 Detail of Buffer of Named Roads



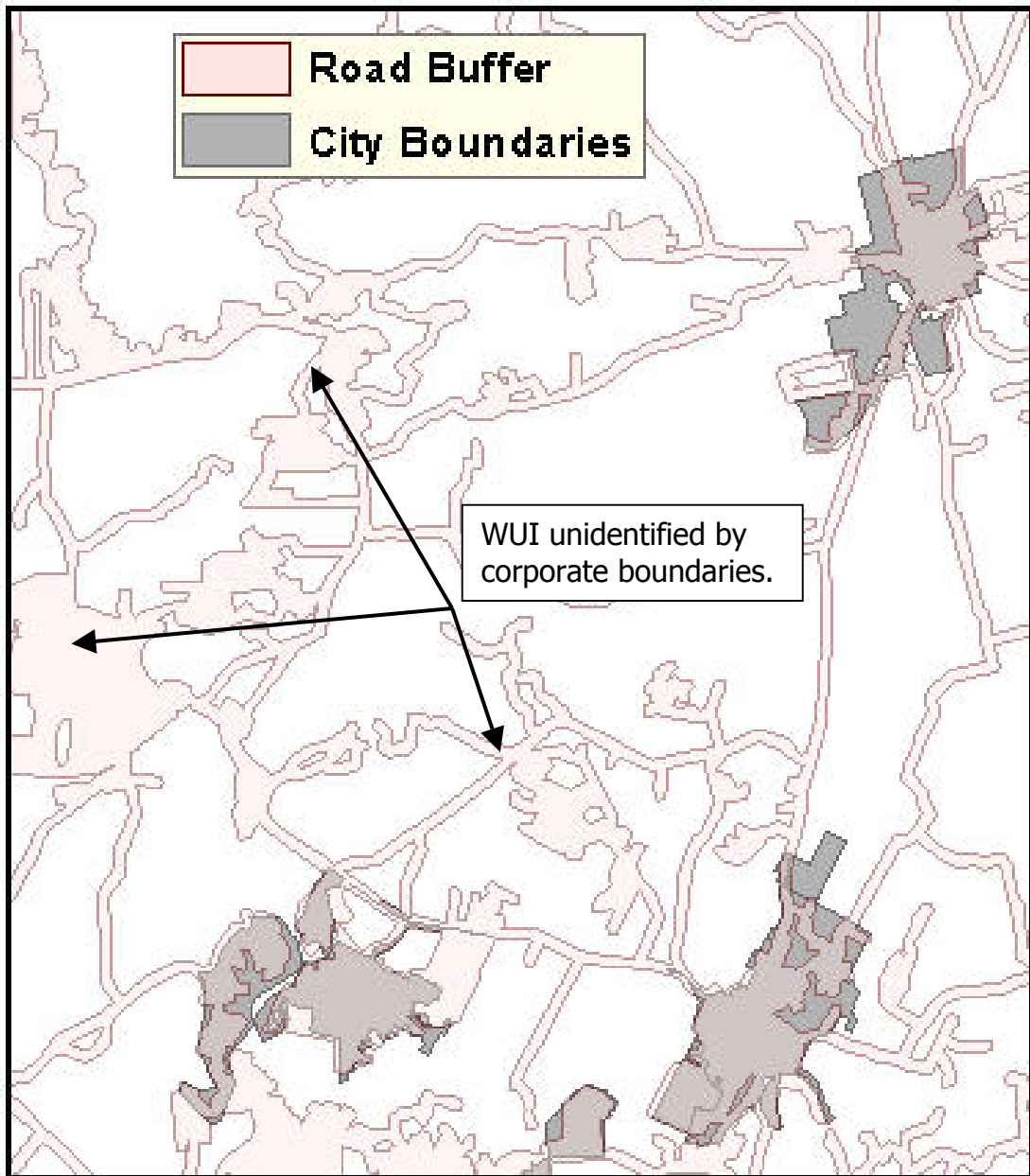


Figure 4.8 Example of Unincorporated Areas Identified by Buffer Method

## 4.2 Threat Classes using Static Features

Two characteristics of landscape that contribute to a heightened threat of wildland fire include fuel model types and slope of the land. Certain vegetation type burn hotter or faster than others and steep slopes cause wildland fire behavior to increase. The remote sensing portion of the project was conducted primarily to identify fuel model types one, four, six and nine. Fuel model classification for the study area is displayed in Figure 4.9.

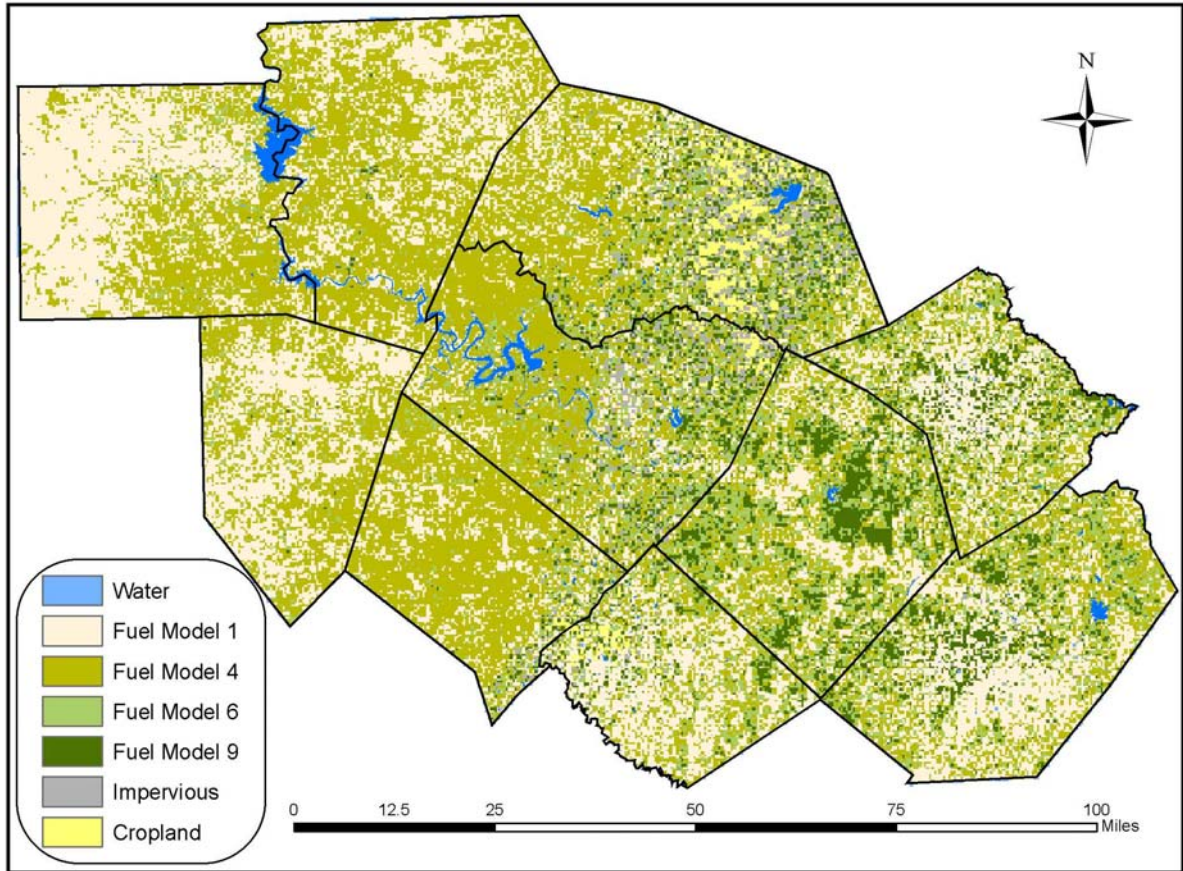


Figure 4.9 Fuel Model Classifications for CAPCO Study Area

Fuel Model One, short grassland, is found throughout the ten-county study area. Fuel Model Four, shrubs, is located west of a line that approximately follows Interstate 35 running north to south through the center of the study area. There is scattering of Fuel Model Six, also shrub, throughout the area. The fourth Fuel Model type, Nine, is located primarily in the eastern portion of the study area.

A total of 200 points were chosen randomly from within 41 U.S.G.S. 1:24,000 quad map areas for accuracy testing (Figure 4.10). Classification accuracy was tested by identifying the fuel model type at a specific point in the classified file and then comparing it to the same location in the corresponding DOQQ photograph. The initial accuracy examination identified two problems with classification accuracy: the difference in scale (30 meter vs. 2 meter) and the absence of cropland in the classified image. Initial classification resulted in a 74% overall accuracy – the satellite classification land cover type was the same as identified in the DOQQs at 147 of 199 locations (Table 4.1).

Classification error can perhaps be explained in several ways. The highest source of error was between grassland and other land covers, particularly cropland. It is easy to understand a misclassification between grassland and low shrub, bare or cropland, depending upon the season and rainfall conditions. If these three classes were added to the grassland category, the overall accuracy would increase to 82%. This is also true for the bare in the imagery to grassland and cropland in the DOQQ. A shift in this category would increase to 84%.

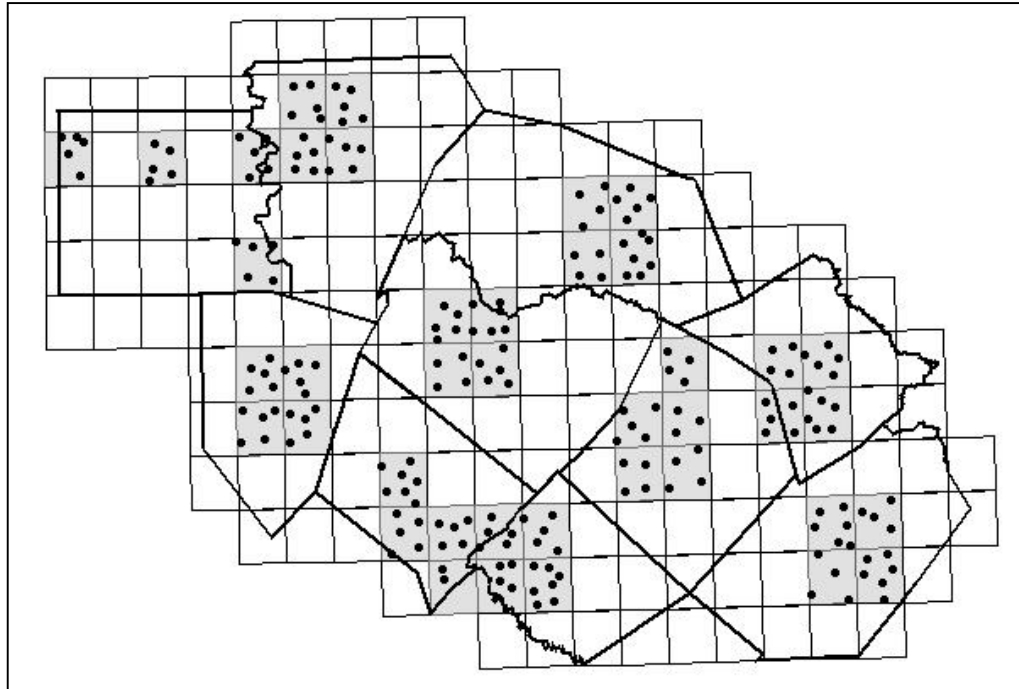


Figure 4.10 Test Locations Used for Accuracy Assessment

Table 4.1 Classification Error Matrix

DOQQ Aerial Photography (2 meter)

	Water	FM1	FM4	FM6	FM9	Bare	Crop
Water	4						
FM1		67		10	3	1	6
FM4		6	36	5	1		
FM6			1	7	1		1
FM9	1	3		3	12	1	2
Bare		3				4	1
Crop		2		1			17

Classified Image (30 meter)

Classification error that is the most troublesome is where grassland was mistaken for Fuel Model 9 (timber litter) or vice versa. The fuel models exhibit major fire behavior differences and therefore are particularly important to the methodology. A possible explanation for the error is the seasonality of the satellite imagery; extremely green grass in the spring could possibly confuse the classification. This is an area that will require refinement.

Fuel models were categorized in GIS into four "threat" classes based upon their potential severe fire behavior, ranging from "Low" to "Extreme". Fire behavior considered Rate of Spread (ROS), Fireline Intensity (FI) and Flame Length (FL). Fuel Model 9 (timber litter) and the Cropland class were combined into the "Low" category. Model 1 (grassland) was placed in the "Moderate" category for although it has a potential high ROS, the FI and FL are lower than the shrub group models. Fuel Model 6 (2.5 feet shrubs) were listed as "High" category. Fuel Model 4 was classified as "Extreme" category due to relatively high ROS but extremely high FI and FL under certain conditions of RH and wind speed. Fuel Model 4 is the vegetation type of greatest concern to emergency personnel for the western portion of the study area. Figure 4.11 demonstrates a map of the fuel model threat classes.

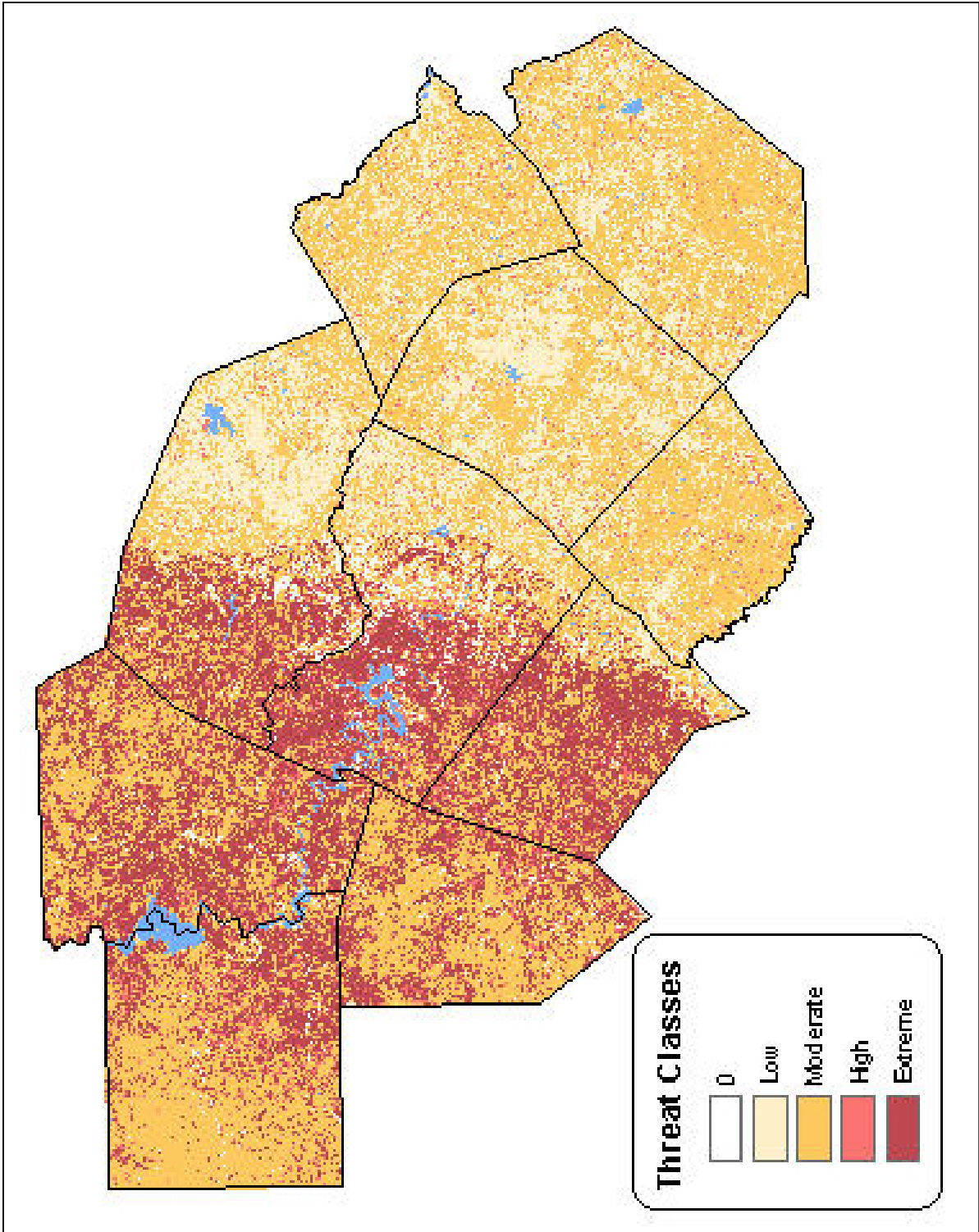


Figure 4.11 Fuel Model Threat Classes

The second layer added to the static threat methodology was slope. Digital elevation data converted to slope and then to 4 slope classes representing potential threat from increased wildland fire behavior, ranging from “Low” to “Extreme”. The slope component is displayed in Figure 4.12.

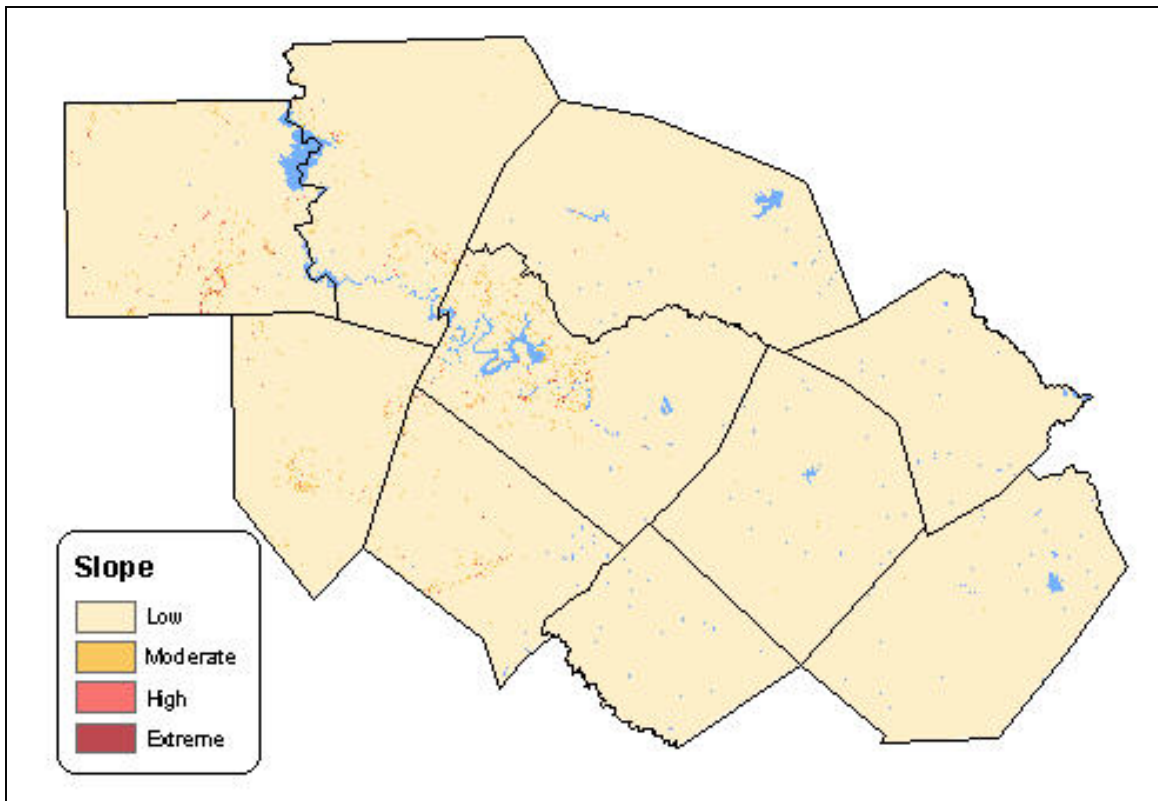


Figure 4.12 Slope Threat Classes

The slopes that exhibit the highest threat are located in the western portion of the study area, the Llano Uplift, that has much greater relief than the Blackland Prairies of the east. Figure 4.13 shows a detail of a portion of

western Travis County that has considerable relief and potential problems from fire behavior due to high slopes.

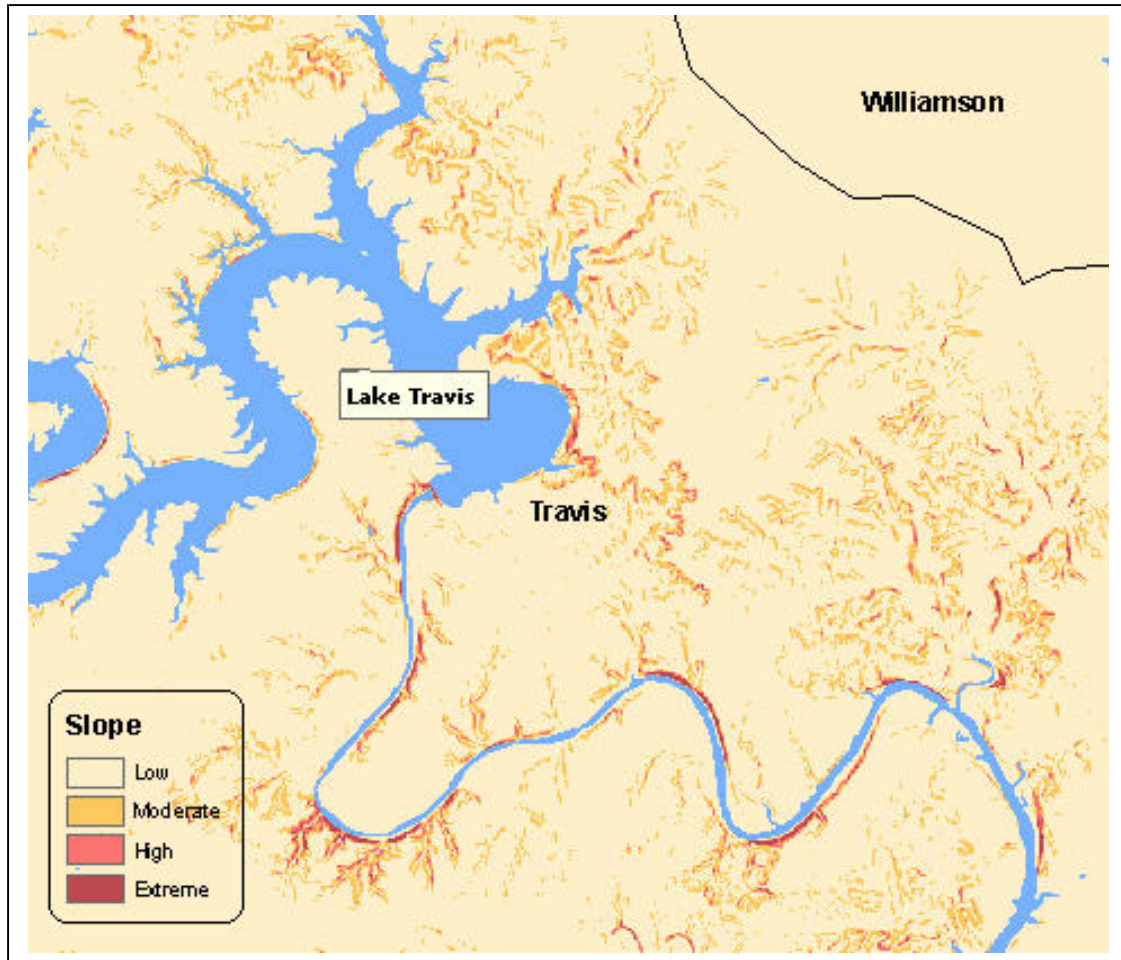


Figure 4.13 Detail of Slope Threat in Western Travis County

The third component of the static threat involves transportation routes: road and rail. Since the majority of wildland fires in Texas start as a result of human activities along road and rail routes, the greatest threat from wildland fire occurs in proximity to these features. For purposes of the threat analysis, a 400 feet buffer along both sides of road and rail was created. The result of the



combination was assigned to four classes ranging from "Low" to "Extreme" as displayed in Figure 4.14. A detail of a section of the study area where multiple threat levels occur is displayed in Figure 4.15.

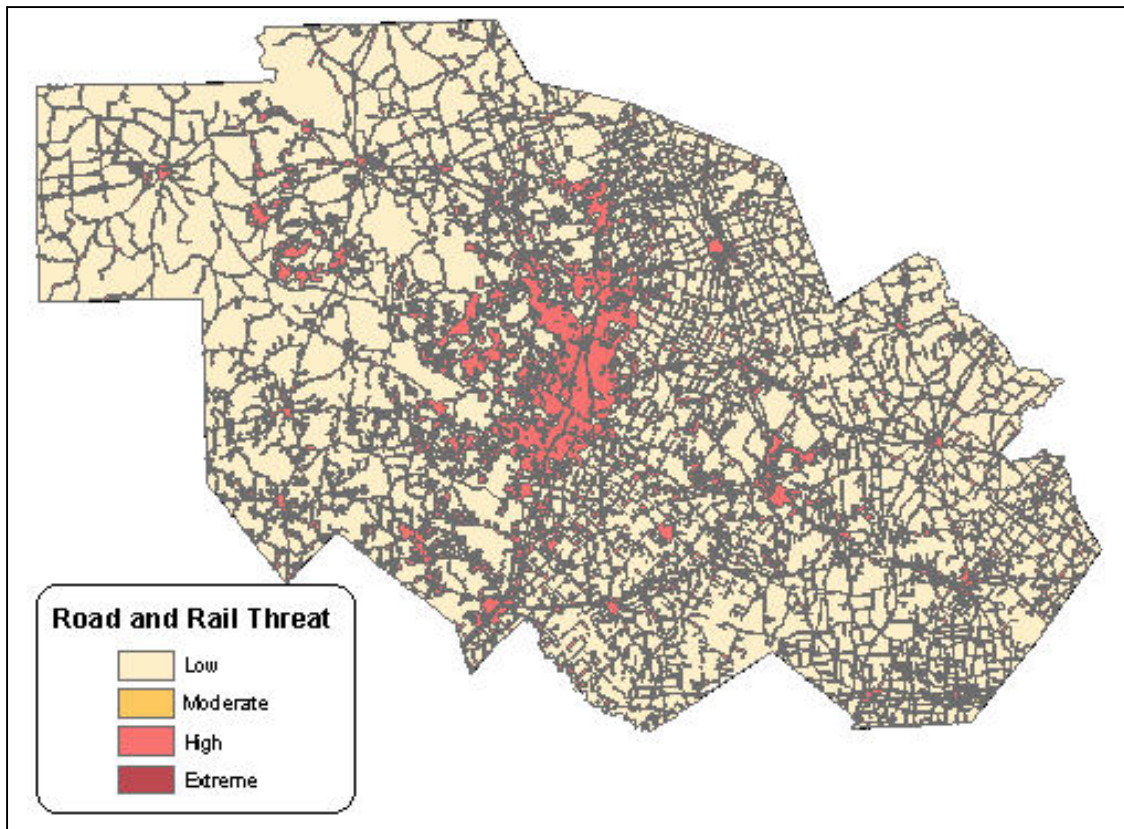


Figure 4.14 Threat from Roads and Railroad Corridors

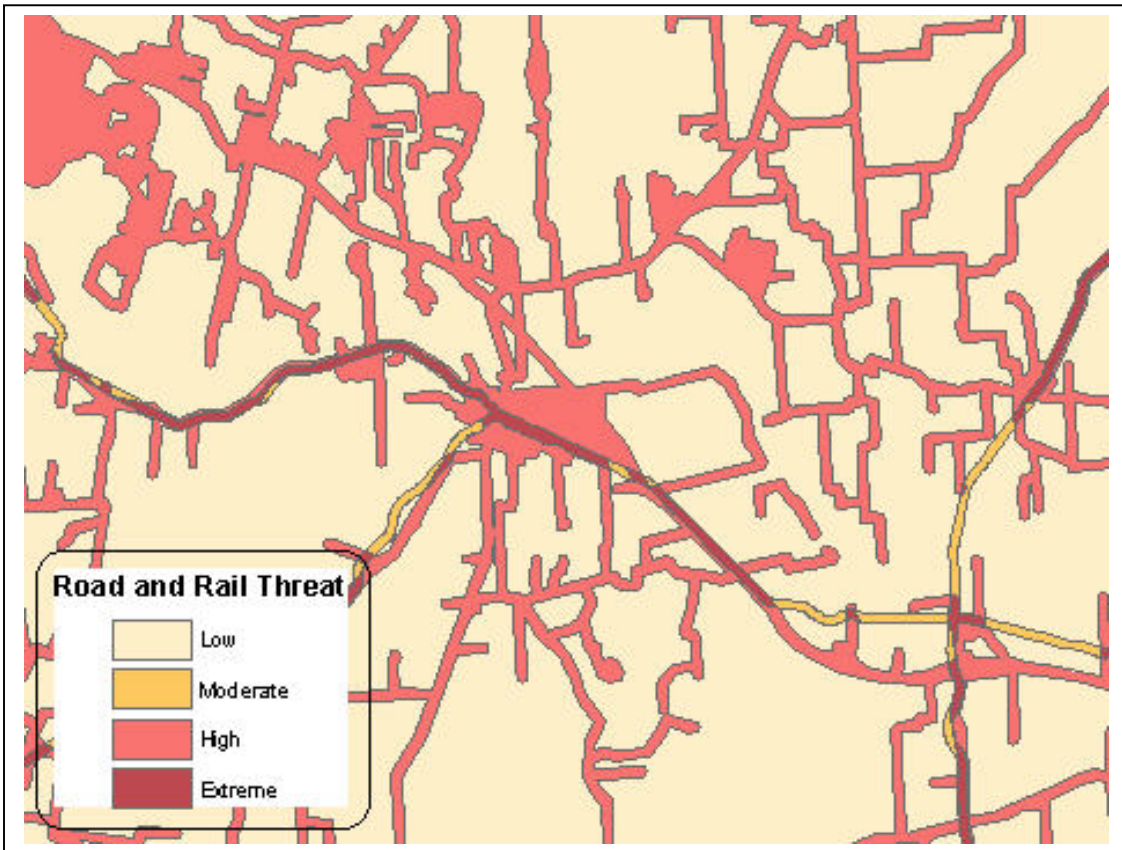


Figure 4.15. Detail of Threat from Road and Railroad Corridors

The final component of the static threat incorporates the location of fire stations that can respond to wildland fire. According to conversations with Forest Service personnel (Gray, 2004), 5 miles from a fire station is a reasonable distance to consider for rapid emergency response purposes; beyond that distance, and under extreme weather conditions, fires will have a chance to become well established and, if they contact a structure, will likely cause considerable damage before they can be extinguished. Thus, areas beyond 5

miles from a fire station are under greater threat than those within a 5-mile buffer. (Note that this does not take into consideration transportation corridors).

As explained in section 4.1, the majority of structures comprising the WUI are considered to be within 400 feet of a named road. Structures are therefore within the same buffer that is considered to be a high source of ignitions – roads. The road buffer is then considered to be not only an ignition source but likely location of structures and thus a high threat areas. Areas outside of the road buffer are under a lower threat. In this overlay, the railroad buffer is absent since structures are less likely to lie within a railroad buffer.

The combination of road buffer and emergency response buffers produced a map with four classes ranging again from “Low” to “Extreme”. Low represents areas that are outside of the WUI (road) buffer and within 5 miles of a fire station. An “Extreme” area is within the WUI buffer and outside of the 5-mile response buffer. This area is likely to have structures and is subject to slow emergency response. Figures 4.16 and 4.17 display the results of the overlay. In Figure 4.16, please note the clusters of development, as defined by the merged road buffers, which lie outside the 5-mile response area. These clusters are typical of wildland urban interface areas that develop along transportation routes outside of incorporated areas and beyond the protection of emergency response.

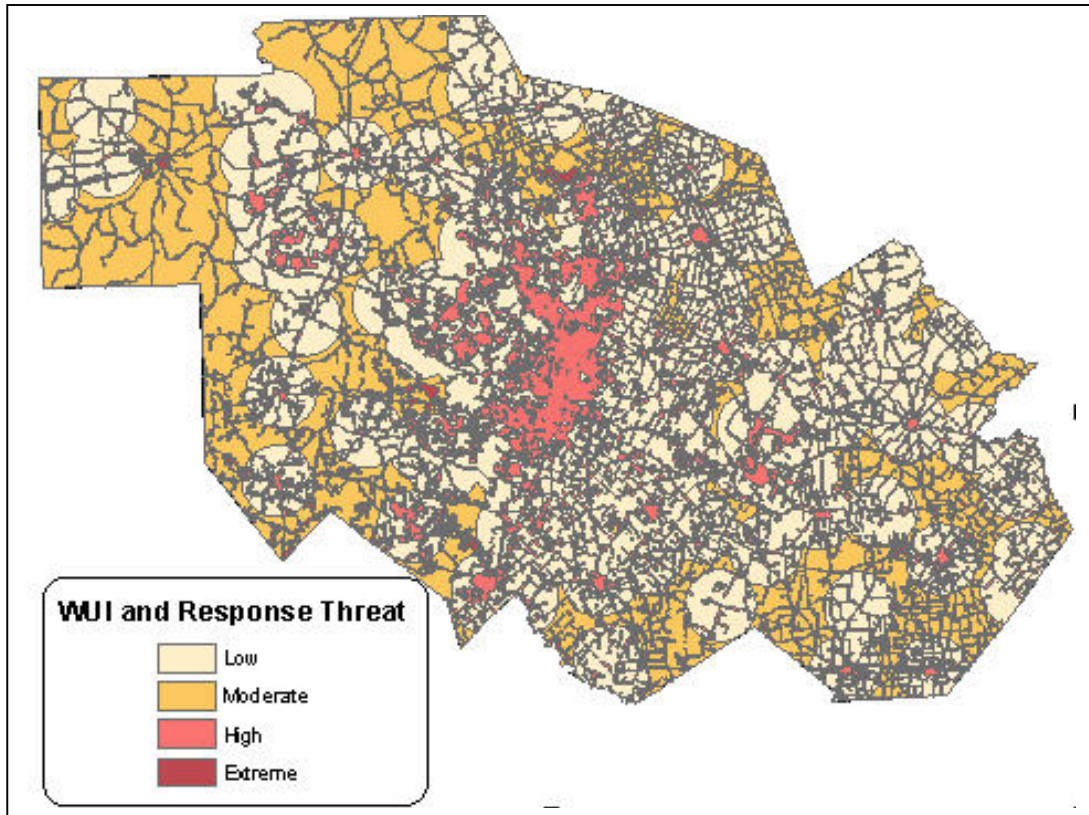


Figure 4.16 Threat to WUI

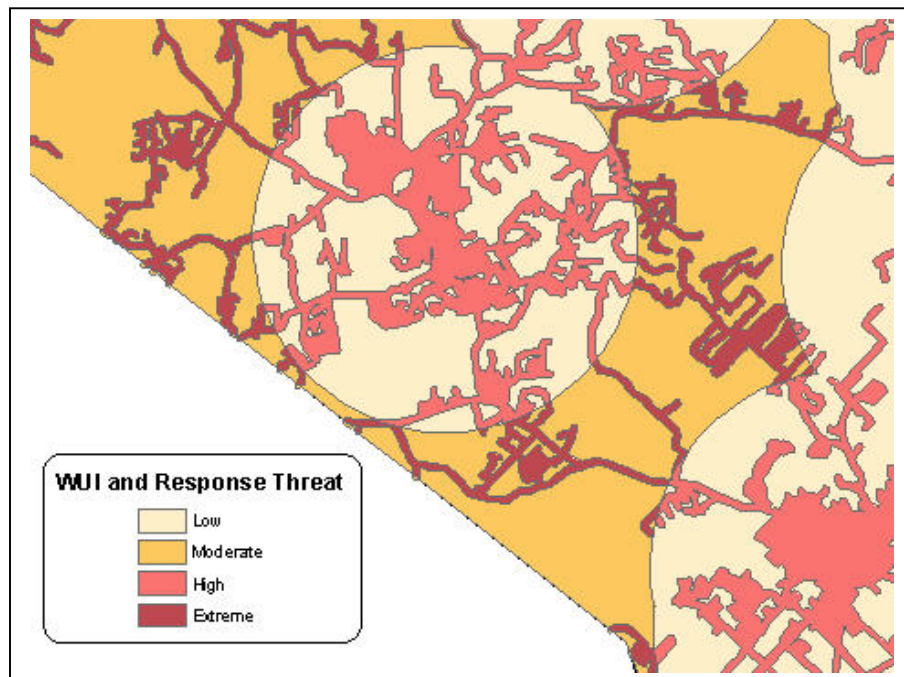


Figure 4.17 Detail of WUI Threat Overlay

The final overlay for the static threat methodology consisted of the four threat layers: fuels, slope, road and rail, and WUI. The four components contribute unequally to the overall threat and therefore were weighted for input in this particular overlay scenario. Fuels are obviously most important in that without fuel there is no fire. A weighting value of 40% was assigned to the fuel threat layer. Slope is a major factor in wildland fire with higher slopes contributing to extreme behavior. The slope threat layer was assigned a weighting value of 30%. The road and rail layer and the WUI layer are somewhat arbitrary in that they represent possible locations that contribute to fire ignitions and threaten structures in the interface. Both of these layers were assigned a weighting value of 15% each. The four weighted layers were overlaid to produce a final threat layer representing static features as displayed in Figures 4.18 and 4.19.

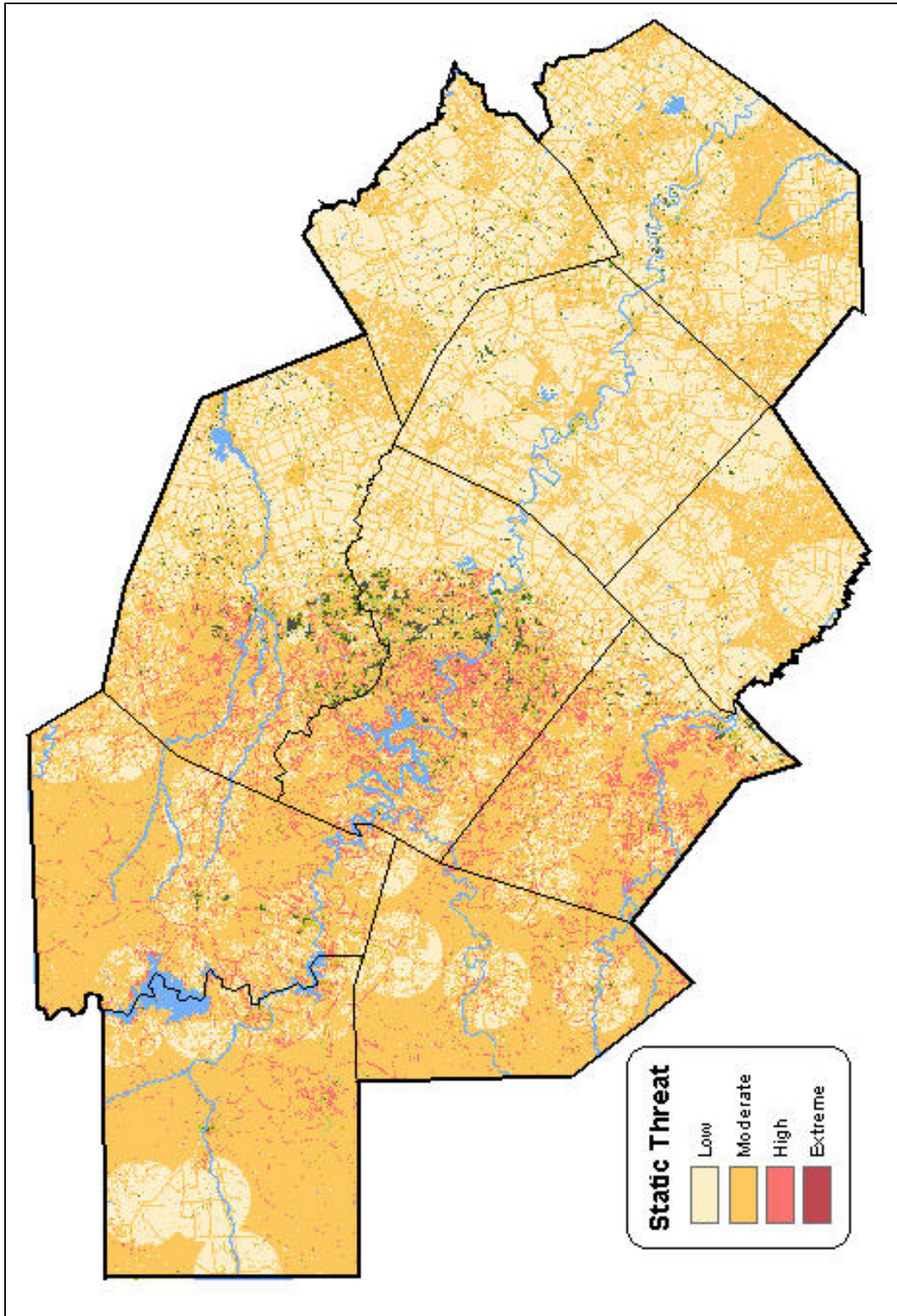


Figure 4.18 Threat Classes from Combined Static Features

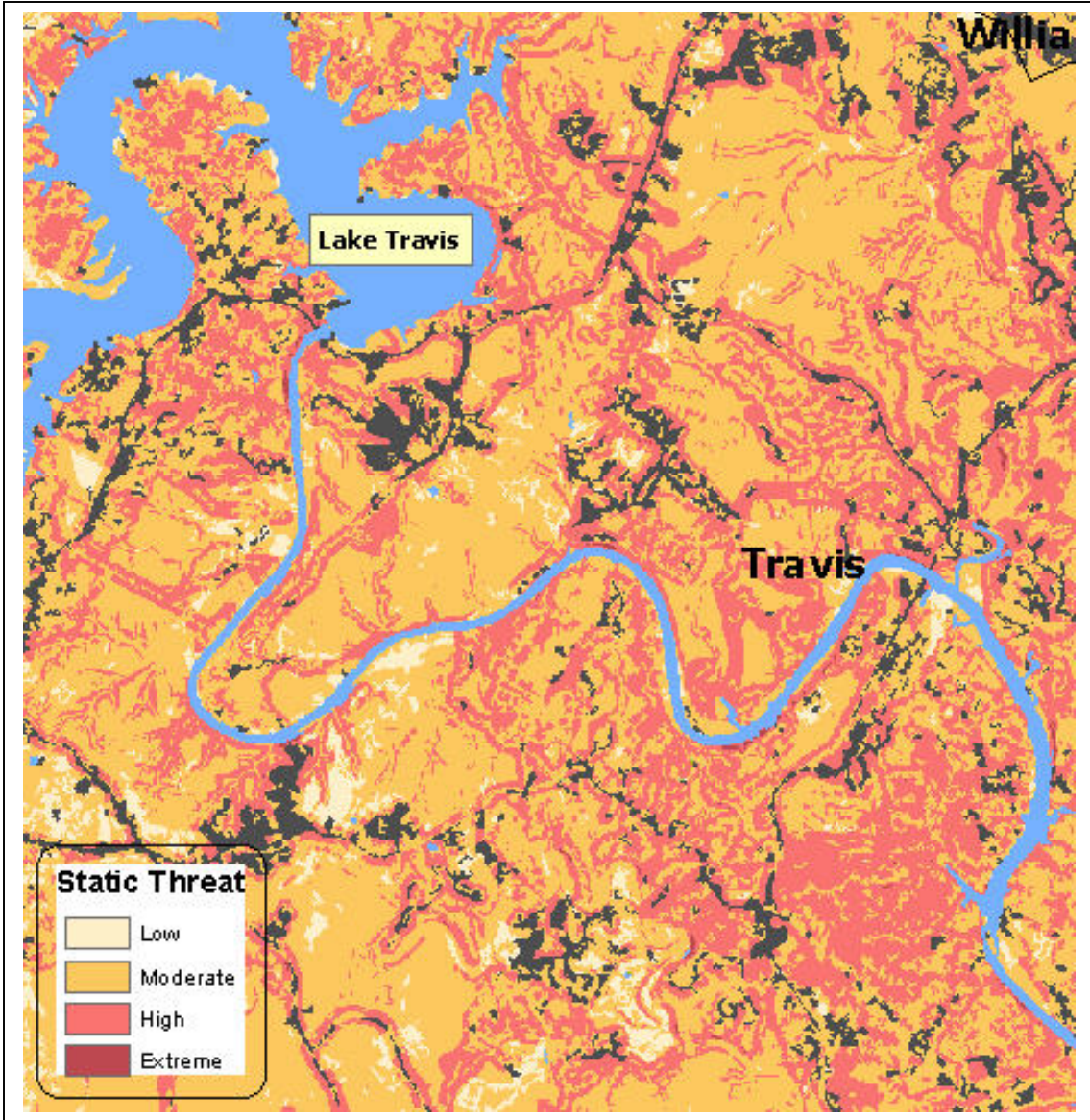


Figure 4.19 Detail of Threat Classes for Static Features

### 4.3 Natural Resource Features

One of the goals of this project was to examine potential threat of wildland fire to natural resources. Specifically, this analysis examined the overlay of highly erodible soils within important subwatersheds that contribute water to the City of Austin and the Lower Colorado River Authority. The concern is that highly erodible soils, if left exposed after an extreme wildfire that removes the majority of vegetative cover, are subject to being washed down slope by a heavy rainfall event. Soil erosion, as a major contributor to water pollution and sedimentation of reservoirs, is a target of mitigation by land and water resource managers.

This analysis combined information from the U.S. Soil Conservation Service SSURGO database within subwatersheds provided by the City of Austin Water Utilities (Figure 4.20). Overlaying fuel models and slopes with the soils and watershed layers produced a threat analysis. Figure 4.21 displays the U.S. SCS SSURGO database categories of potential damage level to soils following a wildfire. It should be noted in Figure 4.21 that there are inconsistencies in damage levels, particularly evident in the southeast section of the map across county boundaries. Soil polygons often end at county boundaries and do not have the same characteristics in the adjoining county. This problem is recognized and is an inherent problem from the fact that soil data were compiled on a county-by-county basis.



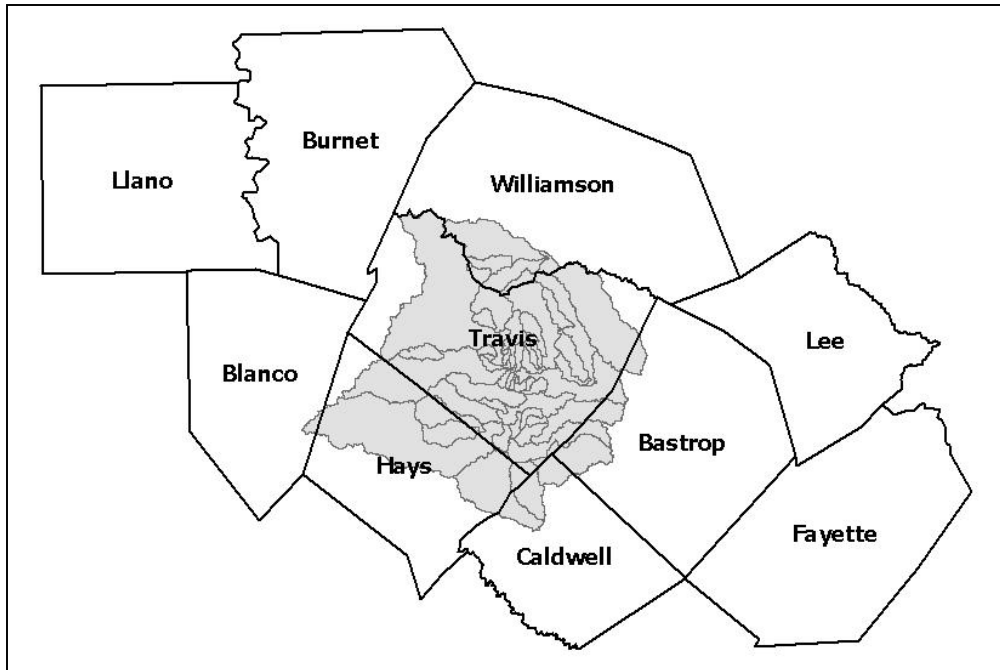


Figure 4.20 Subwatersheds Included in Threat Analysis

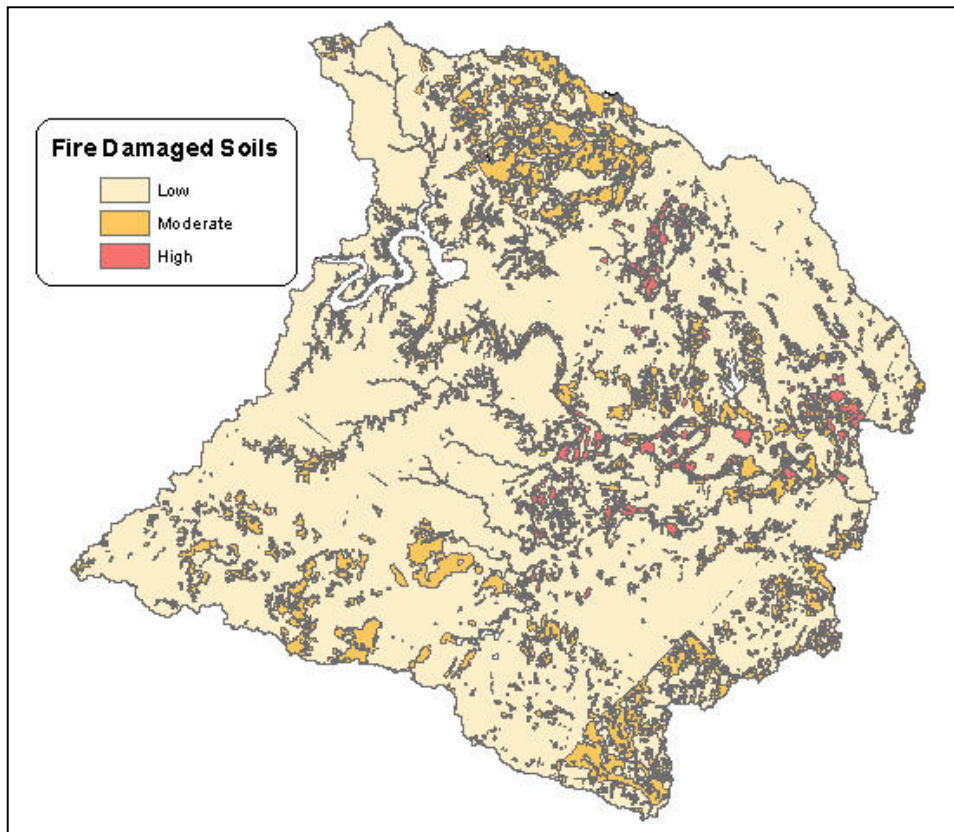


Figure 4.21 Potential Soil Damage Levels from Wildland Fire

Soil that has a high potential for damage following a wildfire may never be subjected to intense fire due to overlying vegetation types. For this analysis, a combination of soil characteristics, fuel model types and slope characteristics were combined to better determine potential threat to subwatersheds. For the overlay, Fuel Models 4 and 6 were considered important in that they can exhibit high fireline intensity with the potential to remove overlying and groundcover vegetation. Although grasses are subject to rapid and complete removal from fire, the area typically has a faster rate of regrowth than shrubs, and thus is considered to be less critical to this analysis. The four-slope class layer ("Low" – "Extreme") was combined with the fuels layer to produce an overlay showing "hot" fuels within at risk soils.

The result of the overlay shows that a small percentage of the surface area of the subwatersheds is subject to damage from fire, using soil damage values obtained from SSURGO data. Less than 1% (7,887 acres) of the 924,052 acres that comprise the subwatersheds is subject to soil damage following a wildfire. Of the total damage, the majority of acreage (7,729) of soil damage falls within the "Low" category. However, there are several subwatersheds that contain a higher percentage of potentially damaged soils. The subwatersheds in Table 4.1 contain approximately 10% and greater surface area of threatened soils.

Due to the small number of acres involved, a figure displaying damaged soils within the subwatersheds is not useful at the scale of this document.

However, a detail of several centralized subwatersheds is displayed in Figure 4.22 as an example. (Please note that all threat categories are combined into one classification color).

Table 4.2 Potential Damaged Soil Acreage

<b>Watershed Name</b>	<b>Soil Acres</b>	<b>Watershed Acres</b>	<b>Percentage</b>
Harper's Branch	31.21	334.48	9.3
East Bouldin	192.78	1214.19	15.9
South Boggy	510.41	3051.42	16.7
West Bouldin outlet	308.45	1800.28	17.1
Blunn	163.4	911.62	17.9

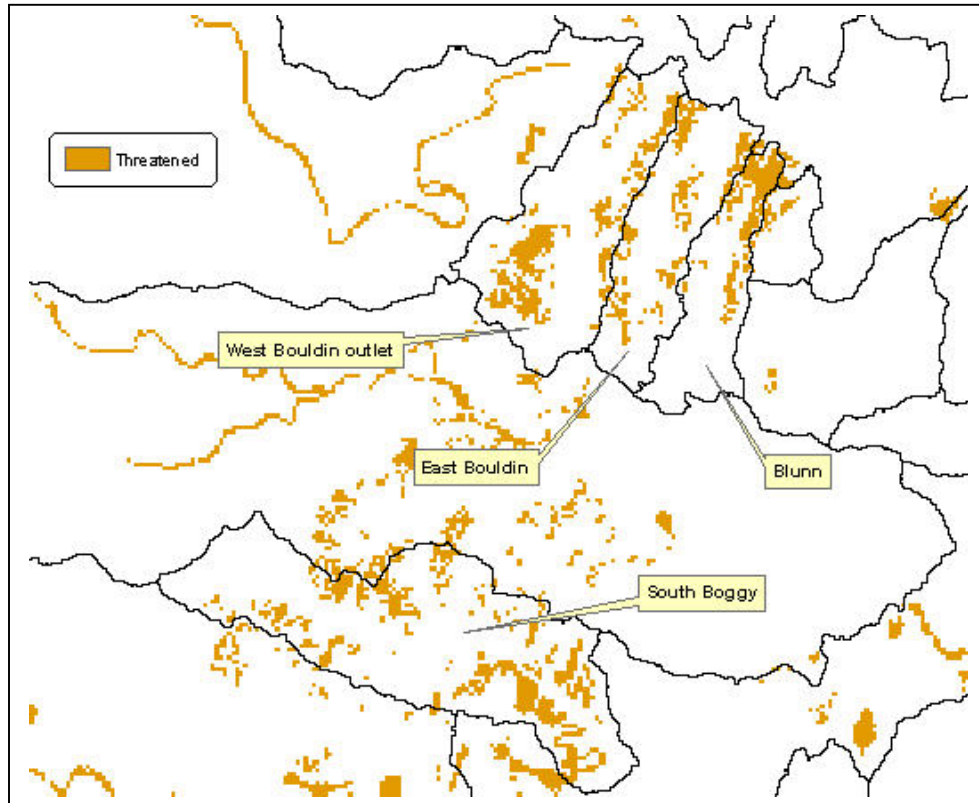


Figure 4.22 Detail of Threatened Soils in Subwatersheds

#### 4.4 Real-Time Weather Component

The final component of this project integrates real-time weather into wildland fire threat. Static features, such as fuel models and topography, drive fire behavior, as examined in section 4.2, but as important, if not more so, are weather factors. Hot, dry, windy conditions create far more extreme wildland fire behavior than calm, moist weather. The methodology in this project sought to incorporate real-time weather conditions recorded at a series of weather stations throughout the study area with the static features to produce threat mapping that is pertinent at a given time.

The fire behavior characteristics that were mapped using steps outlined in section 3.8 included Rate-Of-Spread (ROS), Fireline Intensity (FI and Flame Length (FL). A series of maps were produced for each fire of the three behavior characteristics and four fuel model types. The maps were combined for each fire behavior and presented as potential threat conditions for the study area for a specific time. For demonstration purposes, the weather chosen was taken from March 16, 2003, at 14:00 hours, and was chosen as a representation of weather and wildfire conditions that can exist during the winter months in Texas. Most people are aware of hot and dry conditions in the summer months in central Texas, but wildfire behavior can be high during winter months when fuels are senescent and north winds following a cold front are strong and dry. The following maps reflect those weather conditions.

Under the same conditions of humidity and wind speed, Rate-Of-Spread is much higher in Fuel Model 1 than in the other three fuel models. Grasses dry very rapidly and burn very quickly, even in light wind conditions. Although grass fuels are not as heat intensive nor have high flame lengths, they do pose a threat to wildlife, emergency personnel and WUI due to rapid fire movement. The ROS calculations were categorized into five classes ranging from "Low" to "Extreme". The "Low" class represents ROS less than 1 mph and "Extreme" is greater than 4 mph, a speed that is difficult for emergency personnel to outrun when burdened by fire gear. The following map (Figure 4.22) displays potential ROS for all four fuel models across the study area.

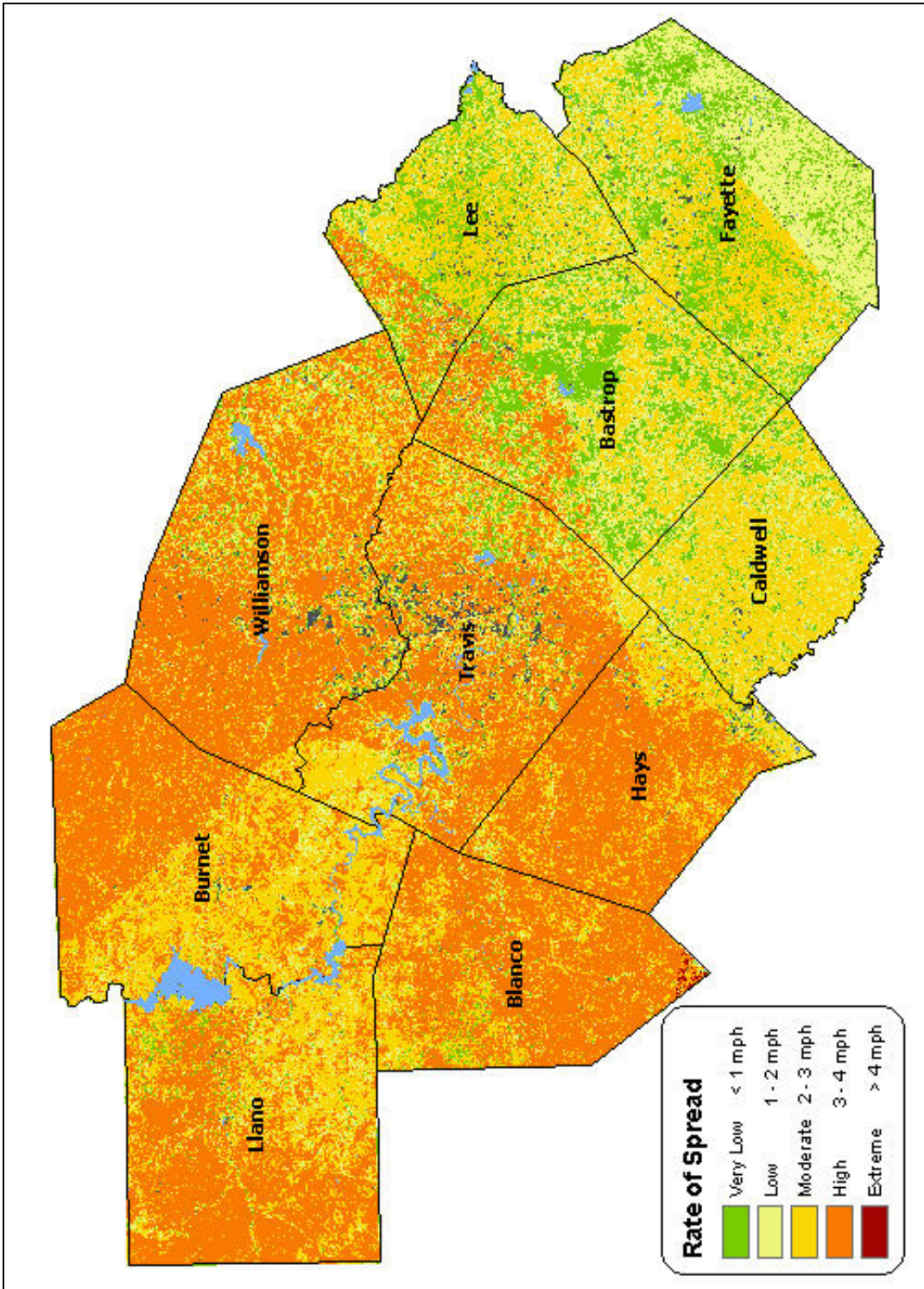


Figure 4.23 Potential Rate-of-Spread Under Specific Weather Conditions

Please note that the Figures 4.22 through 4.27 represent weather from nine weather stations inside and surrounding the study area and the threat maps are a combination of interpolated fire behavior based upon point weather and the fuel types potentially exhibiting that behavior. Another set of weather conditions would produce a completely different set of maps.

The following two maps (Figure 4.23 and 4.24) are examples of Fireline Intensity and Flame Length. The importance of these two fire behavior characteristics pertain to potential damage from fire and the ability of emergency crews to combat fire. High fireline intensity means, literally, that the fire is extremely hot. It is difficult to get close to a hot flaming front and the heat from such a front preheats fuels in its path and also has high potential for igniting building materials such as asphalt shingles and wood siding. Heavier, woody fuels, such as the shrub group, have higher FI, particularly Fuel Model 4 that is approximately 6 feet high and is often highly resinous vegetation, such as Eastern red Cedar or Ashe Juniper.

Flame length affects both flame spread and emergency response. High flame lengths, particularly when pushed by the wind, preheats downwind fuels, contributing to damage and rate of spread. High flame lengths burn not only low vegetation but also can often torch canopies of short trees. Flame length is also a driver of emergency response tactics. Flames of 4 feet and less can usually be fought directly whereas flames greater than 4 feet in height require indirect personnel attack, mechanized approaches or other tactics. Fireline intensity and

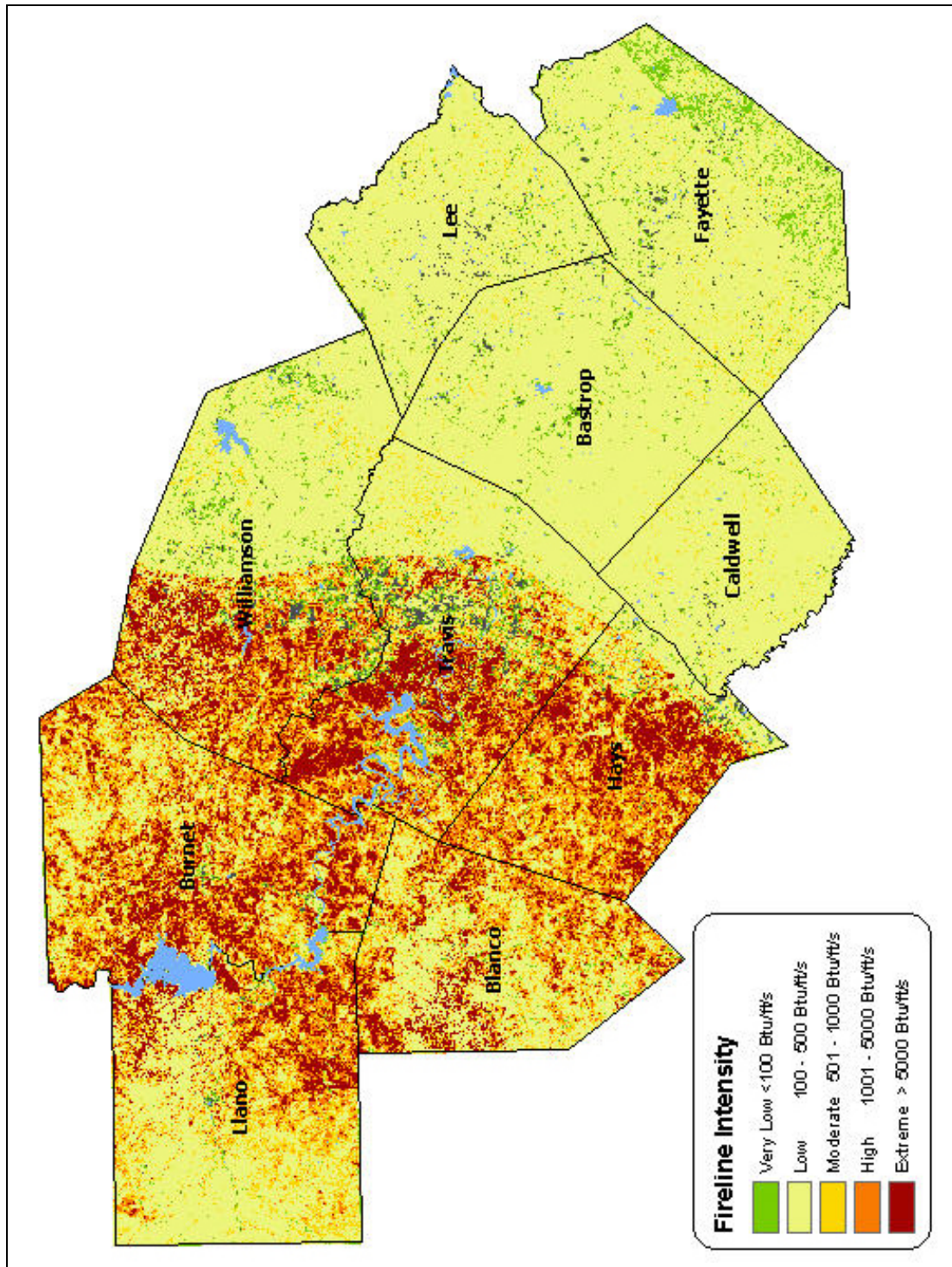


Figure 4.24 Fireline Intensity Threat from Specific Weather Conditions



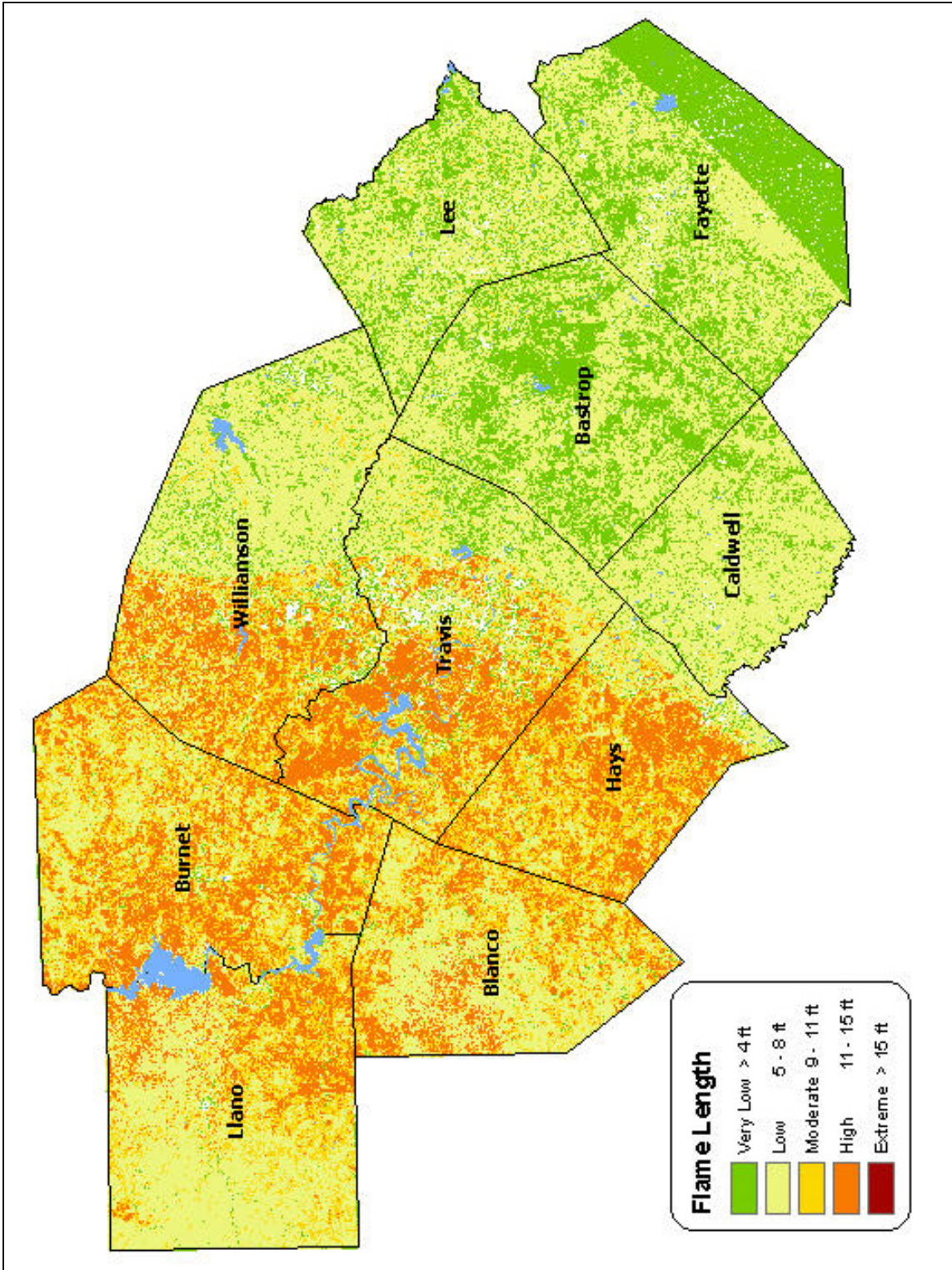


Figure 4.25 Flame Length Threat from Specific Weather Conditions

flame length have a direct relationship – the hotter the fire, the longer the flame length. Increased flame length is associated with Fuel Models 4 and 6 in the shrub group.

The final map in this series of weather related conditions involves Probably of Ignition (POI). POI from the BehavePlus fire model is based upon fuel shading from the sun, 1-hour (grasses) fuel moisture and dry-bulb temperatures. The POI in this case is the probability that a firebrand will cause an ignition. POI is another indicator of threat conditions when responding to a wildland fire and therefore is useful information for emergency response personnel. Figure 4.25 displays POI for the demonstration weather conditions.

The mapped results of the methodology were in digital format so as to be useful by natural resource managers and emergency management personnel. One example of the application of the use of the results is for emergency response to an imaginary wildland fire reported in the 20,000 block of Thurman Bend Rd., in Travis County. Emergency personnel can locate the address, using address geocoding, and determine the potential rate of spread, fireline intensity and flame length to help determine proper response and resource dispatch to the fire. In the example in Figures 4.26 and 4.27, the wildland fire is located with “High” ROS but with “Low” flame length.

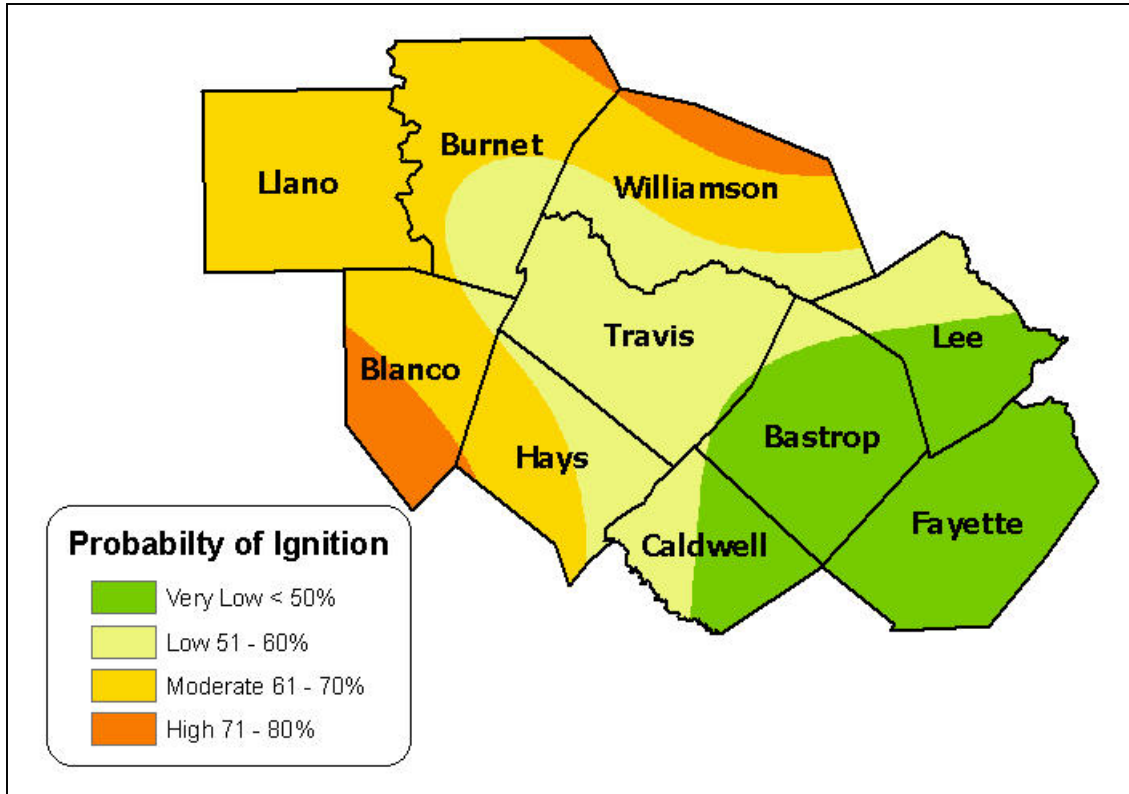


Figure 4.26 Probability of Ignition Based Upon Specific Weather Conditions

The methodology to create the maps for real-time weather conditions was detailed in a step-by-step manner and is available in a pdf format document for distribution to emergency management personnel who use GIS for wildland fire planning.

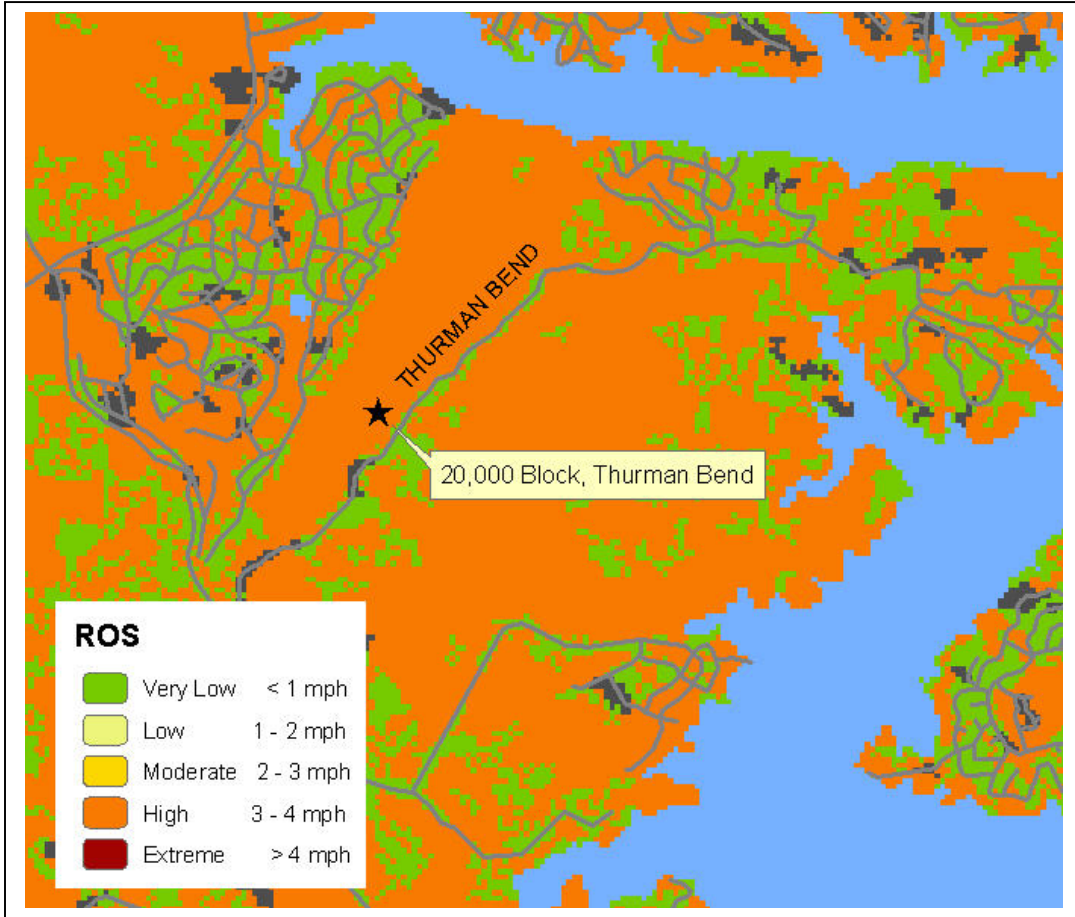


Figure 4.27 Example of ROS Application

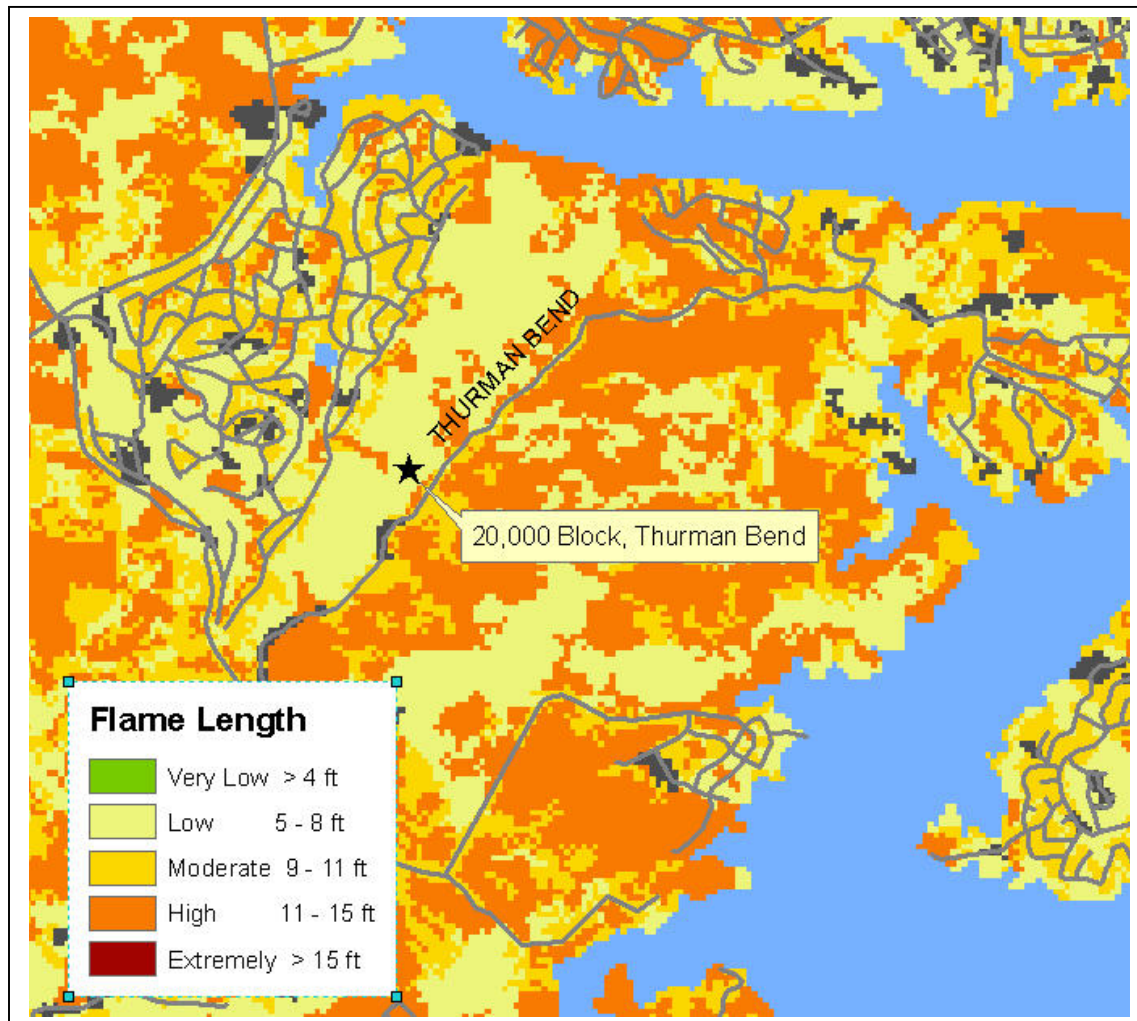


Figure 4.28 Example of Flame Length Application

## CHAPTER 5

### CONCLUSIONS

#### 5.1 Comparison to other wildfire threat models

The Wildland Fire Behavior Mapper (WFBM) methodology developed for this study helps to fill a gap in wildland fire threat analyses provided by other models currently in use in various parts of the country. For example, the Oklahoma Fire Danger Model provides excellent hourly threat analyses for the whole state of Oklahoma based upon a network of weather stations and AVHRR satellite imagery. However, the analyses are based upon a 1 kilometer grid cell and slope is assumed to be less than or equal to 25% for the state, so it is an undervalued component of the analyses. "... the OKFD Model is not designed for specific fire behavior predictions for a given field, fuel type, slope, etc., but rather for the predominant vegetative fuel type over a 1-km square, mainly flat region," (Carlson, 2005).

At a much finer scale is the threat analysis conducted by the City of Austin Fire Department for western Travis County (Baum, et al, 2003). Fuel models polygons were "heads-up" digitized from 1 meter DOQQs (at considerable time and expense) and fire department personnel inventoried, on-foot, defensible space for structures throughout neighborhoods. Although the scale of the spatial information was very detailed spatially, the analysis only considered monthly weather averages, so specific real-time weather events were not included.

The WFBM produced an analysis at an intermediate scale, between that of the city and the state levels, and covered an area of approximately 8,500 square miles. The

model included slope, road networks and potential emergency response in a manner similar to the City of Austin but also real-time weather events, as does the Oklahoma model.

## 5.2 Fuel model classification

The classification of fuel models using Landsat 7 satellite imagery was considered to be ideal for this type of methodology for two main reasons. First, the imagery was relatively inexpensive for the square mileage of the study area. To expand the analyses, a study the size of the State of Texas would require all or portions of 46 Landsat satellite scenes. Although the original cost of all the scenes for Texas is extremely high, compared to most other commercial imagery the cost is low, and a library of images housed at the Texas Natural Resources Information System, available at the cost of copying, provides affordable land cover information.

Second, the methodology used unsupervised classification techniques for fuel model identification. The classification process is relatively easy to conduct using image processing software, some of which is free for download (Landgrebe and Biehl, 2004), and can be used by GIS professionals with little additional training. The goal behind this project was to design methodology that can be easily duplicated in GIS offices in locations throughout the state without great expense for imagery, software and training.

Having stated that unsupervised classification of Landsat 7 imagery appeared ideal for this project, there were several problems with classification accuracy that were

not expected considering the low number of fuel model categories that were used. Five percent of the test sites were classified as grassland, Fuel Model 1, whereas they were determined to be low brush or Fuel Model 6, in aerial photography. The result of the misclassification is different fire behavior estimates for specific weather conditions; in this case higher rate of spread but lower fireline intensity.

Another problem with satellite image classification for fuel models deals with seasonality and land cover, specifically cropland. Large portions of Williamson County, eastern Travis County and Caldwell County are farmed for crops. Depending upon the crop type and the time of the year, fields may be bright green, harvest gold or brown earth. Imagery records the surface at that given time and classification can be confusing. For purposes of this study cropland was classed the same as Fuel Model 1 at a low fuel threat. This is an overestimation of the static threat level under all conditions except if plants are high and dry, as is sometimes the case in summer months with little rainfall. By overlaying the cropland class on top of the static threat map, a visual adjustment can be made to the map to account for lower threat potential.

Following consultation with Texas Forest Service officials, the biggest problem with model results in its current form is that it does not identify high static threat conditions in the piney woods of the Blackland Prairies, such as in eastern Bastrop County. Fire managers in that region often respond to WUI fires in areas that appear as "Moderate Threat" in the static map. The confusing factor in the model is that conifers were assigned to the timber class and were therefore assigned a Fuel Model 6 (timber litter) class. The pine understory, however, is often dense yaupon (*Ilex vomitoria*), a



resinous shrub that acts as a primary fuel source, promoting crown fires in pines by moving flames from litter into low-lying pine branches (Gray, 2005). The static threat map, with current results, does not identify potential fire behaviors associated with yaupon understory. Static threat can be adjusted by teasing out a "Conifer" class from leaf-off imagery and assigning a higher fuel model threat value to the class, in this case a Fuel Model 7 typical of palmetto-galberry under pines in Southeastern forest.

BehavePlus software calculates fire behavior for surface fires, not crown fires, therefore the weather component of the WFBM will not provide adequate information about threat potential due to weather that moves fire into tree crowns. By using Fuel Model 7 for the "Conifer" class, the weather component will still play a role due to fact that fire behavior within Model 7 is higher than that of Fuel Model 9.

### 5.3 Model Testing

An effort was made over a two-year period to obtain historical fire data for the State of Texas but repeated inquiries to state fire offices resulted in the response that there were no historical official records to be found. Ironically, at while presenting results to a Texas Forest Service Regional Fire Manager, it was determined that there are records of a few recent extreme fire events that could be incorporated into the study. Unfortunately, the fire locations were not within the CAPCO study area. At the time of the completion of this study, plans are underway to conduct another threat analysis for a section of North Central Texas, and there are historical wildfire records for a location within the study area. The threat analysis will be tested using historical

weather conditions and static threat components to determine the validity of the model to identify the historical fire event.

#### 5.4 Natural Resource Impacts

The soil overlay results provide useful information for water resource and wildlife managers, particularly in western portions of the study area. The Balcones Canyonlands Preserve (BCP), a 24,000-acre conservation effort in western Travis County co-managed by the City of Austin and Travis County will use results of the model to examine potential impacts to important streams, watersheds and habitats within its boundary (Connally, 2003). Numerous streams are habitat to several aquatic Threatened and Endangered (T&E) species. Identification of high erosion potential slopes within the watersheds can direct mitigation efforts in case of a wildfire that results in extreme vegetation loss.

In addition to aquatic species, the BCP is home to two T&E bird species. One of the initial goals of the WFBM was to identify high threat areas within nesting habitats for T&E species. Although attempts were made to obtain historical nest locations and/or habitat ranges for the two species, the information was either not available in digital map format or was protected due to the importance to development in the area. The results from this project will be made available to the Texas Parks and Wildlife and other resource managers in the area for use within their planning programs.

## 5.5 Future Plans for the WFBM

The methodology was designed to be relatively simple, incorporate commonly used remote sensing and GIS software, and to be beyond the CAPCO study area. One of the major difficulties with the model in its current form is that it requires considerable “hands-on” to gather data from weather stations, enter weather into BehavePlus, place the results into a database, and then run the GIS mapping component. The GIS component has been automated into an ArcGIS™ Model that will take the fire behavior information from database to mapped output.

The next goal is to automate weather data collection and fire behavior calculation. A verbal agreement has been obtained with the Texas Mesonet at Texas A&M University to allow direct download of hourly weather data (Creager, 2004). The Texas Mesonet site will provide a more dense coverage of weather stations allowing for better interpolation of weather/fire behavior across the study area.

A second goal is to automate fire behavior calculations. An agreement will be sought from the authors of Behave to incorporate the source code for the basic fire behavior components into the model. A computer program will be required which will extract pertinent weather data for a given time, feed the information to the fire behavior calculator, write the results to a database which will be read by the GIS model and mapped. The concept is that this model can be designed to run automatically every hour, as required during periods of high fire danger, or for planning purposes using simulation data.

Ultimately, whether or not the model is completely automated, the resulting threat maps can be authored on the web using ArcIMS™ (ESRI, Inc.) map server software. This will make weather-based wildfire threat maps readily available to regional fire managers throughout the study area.

## REFERENCE LIST

- Albini, F. A. 1976. Estimating wildfire behavior and effects. USDA, For. Serv. Gen. Tech. Rep. INT-30. Intermountain. Forest and Range Experimental Station, Ogden, UT. 92 p.
- Albright, D., and B.N. Meisner, 1999, "Classification of Fire Simulation Systems," Fire Management Notes, U.S. Department of Agriculture, Forest Service, Vol. 59, No. 2, p. 5.
- Allgöwer, B., J.D. Carlson, and J.W. van Wagendonk, 2003, "Introduction to Fire Danger Rating and Remote Sensing – Will Remote Sensing Enhance Wildland Fire Danger Rating?" in Wildland Fire Danger: Estimation and Mapping, Chuvieco, Editor, World Scientific, New Jersey, 264 pp.
- Andrews, P.L., 1998, "An Integrated Wildland Fire Decision Support System – Progress and Plans," White Paper, USDA Forest Service, Rocky Mountain Research Station, P.O. Box 8089, Missoula, Montana, 59807, 13 pp. <http://www.firelab.org/fbp/fbpps/fbpps/pandrews/intdecision.pdf>.
- Andrews, P.L., C.D. Bevins, and R.C. Seli, 2004, BehavePlus fire modeling system Version 3.0 User's Guide, United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-DRAFT, 153 pp.
- Andrews, P.L., and L.P. Queen, 2001, "Fire modeling and information systems technology," *International Journal of Wildland Fire*, Vol. 10, p.343-352.
- Anderson, H.E, 1982, "Aids to determining fuel models for estimating fire behavior," USDA Forest Service, Gen. Tech. Rep. INT-122, 22 pp.
- Anderson, L., 1995, "Terrestrial and Wildlife Habitat," in Fire Effects Guide, National Wildfire Coordinating Group, Sponsored by 'Prescribed Fire and Fire Effects Working Team,' National Interagency Fire Center, Boise, Idaho, NFES 2394.
- Atkinson, D.R., 2000, in Preface to Mapping Wildfire Hazards and Risks, Sampson, Atkinson and Lewis, Editors, Food Products Press, New York, 343 pp.
- Bachman, A. and B. Allgöwer, 2001, "A Consistent Wildland Fire Risk Terminology is Needed", *Fire Management Today*, Volume 61, No. 4, p. 28.

- Baum, K, C.K. Thies and K. A. Kilgore, 2003, "Urban-Wildland Interface Risk Model for the West Austin / Travis County Study Area," a GIS-based model developed by the City of Austin Fire Department and the Texas Forest Service, Bastrop Office; based on personal conversations with the contributors.
- Bradshaw, L, and E. McCormick, 2000, Fire Family Plus User's Guide, Version 2.0, U.S. Dept. of Agriculture, Forest Service, Rocky Mountain Research Center, Gen. Tech. Report RMRS-GTR-67-WWW, 124 pp.
- Burton, T.A., D.M. Dether, J.R. Erickson, J.P. Frost, L.Z. Morelan, L.F., Neuenschwander, W.R. Rush, J.L. Thornton, and C.A. Weiland, 1999, "A Fire-Based Hazard/Risk Assessment," Fire Management Notes, U.S. Department of Agriculture, Forest Service, Vol. 59, No. 2, p. 31.
- Cao, C. and N. S-N. Lam, 1997, "Understanding the Scale and Resolution Effects in Remote Sensing and GIS", in Scale in Remote Sensing and GIS, D.A. Quattrochi and M.F. Goodchild, Eds., CRC Press Inc., Boca Raton, Florida, 57-72.
- CAPCO, 2004, Capital Area Council of Governments, Information Clearinghouse , [http://www.capcog.org/Information\\_Clearinghouse/geospatial\\_main.asp](http://www.capcog.org/Information_Clearinghouse/geospatial_main.asp).
- Carle, David, 2002, "Burning Questions: America's Fight with Nature's Fire", Praeger Publishers, Westport, CT., 298 pp.
- Carlson, J.D., 2005, Oklahoma Fire Danger Model, on-line wildland fire threat analysis model, <http://agweather.mesonet.ou.edu/models/fire/description.html>.
- Chen, K., R. Blong, and C. Jacobson, 2003, "Towards an Integrated Approach to Natural Hazards Risk Assessment using GIS: With Reference to Bushfires," Environmental Management, Vol. 31, No 4., pp 546-560.
- Chuvieco, E., 2003, Wildland Fire Danger: Estimation and Mapping, Chuvieco, Editor, World Scientific, New Jersey, 264 pp.
- Chuvieco, E., D. Raiño, J. Van Wagtendok, F. Morsdof, 2003, "Fuel Loads and Fuel Type Mapping," in Wildland Fire Danger: Estimation and Mapping, Chuvieco, Editor, World Scientific, New Jersey, pp. 119-142.
- Clark, B., 1994, "Soils, Water and Watersheds," in Introduction to Fire Effects RX340, National Wildfire Coordinating Group, Sponsored by Prescribed Fire and Fire Effects Working Team, National Interagency Fire Center, Boise, Idaho, NFES 2394.

- CNN, 1996, "Raging wildfires leave path of destruction in Texas," February 22, 1996, CNN Interactive News website, [http://www.cnn.com/US/9602/texas\\_wildfires/](http://www.cnn.com/US/9602/texas_wildfires/)
- CNN, 2000, "Texas takes the lead in number of U.S. wildfires," September 7, 2000, CNN.com Interactive News website, <http://archives.cnn.com/2000/US/09/06/wildfires.02/>.
- Connally, K., 2003, personal conversations. Travis County Environmental Specialist and BCCP Coordinator, Austin, Texas,
- Cordell, H.K., and E.A. Macie, 2002. "Population and Demographic Trends." In Human Influences on Forest Ecosystems: The Southern Wildland-Urban Interface Assessment, E. Macie, L.A. Hermansen (eds.), Asheville, North Carolina, U.S. Department of Agriculture, Forest Service, Southern Research Station, General Technical Report SRS-55, pp. 11-34.
- Core, J.E., and J.L. Peterson, 2001, "Public Health and Exposure to Smoke," in Smoke Management Guide for Prescribed and Wildland Fire: 2001 Edition, National Wildfire Coordination Group, National Interagency Fire Center, Boise, Idaho, NFES 1279, 226 pp.
- Cowen, D.J., and J.R. Jensen, 1998, "Extraction and Modeling of Urban Attributes Using Remote Sensing Technology," in People and Pixels: Linking Remote Sensing and Social Science, D. Liverman, E.F. Moran, R.R. Rindfuss and P.C. Stern, Eds., National Academy Press, Washington, D.C., 244 pp.
- Creager, G., 2004, Personal conversations, Network Engineer, Texas Mesonet web weather services, Dept of Atmospheric Sciences Texas A&M University, <http://mesonet.tamu.edu/>
- CSFS, 2002, "Colorado Wildland Urban Interface Hazard Assessment Methodology," Colorado State Forest Service, <http://www.colostate.edu/Depts/CSFS/Methodology.pdf>
- Dash, N., 1997, "The Use of Geographic Information Systems in Disaster Research," in International Journal of Mass Emergencies and Disasters, Vol. 15, No. 1, pp. 135-146.
- Demming, J.E., R.E. Burgan, J.D. Cohen, 1977, "The National Fire-Danger Rating System," 1978. Gen. Tech. Rep. INT-39, Intermountain Forest and Range Experiment Station, Ogden, UT: U.S.D.A., Forest Service.

- Donnay, J-P, M. J. Barnsley and P. A. Longley, Eds., 2001, "Remote Sensing and Urban Analysis", Remote Sensing and Urban Analysis, Taylor and Francis, London and New York, 268 pp.
- Englefield, P., B. Lee, and R. Suddaby, 2000, "Spatial Fire Management System," in Proceedings of Environmental Research Systems, Inc. (ESRI) User Conference 2000, <http://gis.esri.com/library/userconf/proc00/professional/papers/PAP489/p489.htm>.
- Epstein, J., K. Payne, and E. Kramer, 2002, "Techniques for Mapping Urban Sprawl," Photogrammetric Engineering & Remote Sensing, Vol. 63, No. 9, pp. 913-918.
- ERSI, 2000, "Wildland Fire Information Management Technology," An ERSI White Paper, ESRI, Inc. [http://www.esri.com/library/whitepapers/pdfs/wildland\\_fire.pdf](http://www.esri.com/library/whitepapers/pdfs/wildland_fire.pdf), 10 pp.
- FEMA, 1998, "Texas Wildfires," FEMA News article release, Federal Emergency Management Agency News website, <http://www.fema.gov/nwz98/tx0727.shtm>.
- FEMA, 2002, "Fires in the Wildland/Urban Interface", Topical Fire Research Series, U.S. Fire Administration, Federal Emergency Management Agency, Vol. 2., Issue 16, <http://www.usfa.fema.gov/downloads/pdf/tfrs/v2i16-508.pdf>
- Finney, M.A., and P.L. Andrews, 1999, "FARSITE – A Program for Fire Growth Simulation," Fire Management Notes, U.S. Department of Agriculture, Forest Service, Vol. 59, No. 2, p. 13.
- Gerard, S., and J. Pets, 1998, "Isolation or Integration? The Relationship Between Risk Assessment and Risk Management," in Risk Assessment and Management, R.E. Hester and R.M. Harrison, Eds. The Royal Society of Chemistry, Cambridge, UK., 168 pp.
- Goncalves, P.P. and P.M. Diogo, 1994, "Geographic Information Systems and Cellular Automata: A New Approach to Forest Fire Simulation," EGIS '94, Utrecht: EGIS Foundation, 1:603-617.
- Gottschalk, J., 2002, Firefighting, DK Publishing, Inc., New York, New York, 160 pp.
- Graham, R.T., 2003, "Hayman Fire Case Study," Russell T. Graham, Technical Editor, General Technical Report RMRS-GTR-114 (Revision), USDA, Forest Service, Rocky Mountain Research Station, 404 pp.



- Graham, J.D. and Wiener, J.B., 1997, Risk versus Risk: Tradeoffs in Protecting Health and the Environment, Graham and Wiener, Eds. Harvard University Press, 337 pp.
- Gray, R., 2003; 2005, Urban Wildland Interface Specialist, Texas Forest Service, Bastrop Office, Texas, personal communications.
- Green, K, M. Finney, J. Campbell, D. Weinstein, and V. Landrum, 1996, "Fire!™ Using GIS to Predict Fire Behavior," in Raster Imagery in Geographic Information Systems, S. Morain and S. Lopez Baros, Eds., Onward Press, Santa Fe, New Mexico, 495 pp.
- Gulch, R., 2002, "Urban Growth Detection Using Texture Analysis on Merged Land sat TM and SPOT-P Data," Photogrammetric Engineering & Remote Sensing, Vol. 68, No.12, pp1283-1288.
- Hamrick, D., 2004, Fredericksburg Texas Forest Service Regional Fire Coordinator, personal communication.
- Harkins, K.C., P. Morgan, L.F. Neuenschwander, A. Chrisman, A. Zack, C. Jacobson, M. Grant, N. Sampson, 1999, "The Idaho Panhandle National Forests Wildfire Hazard-Risk Assessment," in Proceedings from the Joint Fire Science Conference and Workshop, "Crossing the Millennium: Integrating Spatial Technologies and Ecological Principals for a New Age in Fire Management," Vol. I and II, Published by the University of Idaho and the International Association of Wildland Fire, <http://jfsp.nifc.gov/conferenceproc/>.
- Harris, P.M, and S.J. Ventura, 1995, "The Integration of Geographic Data with Remote Sensed Imagery to Improve Classification in an Urban Area," Photogrammetric Engineering & Remote Sensing, Vol. 61, No. 8, pp. 993-998.
- Hawkes, B., and J. Beck, 1999, "A Wildfire Threat Rating System," Fire Management Notes, U.S. Department of Agriculture, Forest Service, Vol. 59, No. 2, p. 25.
- Hay, C.M., 2000, "Wildfire Hazard – Values at Risk Evaluations the Kenai Peninsula," The Anchor Point Group, Lafayette, CO., [http://clem.mscd.edu/~hayc/Gen\\_Pages/Wildfire/Kenai\\_whre.htm](http://clem.mscd.edu/~hayc/Gen_Pages/Wildfire/Kenai_whre.htm).
- Hermansen, L.A., 2003, "The Wildland-Urban Interface: An Introduction," in national Planning Conference Proceedings, Session: Environment, Energy, Natural Resources, and Sustainability, Denver, CO., April 2003, <http://www.caed.asu.edu/apa/proceedings03/HERMAN/herman.htm>

- Hermansen, L.A., and E.A. Macie, 2002. Introduction. In Human Influences on Forest Ecosystems: The Southern Wildland-Urban Interface Assessment, E. Macie, L.A. Hermansen (eds.), Asheville, North Carolina, U.S. Department of Agriculture, Forest Service, Southern Research Station, General Technical Report SRS-55, pp. 1-7.
- Jensen, J.R., 1996, Introductory Digital Image Processing: A Remote Sensing Perspective, Second Edition, Prentice Hall, New Jersey, 318 pp.
- Jensen, J.R., 2000, Remote Sensing of the Environment, Prentice Hall, New Jersey, USA, 544 pp.
- Johnson, E.A., and K. Miyanishi, 2001, Forest Fires: Behavior and Ecological Effects, Academic Press, San Diego, 594 pp.
- Kilgore, K., 2004, GIS Analyst, Texas Forest Service, Bastrop Office, Texas, personal communications.
- Landgrebe, D., and L. Biehl, 2004, Multispec, remote sensing processing system software, Laboratory for Applications of Remote Sensing, Purdue University, West Lafayette, Indiana, <http://dynamo.ecn.purdue.edu/~biehl/MultiSpec/>
- Kuo, C-Y., T-Y. Chou and R-Y. Lee, 2001, "Identification of Urban Characteristics Using IKONOS High Resolution Satellite Imagery," Proceedings, ARCS 2001 – 22<sup>nd</sup> Asian Conference on Remote Sensing, 5-9 November, 2001, Singapore, Vol 2, pp. 1219-1223.
- Leica, 2003, Erdas Imagine 8.7 On-line Manuals, Erdas Imagine software, Leica Geosystems GIS and Mapping LLC, Atlanta, GA, p. 258.
- Lillisand, T.M., and R.W. Kiefer, 1994, Remote Sensing and Image Interpretation, John Wiley & Sons, New York, 750 pp.
- Liu, Pin-Shuo and Yue-Hong Chou, 1997, "A Grid Automation of Wildfire Simulation," in Proceedings of Environmental Research Systems, Inc. (ESRI) User Conference 1997, <http://gis.esri.com/library/userconf/proc97/proc97to200/pap158/p158.htm>
- Lowe, Joseph D., 2001, Wildland Firefighting Practices, Delmar - Thomson Learning, Albany, New York, 348 pp.
- MacDonald, L.H., R. Sampson, D. Brady, L. Juarros, and D. Martin, 2000, "Predicting Post-Fire Erosion and Sedimentation Risk on a Landscape Scale: A Case Study from Colorado", in Mapping Wildfire Hazards and Risks, R.N. Sampson, R. D. Atkinson and J.W. Lewis, Eds., Food Products Press, New York, 343 pp.

- Masser, I, 2001, "Managing our Urban Future: The Role of Remote Sensing and Geographic Information Systems," *Habitat International*, 25, pp. 503-512.
- Maud, S., and N. Mackay, 1998, "Aquatic Risk Assessment and Risk Management for Pesticide," in Risk Assessment and Management, R.E. Hester and R.M. Harrison, Eds., The Royal Society of Chemistry, Cambridge, UK., 168 pp.
- McKenzie, D., Z.M. Gedalof, D.L. Peterson, and P.W. Mote, 2004, "Climate change, wildfire and conservation," *Conservation Biology*, 18(4): 890-902.
- McMahan, C.A., R.G. Frye, and K.L. Brown, 1984, "The Vegetation Types of Texas – Including Cropland," published by Texas Parks and Wildlife Department, Austin, Texas, PWD Bulletin 7000-120, [http://www.tpwd.state.tx.us/gis/vegetation\\_types/](http://www.tpwd.state.tx.us/gis/vegetation_types/)
- Menakis, J.P., R.E. Keane, and D.G. Long, 2000, "Mapping ecological attributes using an integrated vegetation classification system approach," *Journal of Sustainable Forestry*, 11(1-2), 245-263.
- Mesev, V. and P.A. Longley, 1999, "The Role of Classified Imagery in Urban Spatial Analysis", in Advances in Remote Sensing and GIS Analysis, P.M. Atkinson and N.J. Tate, Eds., John Wiley & Sons, Chichester, England, 273 pp.
- Miller, J.D., J.W. Nyhan, and S.R. Yool, 2003, "Modeling Potential Erosion due to the Cerro Grande Fire with a GIS-based implementation of the Revised Universal Soil Loss Equation", *International Journal of Wildland Fire*, Vol. 12, pp. 85-100.
- Mora, F., and G. Hernandez-Cardenas, 1999, "Modeling and Mapping Wildfire Potential in Mexico Based on Vegetation and Drought Conditions using Remote Sensing and GIS Technology", in *Contributed Papers from the Modeling Session, The Joint Fire Science Conference and Workshop, Boise, Idaho, June 15-17, 1999*, <http://jfsp.nifc.gov/conferenceproc/Mo-03Moraetal.pdf>.
- NIFC, 2004, "Historical Wildland Fire Statistics," National Interagency Fire Center, Boise, Idaho, <http://www.nifc.gov/stats/historicalstats.html>
- NIFC, 2005, "Historical Wildland Firefighter Fatalities," National Interagency Fire Center, Boise, Idaho, <http://www.nifc.gov/reports>.
- NFP, 2004, National Fire Plan web site, <http://www.fireplan.gov/index.html>
- NRCS, 2004, "National Muir Database Download" webserver, USDA-NRCS Soil Survey Division, <http://ortho.ftw.nrcs.usda.gov/cgi-bin/muir/dmuir.cgi?-F>

- NWCG, 1994, "Introduction to Wildland Fire Behavior S-190," National Wildfire Coordinating Group, Great Basin Supply Cache, Boise ID, NFES 1860, 66 pp.
- NWCG, 1996, Glossary of Wildland Fire Terminology, National Wildfire Coordinating Group, U.S. Department of Agriculture, PMS 205, NFFS 1832, 148 pp.
- NWCG, 1998, "Appendix B: Fire Behavior," Fireline Handbook, National Wildfire Coordinating Group, Great Basin Supply Cache, Boise ID, NFES 0065, 115 pp.
- O'Looney, J., 2000, Beyond Maps: GIS and Decision Making in Local Government, ESRI Press, Redlands, CA, 225 pp.
- OCS, 2004, Oklahoma Fire Danger Model, An online fire danger model, The Oklahoma Climatological Survey in conjunction with the University of Oklahoma and Oklahoma State University,  
<http://agweather.mesonet.ou.edu/models/fire/description.html>.
- Planning SA, 1999, "Wildfire Threat Analysis in the GIS Environment," Department for Transport and Urban Planning, South Australian Planning and Development Assessment System, Government of South Australia,  
<http://143.216.252.11/publications/426p.pdf>.
- Pyne, S.J., P.L. Andrews, and R.D. Laven, 1996, Introduction to Wildland Fire, Second Edition, John Wiley & Sons, New York, 769 pp.
- Pyne, S.J., 2001, Fire: A Brief History, Weyerhaeuser Environmental Books, University of Washington Press, Seattle, Washington, 204 pp.
- Radke, J., 1995, "A Spatial Decision Support System for Urban/Wildland Interface Fire Hazards," In Proceedings, 1995 ESRI International User Conference, Palm Springs, CA, May, 1995,  
<http://gis.esri.com/library/userconf/proc95/to200/p175.html>.
- Rey, M.E., 2002, Statement in "The National Fire Plan and outlook for the 2002 wildfire season," Hearing before the Subcommittee on Department Operations, Oversight, Nutrition and Forestry Committee on Agriculture, House of Representatives, 107 Congress, Second session, June 13, 2002, Serial No. 107-19.
- Rothermel, R.C., 1972, "A Mathematical Model for Predicting Fire Spread in Wildland Fuels," General Technical Report INT-115, Ogden, UT, USDA Forest Service, Intermountain Forest and Range Experiment Station, 40 pp.

- Rothermel, R.C., 1983, "How to Predict the Spread and Intensity of Forest and Range Fires," General Technical Report INT-143, Ogden, UT, USDA Forest Service, Intermountain Forest and Range Experiment Station, 161 pp.
- Reinhardt, E.D., R.E. Keane, and J.K. Brown, 2001, "Model Fire Effects," International Journal of Wildland Fire, Vol. 10, pp. 373-380.
- Sampson, R.N., and L.F. Neuenschwander, 2000, "Characteristics of the Study Area, Data Utilized, and Modeling Approach," Mapping Wildfire Hazards and Risks, Food Products Press, Binghamton, New York, 343 pp.
- Sampson, R.N., R.D. Atkinson and J.W. Lewis, 2000, Editors, Mapping Wildfire Hazards and Risks, Food Products Press, Binghamton, New York, 343 pp.
- Scifres, C.J., and W.T. Hamilton, 1993, Prescribed Burning for Brushland Management: The South Texas Example, Texas A&M University Press, College Station, Texas, 246 pp.
- Smith, Mark, 2003, "Southern California Firestorm 2003: Report for the Wildland Fire Lessons Learned Center," Prepared by Mission-Centered Solutions, Inc., Parker, CO, and Guidance Group, Inc., Washburn, WI, for Paula Nasiatka, Lessons Learned Center Manager, National Advanced Resource Technology Center, Marana, AZ, [http://www.wildfirelessons.net/ICTs/LLCICT\\_SoCa\\_Final\\_Report\\_121903.pdf](http://www.wildfirelessons.net/ICTs/LLCICT_SoCa_Final_Report_121903.pdf), 70 pp.
- Spencer, C.N., K.O. Gabel, and F.R. Hauer, 2003, "Wildfire effects on stream food webs and nutrient dynamics in Glacier National Park, USA," Forest Ecology and Management, 178 (2003), pp. 141-153.
- Suter, G.W., 1993, Ecological Risk Assessment, Lewisville Publishers, Boca Raton, 538 pp.
- TICC, 2005, Remote Automated Weather Station (RAWS) Hourly Observation, Texas Interagency Coordination Center, Lufkin, Texas, web site hosted by Texas A&M University, <http://www.tamu.edu/ticc/stations%5B1%5D.htm>
- TNRIS, 2004, Texas Natural Resources Information Systems, Digital data web server, <http://www.tnr.is.state.tx.us/>.

- TPWD, 2004, "The Natural Regions of Texas," GIS shapefile and metadata published by Texas Parks and Wildlife Department, Austin, Texas. Based upon "Preserving Texas' Natural Heritage," Lyndon B. Johnson Scholl of Public Affairs Policy Research Project Report, Number 31, 1978, <http://www.tpwd.state.tx.us/nature/ecoreg/pages/intro.htm#winedale>
- U.S. Census, 2000, U.S. Census Bureau, American FactFinder, GCT-PH1. Population, Housing Units, Area, and Density: 2000, web access, [http://factfinder.census.gov/servlet/GCTTable?\\_bm=y&-geo\\_id=04000US48&-\\_box\\_head\\_nbr=GCT-PH1&-ds\\_name=DEC\\_2000\\_SF1\\_U&-format=ST-7](http://factfinder.census.gov/servlet/GCTTable?_bm=y&-geo_id=04000US48&-_box_head_nbr=GCT-PH1&-ds_name=DEC_2000_SF1_U&-format=ST-7)
- U.S. Congress, 2002, "The National Fire Plan and outlook for the 2002 wildfire season," Hearing before the Subcommittee on Department Operations, Oversight, Nutrition and Forestry Committee on Agriculture, House of Representatives, 107 Congress, Second session, June 13, 2002, Serial No. 107-19.
- USDA, 1995 "Federal Wildland Fire Policy: Policy and Program Review," U.S. Dept. of the Interior and U.S. Dept. of Agriculture, <http://www.fs.fed.us/land/wdfirex.htm>
- USDA, 2002, "Federal Wildland Fire Policy: Wildland/Urban Interface Protection," USDA Forest Service web site, <http://www.fs.fed.us/land/wdfire7c.htm>
- USGS, 1986, "Land Use and Land Cover Digital Data from 1:250,000 and 1:100,000 Scale Maps: Data Users Guide 4," U.S. Dept. of the Interior, U.S. Geological Survey, National Cartographic Information Center, Reston, Virginia.
- USGS, 2005, Landsat Project Website, [http://landsat.usgs.gov/l7\\_processlevels.html](http://landsat.usgs.gov/l7_processlevels.html)
- USGS\_SDDS, 2005, Seamless Data Distribution System, U.S. Geological Survey /EROS Data Center distribution website, Sioux Falls, SD, <http://seamless.usgs.gov/website/seamless/viewer.php>.
- Weatherford, B.F., 2002, "Study Supports Cooperative Fire Protection in the West," in Fire Management Today, Vol. 62, No. 1, pp., United States Department of Agriculture, Forest Service, <http://www.fs.fed.us/fire/planning/firenote.htm>
- Weaver, 2005, from personal communication with Traci Weaver, Texas Forest Service Information Officer and Fire Prevention Specialist.
- Webster's, 1983, Webster's New Twentieth Century Dictionary, Second Edition, Simon and Schuster, New York, 2, 129 pp.

- Weinstein, D., K. Green, J. Campbell, and M. Finney, 1995, "Fire Growth Modeling in an Integrated GIS Environment," from Proceedings in Environmental Systems Research Inc., ESRI, User Conference,  
<http://gis.esri.com/library/userconf/proc95/to100/p092.html>.
- Whelan, R.J., 1995, The Ecology of Fire, Cambridge University Press, 346 pp.
- White House, 2002, "Healthy Forest: An Initiative for Wildfire Prevention and Stronger Communities," The White House web site,  
<http://www.whitehouse.gov/infocus/healthyforests/sect2.html>.
- Wischmeier W.H., and D.D. Smith, 1978, "Predicting Rainfall Erosion Losses: A Guide to Conservation Planning," U.S. Dept. of Agriculture, Agricultural Handbook No. 537.
- Wolf, T., 2003, In Fire's Way: A Practical Guide to Life in the Wildfire Danger Zone, University of New Mexico Press, Albuquerque, N.M., 168 pp.
- Wright, H.A., and A.W. Bailey, 1982, Fire Ecology: United States and Southern Canada, John Wiley & Sons, New York, 501 pp.