Vulnerability to Natural Hazards: Study of Subdivisions Burned by the Hayman Fire Using IKONOS Imagery and High Resolution GIS Data

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Abstract

In wildfire, vulnerability changes at subdivision or house level, due to changes in topography, built environment and socioeconomic condition. Therefore, analysis using aggregate data at large spatial units, as done in most of the vulnerability to natural hazard research, does not reflect vulnerability of subdivisions or houses, does not help to identify factors that make the houses vulnerable to wildfire, nor does it help in the formulation of wildfire mitigation strategies. Further, vulnerability is a function of natural setting, built environment and socioeconomic conditions and should be studied together. This research attempts to address these issues studying subdivisions burned by the Hayman Fire in 2002. Primary data source is IKONOS imageries, taken before and after the fire. The IKONOS imageries are overlaid with parcel, subdivision and Digital Elevation Model to extract information on natural setting and built environment. The land value of parcel and the Census data are included in socioeconomic condition. The data is analyzed using logistic regression with vulnerability as dependent variable measured in terms of burned and unburned houses and independent variables as elevation, slope, aspect, vegetation, defensible space, road width, road type, parcel size and land value. For the given setting of natural and built environment, houses located at higher elevation and steeper slope, surrounded by dense vegetation, provided with narrow roads are more vulnerable than other houses. Data also shows that poverty and ethnic minority has not made houses vulnerable to wildfire. Therefore, the issue in the study area is how people have implemented wildfire mitigation measures to cope up with the natural setting. Finally, the proposed methodology may be useful to prepare strategies towards assessing, monitoring and reducing wildfire risk in the wild-land urban interface.

Key words:
Natural hazard, wildfire, vulnerability, IKONOS, GIS

Introduction

Number of structures burned by wildfires is increasing every year in the United States. Number of structures burned in 2000 and 2001 was 861 and 731, whereas it is increased to 2,381 in 2002 and 5,781 in 2003 (NIFC, 2006). This increasing trend of burning of structures by wildfires has drawn the attention of researchers studying vulnerability of buildings and people to wildfire. This research aims to study factors that make a house or subdivision vulnerable to wildfire.

In natural hazards, vulnerability models are mostly based on human ecology theory. The theory states that natural system and human use system interact to generate or exacerbate the vulnerability of a community from the natural hazards (Kates, 1971; Mileti, 1999; Cutter et al, 2003). This concept is more pronounced in the case of wildfire hazard. First, peoples' desire to live close to the nature has increased the population pressure in the wild-land urban interface, which is prone to wildfire (Van der Vink, et al. 1998; McKee et al, 2004; Collines, 2005; FRFT, 2006). Second, people preserve forest environment around their houses for aesthetics and they care less about the safety measure for wildfire hazards (Seigel, 1996, McKee et al, 2004). Third, forest conservation is emphasized along with suppression of fire, which has accumulated fuel in the wild-land urban interface (McCaffrey, 2004; FRFT, 2006). These human activities have accumulated wildfire risk even to those structures, which were not at risk at the time of their construction.

Vulnerability to natural hazard refers to potential to loss. As per Blaikie et al. (1994), vulnerability is the characteristics of a person or group in terms of their capacity to anticipate, cope with, resist to and recover from the impact of natural hazards. Accordingly, vulnerability is being assessed using demographic and socioeconomic condition of people at a certain spatial units. Some studies have argued that the weak demographic and poor socioeconomic conditions might not coincide with the hazard and hence vulnerability study should assess both conditions and their coincidence in order to find population vulnerable to hazards (Cutter et al., 2000). Accordingly, studies have estimated hazard(s) and overlaid it to the index computed from demographic and socioeconomic variables at the Census Block Group (as in cutter et al., 2000). The research results computed at the large spatial units such as County, Track, and Block

Group help to compare which spatial unit is more vulnerable than another, but do not help planners and activists formulate short and medium term plans and demands (Wisner, 1993). In wildfire case, the vulnerability changes at house or subdivision level due to changes in topography, built environment and socioeconomic condition. Therefore, analysis using aggregate data at large spatial units does not reflect vulnerability of subdivisions or houses, does not help to identify factors that make the houses vulnerable to wildfire, nor does it help in the formulation of wildfire mitigation strategies. In order to address this problem, this study attempts to analyze data at subdivision and house level. It takes the subdivisions burned by the wildfire and considers the burned subdivisions and houses as vulnerable house. Then it explores the natural, built environment and socioeconomic condition that made the subdivisions and houses vulnerable to wildfire.

Natural setting of a place in the wildfire involves fuel, topography and weather condition of that place. Fuel consists of grass, shrub, timber litter, and timber slash. Topography includes elevation, slope, aspect and country shape (National Wildfire Coordinating Group, 1994; National Fire Protection Association 299, 1997; Colorado State Forest Services, 2001). The weather condition involves temperature, wind, relative humidity, and precipitation (NWCG, 1994). For a wildfire to occur fuel, oxygen and heat are required, which are sometimes referred to as components of 'fire triangle'. Weather condition, specifically wind, temperature and relative humidity changes constantly and is difficult to predict. It is almost impossible to measure these components for an individual houses at the time of wildfire. This research could not include the weather related-variables, although they have important role in burning houses, assuming that extreme weather condition is essential for all wildfires to occur. Table 1, shows the definition of variables pertaining to natural setting and their significance in fire behavior.

Insert Table 1 here

The built environment refers to how planning is implemented for wildfire mitigation at each house and at the subdivision level. NFPA 299 (1997) provides the guidelines for the wildfire mitigation plan. Basically, this plan emphasizes in minimizing fuel around houses and maximizing efficiency of the emergency response. Therefore, planning variables included here are, vegetation, defensible space, road width, road type, and parcel size. Table 1 shows the details of these variables.

This research could not find demographic and socioeconomic data at the household level. The smallest spatial unit the Census collects and compiles socioeconomic data is the Census Block Group. For demographic data, the smallest spatial unit is the Census Block, the smallest Census unit. Studies show that poverty data are highly correlated with other socioeconomic data (Wisner, 1993), but they are not available at the household level. Therefore, this research uses the land value data, which is prepared and used by the County Assessors Office for revenue collection. This study assumes that the higher the land value, the richer is the house owner. But there is no way to fix a cutoff point to separate the poor and non-poor houses. Another variable, very much used in literature, is ethnic minority. It is considered that the ethnic minority are disadvantaged in comparison to their white counterpart, because of the language barrier (Sazz et al, 1997; Cutter et al, 2003; Fothergril & Lori, 2004). These two variables are included to assess the socioeconomic condition in the study area.

Methods

Study area

The study area (39 7’ N to 39 11’ and 105 7’ W to105 12’ W) is located in the south-west corner of Douglas County of the State of Colorado, figure 1. It includes five subdivisions – West Creek, Trout Creek, Thunder Butte, Freedonia Ranch, and Oslon/Camp. All these subdivisions are scattered throughout the wild-land area with no clear demarcation between the subdivisions and the wild-land fuels: wild-land fuels, in most of the cases, are continuous outside of and within the development. Such communities in the wild-land urban interface are referred to as ‘intermix communities’ (Ewert, et al, 1993; USDA and U.S. Department of the Interior, 2001). The study area is in the Lower Montane (altitude ranging from 6000 to 8000 feet), which is unnaturally dense and dominated by Ponderosa Pine, which is highly inflammable (FRFTP, 2006). The area is a part of 138,000 acres of the Colorado Rocky Mountain burned by the Hayman fire, one of the largest and most aggressive wildfires in the United States (USDA Forest Service, 2003). The fire burned several houses in the study area. So, the area has mixes of burned and unburned houses. The area selection was also guided by the availability of IKONOS imageries taken before and after the fire. The selected area was burned on June 18.

Insert Figure 1 here

The Hayman Fire started in June 8 and lasted until July 2 of 2002. During the wildfire, climate was the driest, at least, in the past 30 years. Moisture content of the dead logs and stems along the Front Range was extremely low: most less than 10 percent and some less than five percent (UDSDA, Forest Services, 2003). The USDA, Forest Service document also mentions that the climate was extreme with high temperature and wind of speed 15 mph in most of the day on June 8. This condition persisted until June 9. Relatively calmer wind and higher humidity returned and persisted from June 10 to 17, which lowered the fire speed. The weather condition again exacerbated on the afternoon of June 17. Fire fighter’s report available in Douglas County says that late in the day of June 18, the main fire stalled out on the top of the ridge east of the West Creek. Firefighters deployed in the area developed a plan to burn out from that ridge, but before it could be implemented winds again picked up and the fire burned down off the ridge to the east and crossed Highway 67. Most of the area in the study was burned at that time. Crew pulled into safety zones as needed (Fire narrative, 2002). This shows that in the severe wildfire of this magnitude, available emergency response can be of very little use; the fire continued in its natural way. Residents could not do anything for the protection of their property, because they were already evacuated on June 9 (Red Flag Warning, 2003).

The study area is located in a high wildfire hazard area. Other recent wildfires occurred in the Colorado Rocky Mountain area were Schoonover wildfire in May 2002, Big Turkey wildfire in 1998, and Platte-Springs wildfire in 2002.

Data acquisition

Geographic Information System (GIS) is used to extract data and information on natural setting and the built environment around subdivisions and houses. IKONOS satellite images, taken before and after the Hayman fire, are the primary source of data for the study. Other data sets used are subdivision data, parcel data, Digital Elevation Model (DEM) data, land value data, and Race data. Data acquisition is easier in GIS than in remote sensing software, specifically the ENVI 4.1, because first, in GIS various layers including remote sensing image can be overlaid; second, remote sensing data can be zoomed in and out to desired extent to observe and measure features of remote sensing image.

The IKONOS produces 4-meter multi-spectral (red, blue, green, near infrared) and 1-meter panchromatic imagery. This imagery is projected in the Universal Transverse Mercator (UTM) projection using the North American Datum (NAD) 1983. This image is adequate to observe burned and unburned houses, and measure proposed variables of topography and built environment around them. The contemporary satellites, such as Landsat ETM+ launched in 1999 produces 30-meter multi-spectral (except thermal band - 60 meter) and 15-meter panchromatic image, where buildings and other features of that dimensions are not visible and do not serve the purpose of this research.

The parcel data and subdivision data are obtained from Douglas County Planning Office. They are in “State Plane Colorado Central FIPS 0502 feet” with the NAD 1983. The 7.2-minutes US Geological Survey (USGS) DEMs (10 m) is in UTM and provides elevation data. The DEMs is converted to slope and aspect data using the ‘Surface Analysis’ in GIS. The data is available in the form of float-point, which does not generate the attribute table. The land value data is obtained from the County Assessors’ Office. Race data at the block level is used from the Census 2000.

Burned houses are identified comparing IKONOS imagery taken before and after the fire. Major methods used to acquire required data are (1) digitization of houses and collection of information on these houses and their subdivisions about the vegetation, defensible space, road type, road width and parcel size. Vegetation condition on the parcels and subdivisions is observed visually over the IKONOS image and grouped into four categories – no (value 0), thin (value 1), medium (value 2) and dense (value 3). The vegetation refers to the density of vegetation inside parcels. Here, the vegetation is taken under the built environment; how residents are managing vegetation, such as thinning and pruning fits more in planning than in the natural setting. The defensible space is measured using ‘measure’ tool. Minimum distance between the edge of houses and the center of the canopy of the nearest tree is taken as a defensible space. The road width is measured between the two outer lines of a road. For the road type, the highway 67 is taken as a primary road, branch from it as a secondary and branches from the secondary road are taken as a tertiary roads. The parcel size is simply the area of parcels; (2) conversion of the DEMs float-point data to ‘integer’ to generate an attribute table; (3) computation of average values of elevation, slope and aspect for each parcel and subdivision using the ‘Zonal Statistics’. For the ‘Zonal Statistics’, parcels and subdivisions are used as ‘Zone’ whereas elevation, slope and aspect values are used as the ‘value’; (4) joining of the digitized house data with the parcel data using the ‘Spatial Join’ function. The ‘Spatial Join’ operation takes the coordinates of the two layers to join the two GIS entities – digitized points for houses and parcel polygons. The resulting parcel data with houses is further joined with the land value data to get value of each house. For the table join the common field was ‘State Parcel Number’ in the parcel polygon and the land value data; (5) obtaining Race data within the study area at the Census Block level. All of these data sets and information are then analyzed at subdivision level and parcel level separately. Subdivision data is analyzed case by case, whereas the houses data is analyzed using logistic regression.

Insert Figure 2, 3, and 4 here

Logistic regression is typically used, when the dependent variable is binary or categorical. In logistic regression, some independent variables may be categorical and they need not be normally distributed (Hosmer and Lemeshow, 1989; Rogerson, 2001; Gorsevski et al., 2006). Logistic regression equation in this study consists of the dependent variable “vulner” (vulnerability), which is measured in terms of burned houses (value = 1) and unburned houses (value = 0). The independent variables are elevation, slope, aspect, vegetation, defensible space, parcel size, road width, road type and land value. Race variable could not be included in the model, because it could not be disaggregated at house level. Finally, the logistic regression model takes the form:

$$\ln(vu\ln er) = \alpha + \beta 1(elevtn) + \beta 2(slope) + \beta 3(aspect) + \beta 4(vegden) + \beta 5(defsps) + \beta 6(roadwd) + \beta 7(roadtp) + \beta 8(prclsz) + \beta 9(lanval)$$

Where,

Vulner	= burned or unburned house; measure of vulnerability
elevtn	= average elevation of parcel
slope	= average slope of parcel
aspect	= average aspect of parcel
vegden	= density of vegetation
defsps	= defensible space
roadwd	= road width
roadtp	= road type
prclsz	= parcel size
lanval	= the County Assessors Land Value

Findings and Discussions

At the Subdivision Level

Two tables, 2 and 3, show the data at subdivision level. Table 2 shows the subdivision area, number of houses, and percentage of houses burned. Table 3 shows topographic characteristics of subdivisions. Thunder Butte subdivision has the highest percentage of houses burned. This subdivision had high density of vegetation, dense fuel continuing from the wild-land to the development, and narrow access roads - less than 3 meter width. It has higher average slope than other subdivisions.

Insert Table 2 and 3 here

In other subdivision the burned houses are at higher elevation than the unburned. The burned houses were located in those parcels in the subdivisions, where wild-land fuel was continuous up to the parcel. In West Creek Lake Ranch subdivision, a wide road of average width 17 meter runs North to South, which separates the subdivision from a dense forest in its west side. It seems that the road acted as a no-vegetation zone and stopped fire propagation from the forest. In this subdivision, a creek runs from the South to the North; a lake is preserved on the way of the creek. Most of the houses burned here are at higher elevation and far from the lake. In Trout Creek Ranch also, the burned houses are located at the higher elevation where fuel is continuous from the wild-land up to the parcels. The parcels in the middle of the subdivision have low or no vegetation and houses are not burned there.

While observing the characteristics of subdivisions, it is seen that subdivision is more vulnerable, if it has dense vegetation and that vegetation is continuous from the wild-land. In many cases, it can be observed that even small road played role in stopping the fire propagation. So, the second factor is the narrow road which makes the subdivision vulnerable. A Creeks flows in the lower elevation and the areas along the creek are moist. Such areas are less vulnerable than the areas at higher elevation. Subdivision with steeper slope is also seen to be prone to burning.

At the House Level

At the house level, regression analysis shows that elevation, slope, vegetation, road width and land value are statistically significant. Other variables – road type, parcel size and defensible space - are not statistically significant. This research result supports the literature on wildfire behavior (Prestemon, 2001; NWCG S-190, 1994): houses surrounding by dense vegetation, located at higher elevation and steeper slope, and having narrow roads were burned. The significance of wider road here is to break fire propagation rather than emergency response, because as mentioned above the response mechanism could not work due to life threatening magnitude of fire. The land value is significant in the model, but the odd is 1, which does not explain whether the increase of land value increases the vulnerability of a house to wildfire.

The defensible space is not significant in the model, because not only the burned houses have smaller defensible space, but also the unburned houses. The road type is not significant, because the distance from the highway made no difference as the response mechanism did not work. Similarly, the parcel boundary is not a firm line or wall on the ground, unless parcels owners make their parcel different from surrounding parcels or wild-land. In this case, the boundaries are just lines in the map and did not make any difference on the ground.

Topography, built environment and land value were loaded separately in the model and the result is compared in terms of Negelkerke R^2. The topography yields a value of 0.31 for R^2, whereas the built environment and land value yield 0.11 and 0.05 values respectively. This suggests that the topography played stronger role in burning the houses in the study area. Discussion with the Douglas County planners and analysis of the Census 2000 data reveal that most of the houses in the study area were constructed before the current Wildfire Mitigation Plan. The "Grandfathered in" policy does not allow the planners to retrofit the planning to those residences. Therefore, what result showed is correct that houses were burned because they were not planned to cope up with their natural setting.

Finally, data shows that ethnic minority is not a problem in the study area. Table 4 shows the demographics of the study area. The first column shows the demographics in those Blocks that were affected by fire, whereas the second column shows data at the Census Block Group level. 18 Census Blocks were affected by the Hayman Fire out of 31 Blocks in the Census Block Group. Out of 343 people living in the affected Census Blocks, only one person is Native American and 7 were Hispanic (US Census, 2000). It is again difficult to confirm from this data that whether the burned houses were of the minority population.

Insert Table 5 here

Conclusion

Fire behavior is complex; therefore it is difficult to conclude variables and their critical values for the vulnerability to wildfire with this small study area. It is also difficult to conclude that had the houses adopted planning regulations, they would have been saved. Because, in this fire 0.7 miles fire spotting was reported (USDA Forest Service, 2003); in such cases, the defensible space of 30-feet, as recommended by NFPA 299, would not have been effective to protect those burned houses. However, the study results are congruent with the rationally derived wildfire mitigation criteria. It is practical to minimize fuel around houses by reducing vegetation and providing wide roads. The wide roads would help in better mobilization of emergency response and also help in reducing the chance of fire propagation across acting as a no-vegetation zone.

Literature suggests that poor and ethnic minority live in the wildfire hazard areas and they are more vulnerable than the non-poor in the Western United States (Wildfire Report, 2000; Lyn, 2005). However, this study has not shown that low value houses are more prone to burning than the high value houses. Also, the study result has shown that ethnic minority are fewer in the wildfire burned area. But, it is not to generalize from this study that covers small area that ethnic minority and poor people do not live in the wildfire hazard area in the Western United States.

This study supports literature that the high-resolution remote sensing data can be useful to assess vulnerability at smaller unit such as subdivision and house (Muller et al, 2006; Williamson, 2006). First, as shown in the study, the remote sensing data can be overlaid with parcel data in GIS to identify the boundary of a house. Then the vegetation, defensible space, road condition or other visible features can be observed and measured. The DEM helps to measure elevation, slope and aspect. All of these variables can be monitored over time, which could be helpful to prepare wildfire mitigation strategies. These sets of data and the method would also be useful for emergency management at the time of fire as we can identify safety zone location for firefighters. It also helps to identify houses that can be protected in an area where wildfire is ongoing; firefighters on the ground can be directed to those houses from the office, which helps to save houses without putting firefighter's life in jeopardy.

There are some limitations with this technique, which would be useful to discuss at this point. One of the major limitations of this method is that the information extraction process is entirely manual (Muller, et al., 2006). The fully automatically generated information on building and other variables of built environment is difficult. The spectral reflectance of building and other objects, such as rocks, on the ground are not distinguishable. Similarly, the automatically generated information is difficult for burned houses, because reflectance of the burned houses and the burned ground is same. Another problem with the IKONOS image is that it has error in positional accuracy. Even in the advanced orthorectified imagery, there exists some positional inaccuracy (Space Imaging, 2006). However, for visual and interpretive application such as this research, these images are very useful.

Table 1, Research variables, their definition and significance in wildfire hazard

Factors	Definition	Significance
A) Natural setting 1) Geographic context		
• Elevation	Height above mean sea level	Vegetation type and density changes as the elevation changes.
• Slope	Change in elevation divided by horizontal distance	The higher slope is the worse for the fire propagation. 0 - 9% – 1 (Mild) 10 – 20% - 2 (moderate) 21- 40 – 3 (steep)
• Aspect	Facing of slope (0 for north face and increases in the clockwise direction)	Slope getting more sunlight is dry, which is good for ignition and burning. 0-160 or 200-360 – 1 160-165 or 195-200 - 2 165-175 or 185-195 - 3 175-185 – 4 (4 is the worst aspect)
• Country shape	Canyons, ridge, saddle	Canyon acts as fire chimney
2) Weather factor		
• Temperature	Measurement of warmth or coldness	High temperature means availability of heat for burning.
• Wind	A horizontal movement of air relative to the surface of the earth	It is a carrier of heat and firebrands. It also changes the direction of fire.
• Relative humidity	Ratio of the amount of moisture in the air to the	Fuel gets dry soon at low RH and burns faster than the fuel

(RH) • Precipitation	amount which the air could hold at the same temperature and pressure. Moisture in either liquid or solid form large enough to fall from the atmosphere and reaches to the Earth's surface.	with high moisture content Precipitation increases the moisture content in the fuel and atmosphere. It also cools down the environment.
B) Built environment • Vegetation (fuel model) • Defensible space • Road width • Road type	 Fuel type (grass, shrub, timber litter, timber slash) fuel characteristics (size and shape, moisture, loading, continuity). An area between an improved property and a potential wildfire where the combustibles have been removed or modified. Distance between outer edge of the road Highway is taken as a primary road, the branch from it as a secondary and the branch from secondary	 This provides fuel for fire. It helps to protect life and property, protects spreading of fire started in houses to forest, and provides space for fire fighters to work to protect life and property. It acts as a no-vegetation zone. Large road width is required for the emergency response. Vehicle movement is better in highway than others for emergency management

• Parcel size	is taken as tertiary. Area of parcel	This research wanted to see the effect of the size of parcel, if any.
Socioeconomic • Land value • Minority population	 Price of parcel prepared and used by the County Assessors Office for revenue collection. Households identifying themselves as other than non-white	 Proxy for the low and high income households. Parcels with high value are assumed to be owned by the high income households. The minority population is poor and disadvantaged of language problem.

Source: National Wildfire Coordination Group, 1994; Colorado State Forest Services, 1997; Douglas County, 2006 and others (cited in the text)

Table 2, Summary table of subdivisions

Subdivision	Total area in acres	Average acres per parcel	Number of houses	% houses burned
Camp/Oslon	24.23	4.85	1	0
Freedonia Ranch	117.70	11.77	5	0
Thunder Butt	231.51	4.29	18	94
Trout Creek Ranch	300.26	5.27	46	24
Westcreek Lakes	300.45	1.44	61	18

Source: Computed from IKONOS image, subdivision and parcel data

Table 3, Natural setting data at the subdivision level

Subdivision	Water Body existing	Parcels adjoining to forest (%)	Fuel type	Elevation (ft)	Slope (%)	Aspect (degree)
Camp/Oslon	No	100	2	7724	8	84
Thunder Butte	”	46	3	7612	17	129
Troutcreek Ranch	”	48	2	7622	8	124
Westcreek Lakes	1	28	2	7609	10	197
Freedonia Ranch	No	88	1	8049	8	108

Source: Extracted from IKONOS image, subdivision and parcel data

Table 4, Logistic regression results

Variable	**Exp(B)**	**Error**	**Wald**	**Significance**
Parcel size	1.04	0.04	0.93	0.34
Land value	1.00	0.00	4.78	0.03
Slope	1.19	0.07	6.27	0.01
Aspect	1.00	0.00	0.23	0.63
Elevation	1.02	0.01	4.42	0.04
Vegetation density			10.23	0.02
Thin vegetation	0.00	2.60	8.05	0.00
Medium vegetation	0.13	0.86	5.49	0.02
Dense vegetation	0.32	0.64	3.15	0.08
Road type			3.00	0.22
Primary road	0.65	1.08	0.16	0.69
Secondary road	0.31	0.73	2.56	0.11
Tertiary road	1.12	0.06	3.46	0.06
Defensible space	1.05	0.03	2.20	0.14
Constant	0.00	23.98	4.59	0.03

Table 5, Demographics and socioeconomic condition in study area

Race	**Study area (18 Blocks)**	**Study Block Group (31 Blocks)**
Total population	343	704
White	334	584
African American	0	0
Native	1	13
Asian	0	8
Pacific Islanders	0	28
Hispanic	7	52
Number of poor households		28
Percent of poor households		8
State average percent		10

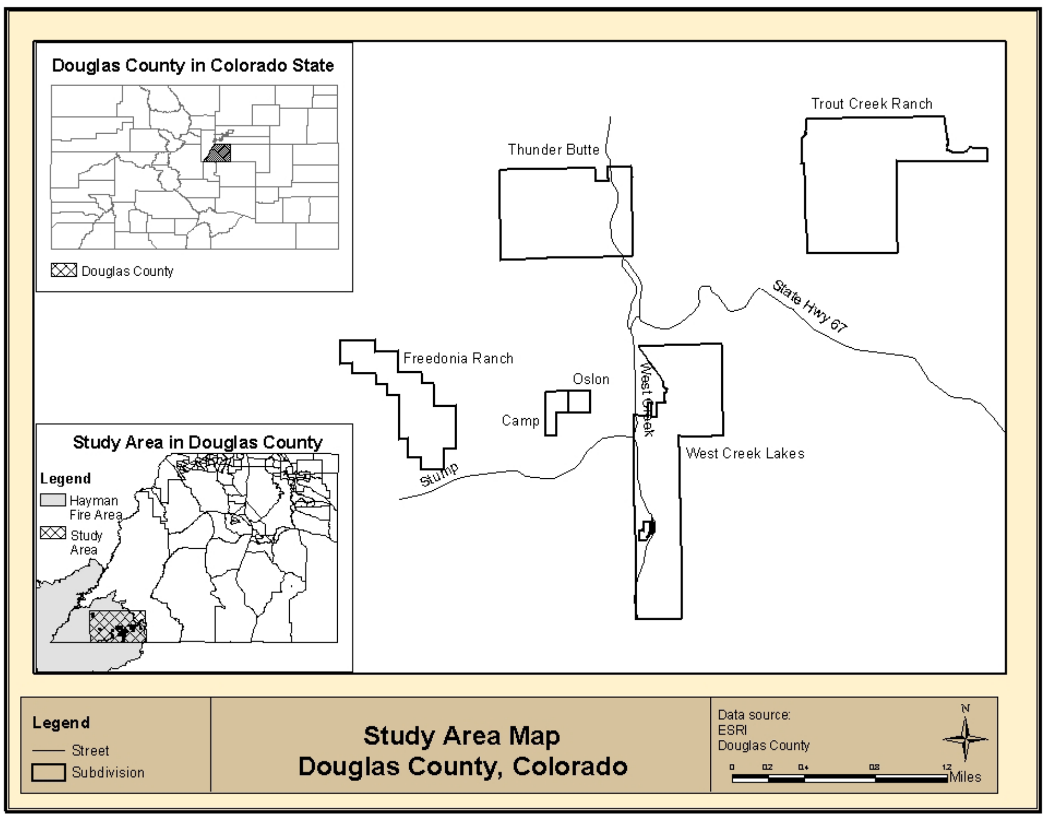

Figure 1, Study area map

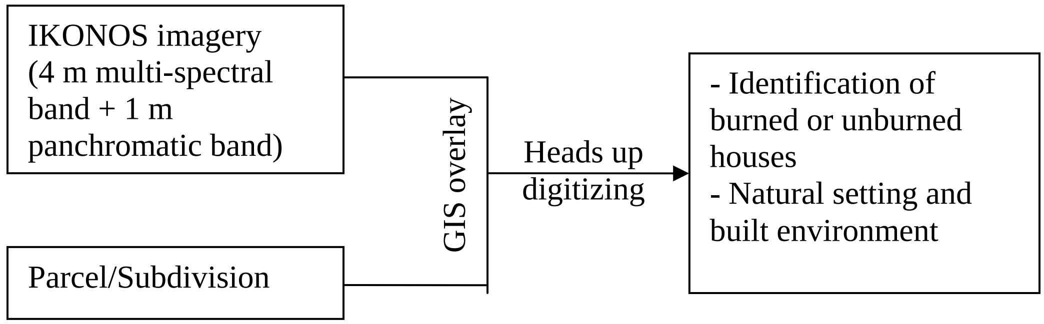

Figure 2, Data digitizing and information extracting in GIS

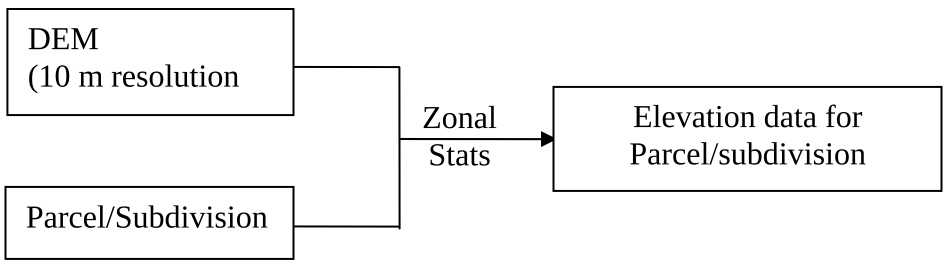

Figure 3, Elevation extraction from DEM in GIS

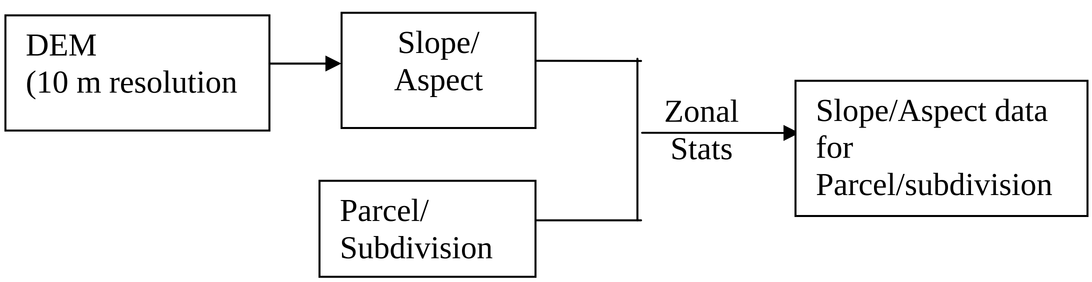

Figure 4, Slope and Aspect data extraction from DEM in GIS

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