

## Chapter Three. Methods

### 3.1 Study areas to be used in developing these methods

Although VDOF will eventually need to apply their techniques to the entire state of Virginia, this thesis was conducted on smaller test areas within the state. These test or “sample” areas must meet several criteria to ensure that they are a good representation of the entire state in the context of this location problem to be solved; hence a systematic method was used to choose their locations:

1. at least one of the test areas should encompass a region of the state that contains a high demand for dry hydrants (i.e., areas with a high density of woodland home communities).
2. these test areas should contain areas with varying degrees of road density and road network complexity since these two factors would likely affect the road network analyses that are included in this project.
3. one of these test areas should also include public lands since a significant portion of the state contains land managed by public agencies.

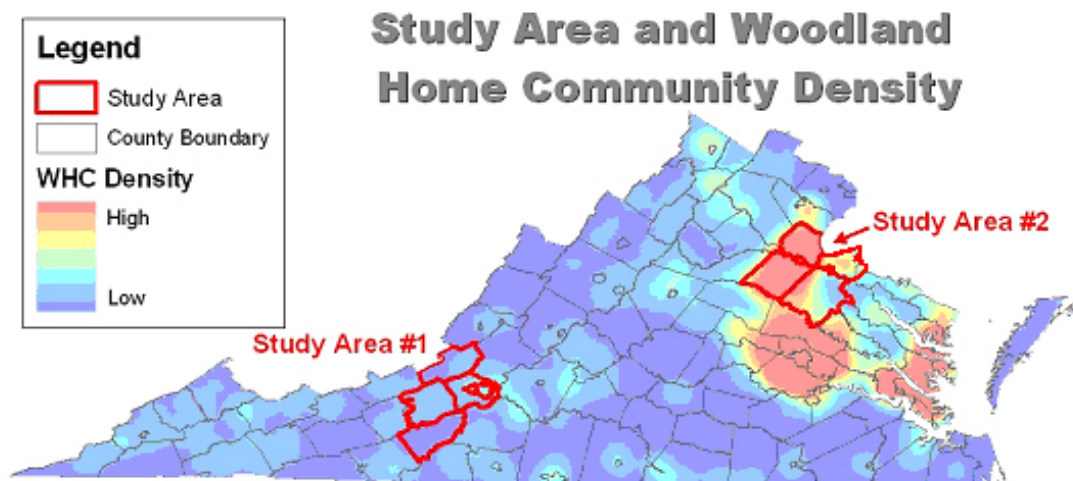


Figure 3.1. Study Areas and Density surface of WHCs in Virginia.

Figure 3.1 shows the counties selected as study areas for this thesis. Study Area #1 consists of Craig, Montgomery, Roanoke and Floyd counties. A large portion of Craig County consists of Jefferson National Forest and thus satisfies the criterion of the presence of public land. This region also contains rural areas (e.g. Craig and Floyd Counties) and urban areas (e.g., Town of Blacksburg, City of Roanoke and Town of Christiansburg) and hence this study area meets the criterion of the presence of high and low density road networks. Study Area #2 consists of Spotsylvania, Stafford, Caroline and King George counties and satisfies the criterion of containing areas of high WHC density. This area also features rural and urban areas (e.g. City of Fredericksburg) and hence areas of high and low road density and road network complexity.

### **3.2 General Assumptions**

For the sake of data development in a timely manner and to focus on the transportation of water to fires, several assumptions were made when preparing the data for the subsequent models. First, the distance between a dry hydrant and an existing road was assumed to be negligible. Secondly, it was assumed that the elevation difference between the road and the water source was less than the maximum lifting capabilities of fire trucks (20 feet). Third, the rate of fire truck travel rate is assumed to be equal when traveling both uphill and downhill. Fourth, it was assumed that there are no absolute obstructions on the road network, such as gates or road closures.

### **3.3 GIS Layers Used**

#### **3.3.1 Overview**

Table 3.1 lists the GIS layers used in this analysis and where elaboration is warranted, these input layers are discussed in more detail. Data manipulation to prepare the data layers for analysis is discussed in detail in subsequent sections of this chapter. All data were projected to the appropriate Virginia State Plane Coordinate System.

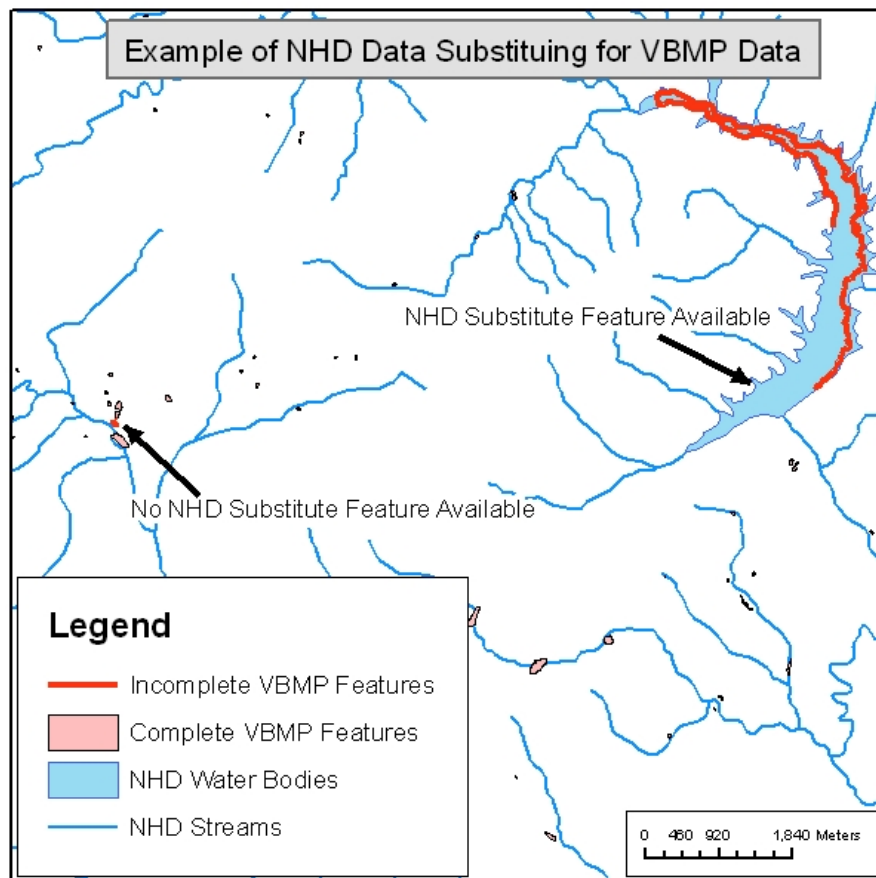
**Table 3.1. Existing GIS datasets used in this thesis.**

| <b>GIS layer(s)</b>                            | <b>Source</b>   | <b>Spatial Entity Type</b> | <b>Reference(s)</b>        |
|--|---|----------------------------|----------------------------|
| Hydrography features – Ponds, Lakes, Shoreline | Virginia Base Mapping Program, National Hydrography Dataset (NHD) | Polygon, polyline          | VBMP (2003)<br>USGS (1999) |
| Road networks                                  | US Census Bureau, 2000 TIGER Line Files                           | Polyline                   | USCB (2000)                |
| Woodland Home Communities                      | Virginia Dept. of Forestry  | Point                      | VDOF (2003a)               |
| Wildfire Risk Assessment                       | Virginia Dept. of Forestry  | Polygon                    | VDOF (2003b)               |
| Existing Dry Hydrants                          | Virginia Dept. of Forestry  | Point                      | Unpublished                |
| Urban Areas                                    | US Census Bureau 2000 TIGER Line Files                            | Polygon                    | USCB (2000)                |
| Virginia County Boundaries                     | The Virginia Economic Development Partnership                     | Polygon                    | Unpublished                |
| Pressurized Hydrants (where available)         | County and City Government Offices                                | Point                      | Various - Unpublished      |

### **3.3.2 Hydrography Layers**

The hydrography features of the Virginia Base Mapping Program’s (VBMP 2003) Digital Terrain Model were employed to establish the candidate hydrant sites. When compared to the USGS National Hydrography Dataset and the Digital Line Graphs of hydrography features digitized from 1:24,000 USGS quads, the VBMP data contain a more complete representation of the state’s water bodies. Compared to the alternatives, the VBMP hydrography data also offers a much higher resolution. The VBMP hydrography features were derived from digital orthophotography captured at scales between 1:1,200 and 1:4,800. Additionally, the VBMP data were captured during drought conditions in the winter and spring of 2002, which appropriately resulted in water body polygons that depict the surface area of potential water sources during

unusually dry weather. Some large water body features included in the Virginia Base Mapping Program dataset were not completed and therefore were unusable. If these incomplete features had a corresponding feature from National Hydrography Dataset (USGS 1999), the NHD feature was substituted (Figure 3.2). Furthermore, some large water bodies, such as Claytor Lake in Pulaski County, were completely absent from the VBMP hydrography dataset. NHD features were substituted in these cases as well.



**Figure 3.2. An example of NHD data substituting for incomplete VBMP data**

### 3.3.3 Virginia Wildfire Risk Assessment

The Virginia Wildfire Risk Assessment GIS Model (VDOF 2003a) was conducted by VDOF over a period spanning 2001 and 2002. This weighted linear combination raster overlay model included many geographic factors, which are discussed below. After some initial processing, each of these input layers was normalized on a scale of 1 to 10. Using their professional judgment and experience, members of VDOF's

Resource Protection Team weighted each of these factors based on their perceived level of influence of wildfire risk in Virginia. All of these normalized raster layers were overlaid on one another and the overlaying cell values were then summed.

Topography has a substantial influence on wildfires in two primary fashions. South-facing slopes generally receive more sunlight than north facing slopes, especially during the fall and spring wildfire seasons. This additional sunlight exposure results in drier fuels that could ignite more readily and increase wildfire intensity. Secondly, steep slopes can also increase wildfire intensity. Because heat from flames rises, it pre-heats and dries uphill fuel, which is known as “convective preheating”. Generally speaking, the steeper the slope, the faster a wildfire will spread uphill. Separate slope and aspect raster layers were derived from the USGS National Elevation Dataset and then normalized on a 1 to 10 scale.

The 1992 USGS National Land Cover Dataset was used in this model as a fuels surrogate. Forested areas were assigned high values – Conifer (Pine) forest cells received a value of 10, mixed forest (hardwood and pine) cells received a value of 9 and Hardwood forest cells received a value of 8. Because crops can serve as wildland fuels, particularly the remains of annual crops after harvesting, agricultural areas were assigned moderate values. Due to the lack of wildland fuels, areas classified as low and high intensity development were assigned low values.

The density of historic wildfires, particularly fires occurring between 1995 and 2001 inclusive, was also included. A continuous Kernel Density Surface was generated from wildfire point data and was then normalized to values ranging from 1 to 10.

Approximately 97% of the wildfires occurring in Virginia between the years 1995 and 2001 inclusive were ignited by humans, usually accidentally but occasionally intentionally. To account for the causal relationship, population density and proximity to roads were also included in the model. A continuous population density surface was generated from US Census Bureau Block centroids and a straight-line distance to roads surface was generated from the USCB TIGER road layer.

After normalizing these two final layers, all of the other normalized layers were weighted and combined (summed). Because wildfire risk at a particular location is influenced by the wildfire risk in the surrounding areas, a circular neighborhood function with a radius

of 250m was applied to the combined raster. The resulting continuous, “smoothed” surface was then ordinalized into three wildfire risk classes low, moderate and high. This methodology is described in more detail in the metadata for this dataset, see VDOF (2003b)

### **3.4 Preparing the Road Network for the Location-Allocation Model**

As discussed in Chapter Two, the Maximal Cover Location Problem (MCLP) model is the most appropriate location-allocation model (LAM) to use when planning the location of emergency facilities. ESRI has implemented the MLCP model in the NETWORK module of their ArcInfo software package and this software was used in this thesis to model hypothetical distribution of future hydrants. To execute the LAM, supply and demand locations must be represented at nodes in the ArcInfo coverage road networks. The following sections discuss the methods used to prepare this road network for analysis and the distribution of hydrant demand.

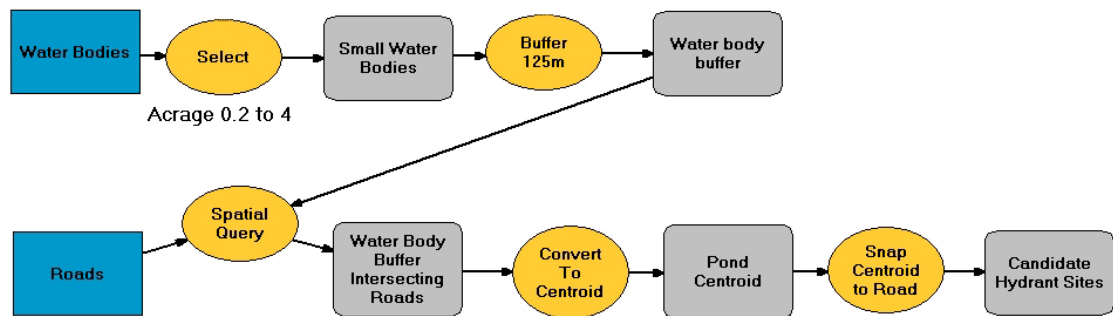
#### **3.4.1 Preparing the Road Network Spatial Features**

The four counties representing the northern study area were buffered by 2 miles and VDOF’s statewide compilation of USCB TIGER road files was clipped to this buffer. The buffer was used because some roads may cross a county boundary and then cross back into the county. If the roads were clipped to the county boundary, then portions of the road networks may become disconnected from the network as a whole. A similar process was conducted on the southern study area, resulting in two road network polyline shapefiles.

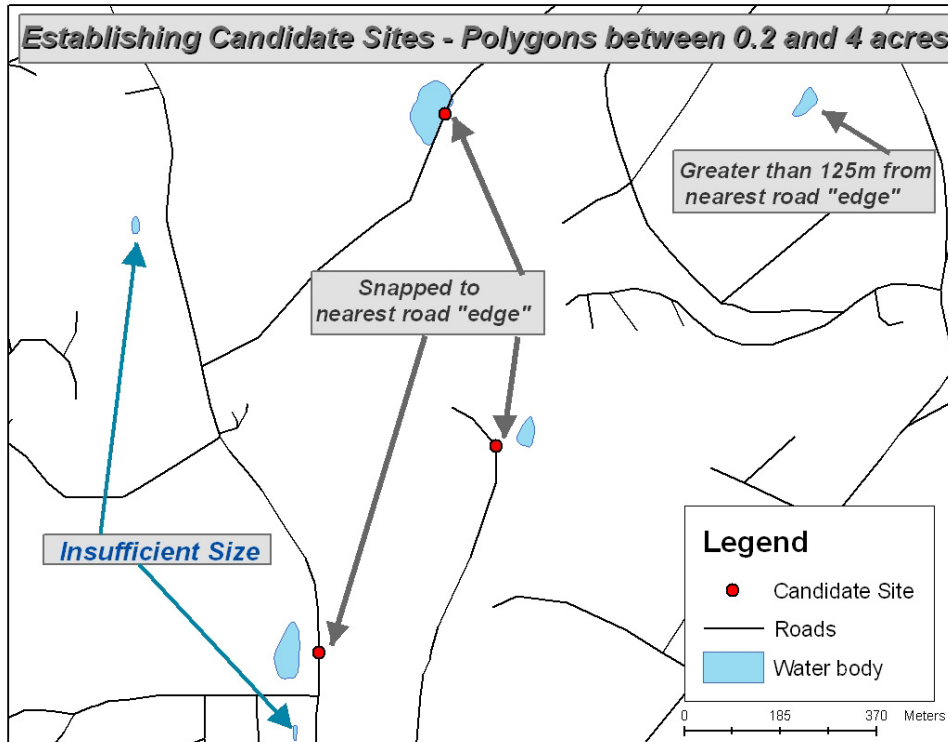
#### **3.4.2 Establishing Candidate Hydrant Sites**

The combined features from the VBMP and NHD were classified into 2 groups: ponds and large water bodies. Water bodies with a surface area of less than 4 acres were classified as ponds. Lakes with surface areas greater than 4 acres, major streams or rivers such as the New and Rappahannock Rivers, and the shoreline of tidal areas were classified as large water bodies. Two different processes were used to establish candidate sites along these two classes of water bodies.

Using their professional judgment and experience, members of VDOF's Resources Protection Team established the minimum pond size that might possibly support a dry hydrant at 1/5 acre; ponds smaller than 1/5 acre were deemed insufficiently sized and were excluded from the database of potential hydrant sites. Ponds that were located within 125m of an existing road, close enough to an existing road where the construction of a hydrant "driveway" would not, by estimate of VDOF staff, be cost-prohibitive, were converted to a centroid point and then "snapped" or moved to the nearest road. The road segment to which these points were snapped was split at the snapped point using Huber's (2002) "Point and Polyline Tools", thereby forcing the creation of nodes at candidate hydrant sites when the roads dataset was later converted to an ArcInfo road network coverage. Figure 3.3 graphically shows this process and Figure 3.4 shows the results on a map.



**Figure 3.3. Graphical representation of establishing candidate locations at smaller water bodies.**

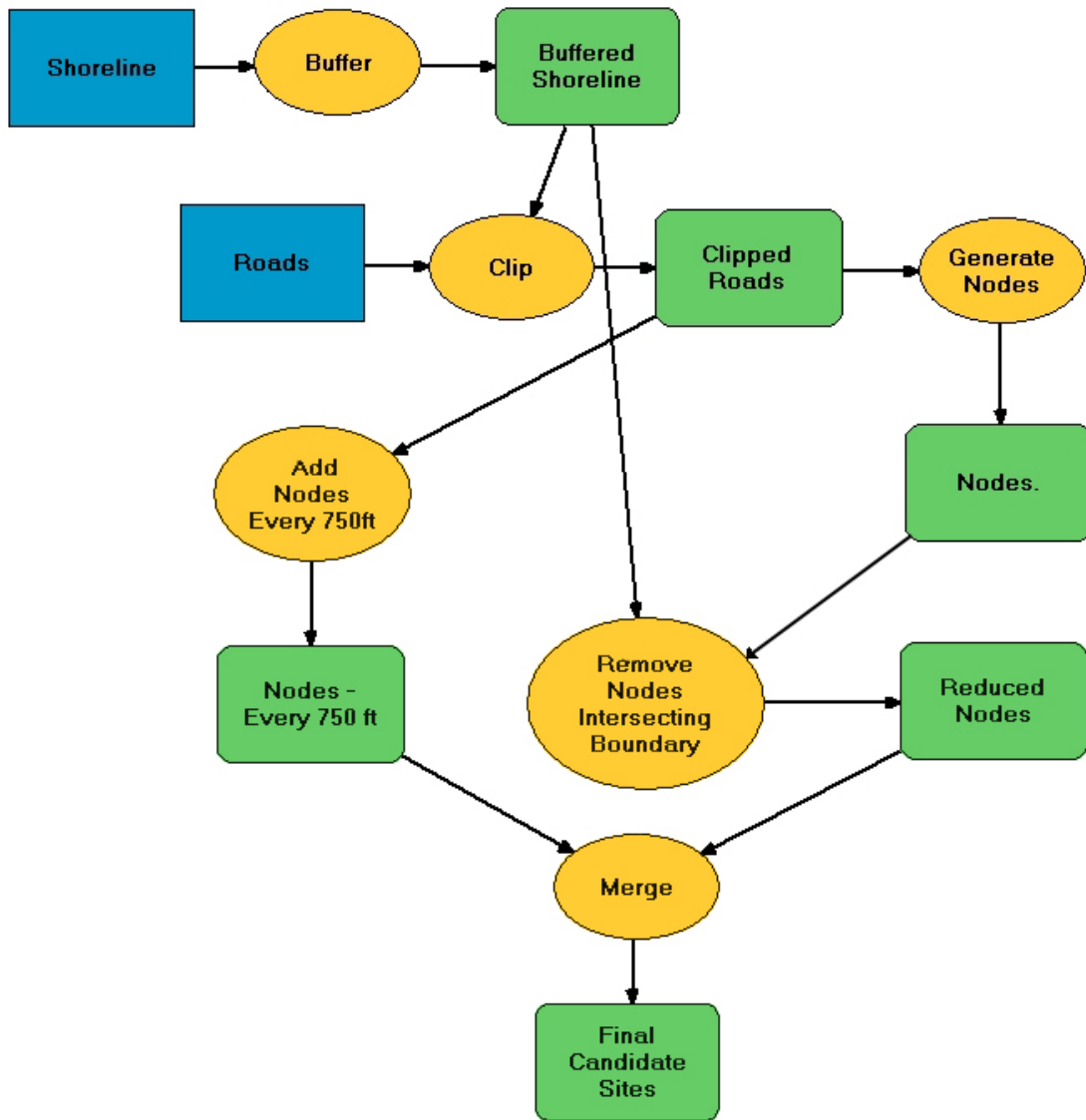


**Figure 3.4. Establishing Candidate Sites at Ponds (water bodies between 0.2 and 4 acres in size).**

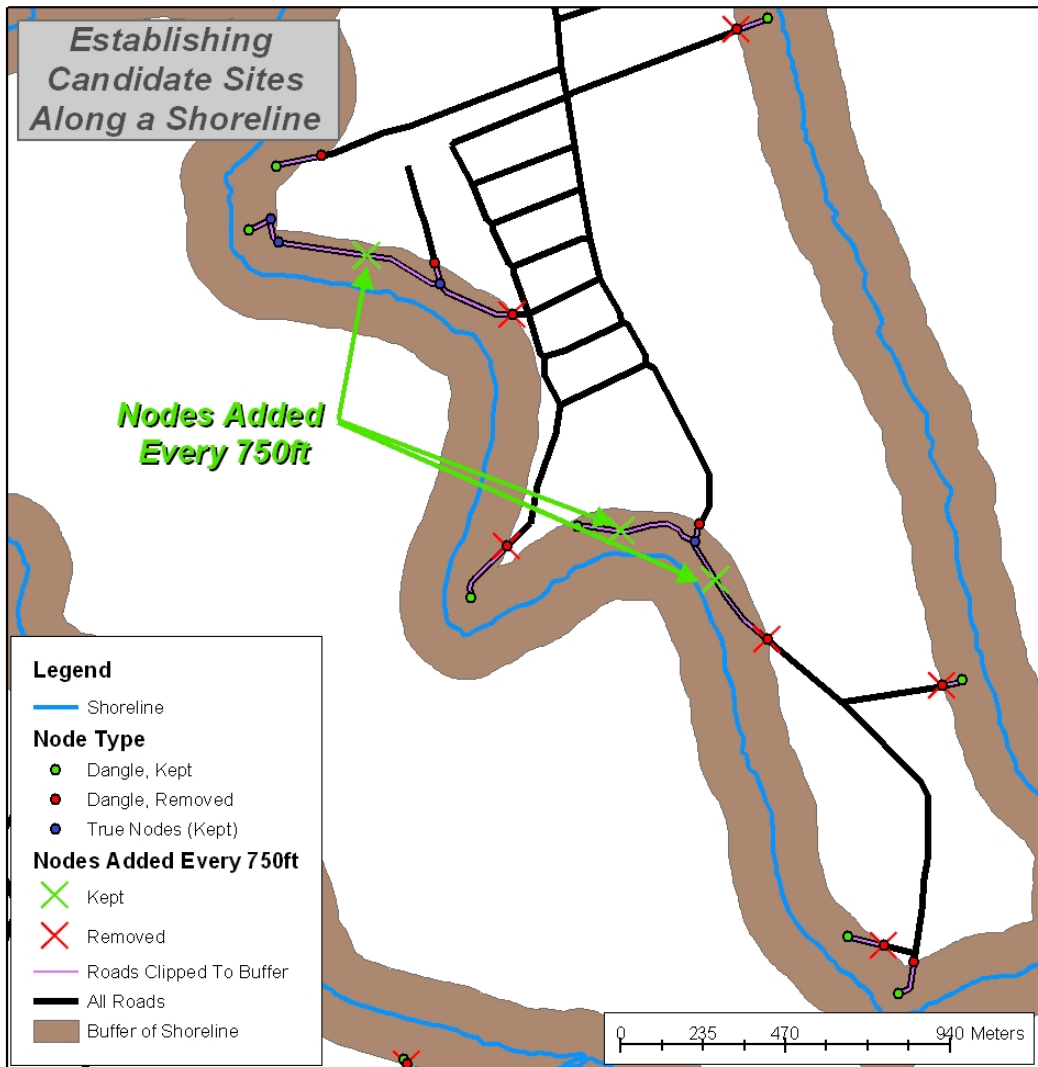
To establish candidate locations along large water bodies, the water bodies were buffered by 125 meters. Line segments in the roads layer were clipped to these buffers. Using the “Point and Polylines Tools” extension (Huber 2002), a point layer representing “dangle nodes” (the end points of line segments) and “true nodes” (points representing road intersections) was generated for the clipped roads shapefile. Using the same extension program, points were added to the resulting line segments every 750 feet to establish candidate sites along long road segments. Adding points to these line segments at intervals of 500 feet and 1000 feet was explored, but visually inspecting the results strongly suggested that points spaced at an interval between these figures would better distribute these candidate sites along the clipped roads layer, hence the use of 750 feet. This process of adding points to represent candidate sites along the road network lines clipped to the water body buffer inadvertently placed points along the outside of the buffer. Because the intent was to establish candidate sites *within* the buffer, the points



intersecting the boundary of buffer polygons were removed. Figure 3.5 graphically shows this process and Figure 3.6 shows a resulting map.



**Figure 3.5. Graphic representation of methods used to establish candidate locations along large water bodies.**



**Figure 3.6. Establishing candidate sites along large water bodies.**

### **3.4.3 Modeling Fire Truck Travel Time – Establishing Impedance on Road Network Arcs.**

#### **3.4.3.1 Overview**

Assigning time impedance to the road network arcs enables ArcInfo to determine the extent of the road network that can be accessed within a specified response time from a candidate hydrant location. For example, if a candidate hydrant location is surrounded

by roads on which a fire truck could travel 25mph, the fire truck could reach all locations that are within 2.5 miles of the candidate location within 6 minutes (1/10 of an hour). Time impedance is established using the formula  $distance = rate * time$ . The distance of each road network arc length was calculated using the GIS. But to determine the time that would be required for a fire truck to travel each arc, a rate or speed must first be assigned to each arc.

### **3.4.3.2 Fire Truck Travel Speeds Used in Other Studies**

The TIGER line files specify the road type of every road in their network in the census feature class code (CFCC) attribute field. This specification would permit one to assign different fire truck travel speeds to different road types. An extensive literature search was conducted in an attempt to obtain peer reviewed research that recommends emergency vehicle speeds for varying road types. No published literature was found. In a telephone interview, Dr. Charles Jennings, editor of the Proceedings of the 1999 International Conference on Fire Service Deployment Analysis, stated that he himself had conducted extensive searches for research that modeled fire truck travel speed. In fact, his discovery of this gap in the literature compelled him to conduct such a research project. However, the lack of funding prevented him from doing so (2003, pers. comm.). Through email correspondence, Dr. Brian Smith, Associate Professor of Transportation Engineering and Management at the University of Virginia, stated that he and his colleagues “could find no published information or research on emergency vehicle travel speeds” (2004, pers. comm.)

Several people who have used GIS in emergency response assessment and/or planning initiatives have used the posted speed limit when assigning fire truck travel speeds to different road types. The City of Wilson, NC used GIS to assess their fire services. In a telephone interview, Fire Chief Don Oliver noted that, out of safety concerns, he does not permit his fire personnel to exceed the speed limit when responding to fires. Hence, they used the posted speed limit for each road in their GIS analysis. He did note that they added a small amount of time where there were known bumps that had previously slowed fire trucks (Don Oliver 2004, pers. comm.). However, the USCB

TIGER roads database used in this thesis does not document such “bumps”, hence the time impedance values assigned to each road arc could not be adjusted to account for these impedances.

Sean Bloom, a former Master’s Student in the Department of Geography at Virginia Tech, used GIS to assess political and administrative implications of utilizing GIS to address a resource allocation problem within the Norfolk Fire Department. When modeling fire truck travel speed, he assigned speed limits that were specified in the traffic code of the City of Norfolk (Bloom 1995).

In a telephone interview, David Simms, Technical Program Analyst with the Prince William County Fire and Rescue System, noted that they also used the posted speed limit in their Fire and Rescue Station Location Analysis. However, he tested these methods before implementing them. Their fire database system records the time at which their fire trucks leave a station and the time at which they arrive at the scene of a fire. As a result, he had a historical record of fire truck response times. Using the posted speed limit, he generated a series of service area polygons around each of the existing fire stations. He then geocoded the addresses of the historical fire incident locations. In the interview he stated that 85-90% of the geocoded fire incidents were located within the correct service area polygon, thereby verifying that using the posted speed limit suited their needs.

In 2000, the City of Wichita, Kansas worked with a consultant firm, Tridata Corporation of Arlington Virginia, to assess the city’s fire station locations. The results of this complex study, which also analyzed projected fire suppression demand and fire department staffing levels, recommended that two new fire stations be constructed and eight of the existing fire stations be moved. This study included determining the areas of the city that could be accessed by non-ladder carrying fire trucks within 6 minutes. This report states that “the 6 minute boundaries are derived by assuming fire vehicles can travel at the posted speed limit on each link in the street network until the 6-minute time limit is reached.” This sentence ended a footnote that stated “The Fire Department thought the assumption about driving at about the speed limit was a reasonable approximation. It varies from time of day, but was a reasonable average approximation” (City of Wichita 2000, pg 16). Later in the study, the assessed the areas of the county

that a ladder-carrying fire truck could reach in 8 minutes. This document did not specify any changes in speed to account for this larger truck, so it was assumed that the posted speed limits were used in this second analysis as well.

Finally, in the email correspondence with Dr. Smith noted above, he also stated that he and his colleagues had “attempted to interest fire departments in the DC area in supporting research to develop good estimates for different classes of roads. [The fire officials] were VERY uninterested and told us that assuming the speed limit worked very well - thus, this really wasn't a problem for them.” Dr. Smith did not specify whether or not he specifically had spoken with the fire officials in Prince William County. He then concluded, “So - based on what we've seen - I would just go with the speed limit” (Smith pers. comm. 2004).

However, Charles Jennings noted that in at least one study, 90% of the posted speed limit was used for ambulances, 75% of the posted speed limit for fire trucks and 65% of the posted speed limit for ladder trucks (2003, pers. comm.). Additionally, the National Fire Protection Agency (1999) suggests augmenting fire truck travel time by using the following formula:

$$T = 0.65 + XD$$

where T is time in minutes, X is a constant speed and D is the distance. This NFPA document notes that “the factor 0.65 represents an acceleration/deceleration constant based on miles per hour developed by the Rand Corporation” (NFPA 1999, pg 1142-38). This NFPA formula cannot be implemented in ArcInfo because the 0.65 time factor would have to be added to every arc. For example, if a secondary road spurs off of a highway, a node is placed at this intersection and the highway is broken into two separate arcs. Using this formula would suggest that the fire truck decelerated when it approached the secondary spur road and then reaccelerated the after it passed the spur.

Because most of the sources cited above used the posted speed limit without any type of reduction in speed, it was decided that most of the subsequent analyses would use this method. However, changes in the fire truck travel speed will change the distance that can be covered in a certain response time. This change in distance traveled will then likely affect the results of the model. To investigate the effects of varying travel speed, in a subsequent section of this chapter the fire truck travel speed will be reduced by 75% in

one analysis and the model results will be compared to the results produced when the posted speed limit is used alone.

#### **3.4.3.3 Assigning Speeds to Each Census Feature Class Code (CFCC)**

A Virginia Department of Transportation official provided internet links to Virginia Law Codes that specify the maximum speed limit for various road types. These four sections of law code are provided in Appendix A of this thesis. However, these codes did not exactly match the road types specified in the TIGER roads attribute table and the perceived match was used. Some of these laws specify lower maximum speeds in “cities and town”. These reduced speeds were applied to all roads that intersect the US Census Bureau’s TIGER Line Files (USCB 2000) that identify urban areas. A table showing the speed assigned to each TIGER CFCC is also provided in Appendix A.

To calculate the time in hours that is required to traverse each road segment, the length of the road in miles was divided by the speed limit. Because it is mathematically impossible to divide by zero, CFCC road types that would not support tanker/pumper fire trucks were assigned speed values of (1 mph). These roads could have been deleted from the database altogether. However, doing so could disrupt the network topology and/or could result in roads that would become “disconnected” from the network. A fire truck traveling at a rate of 1 mph could only travel 1/10 mile in six minutes and therefore this speed was deemed safe to use. After the amount of time in hours to traverse a road segment was calculated, the final impedance values in minutes were calculated by multiplying the hour values by 60.

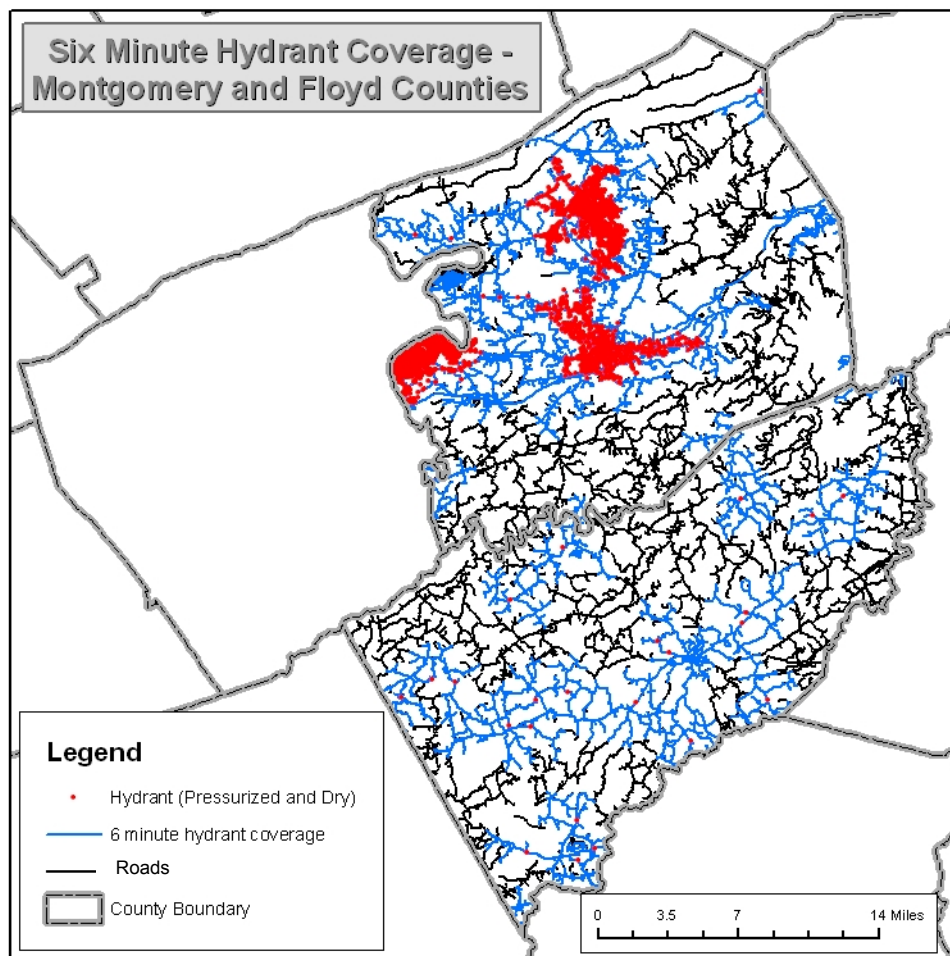
#### **3.4.4 Determining Areas Served by Existing Hydrants**

Where available, GIS point data representing pressurized hydrants were obtained from city and county government sources. These points were merged with existing dry hydrant locations gathered by VDOF personnel. All of the points in this combined hydrant dataset were then snapped to the nearest road arc. The arcs were then split at each of these points to establish nodes in the ArcInfo road coverage. Areas within a six-minute travel time of these hydrants were determined using AML script below:

```
netcover northroads sixminhyd init (1)
```

```
centers hydrants.cen # # 6          (2)
demand minutes #                    (3)
allocate out centers connected       (4)
```

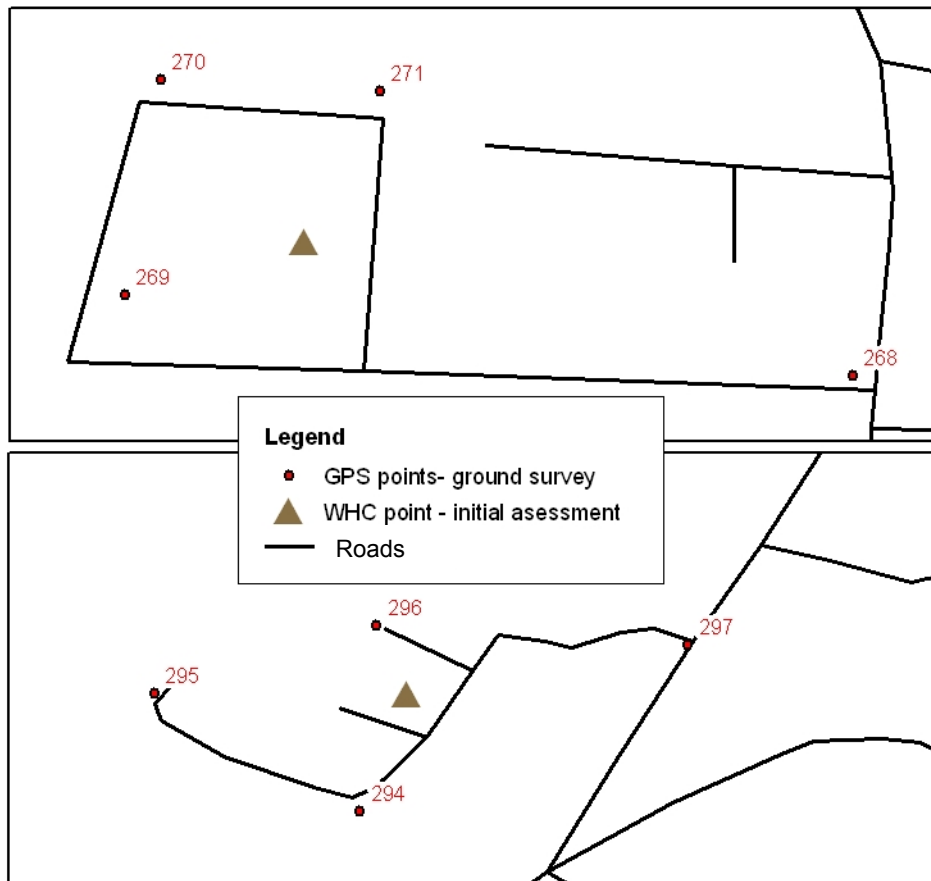
Line 1 of the code specifies the road network (northroads) and the output route file that will represent the extent of the road network that can be reached within a six minute travel time (sixminhyd). The second line of code specifies the INFO table that lists the centers nodes representing existing hydrants and specifies that each hydrant has a ‘supply’ of six minutes. Line 3 specifies the field or “item” in the road attribute table that contains the impedance values – minutes of travel time. The final line executes the ALLOCATE command and the results are shown in Figure 3.7.



**Figure 3.7. Six-minute coverage from existing hydrants in Montgomery and Floyd Counties.**

### 3.4.5 Modeling WHC Extent

WHCs as mapped in the initial survey using digital orthophotography were represented as single points. As a part of the current WHC survey, members of VDOF's wildfire mitigation team are traveling to each WHC mapped in the initial survey to gather detailed data such as the typical dwelling construction materials, dominate vegetation, and fuel loads. These personnel are also gathering GPS points at the periphery of each WHC to better document its extent (Figure 3.8)



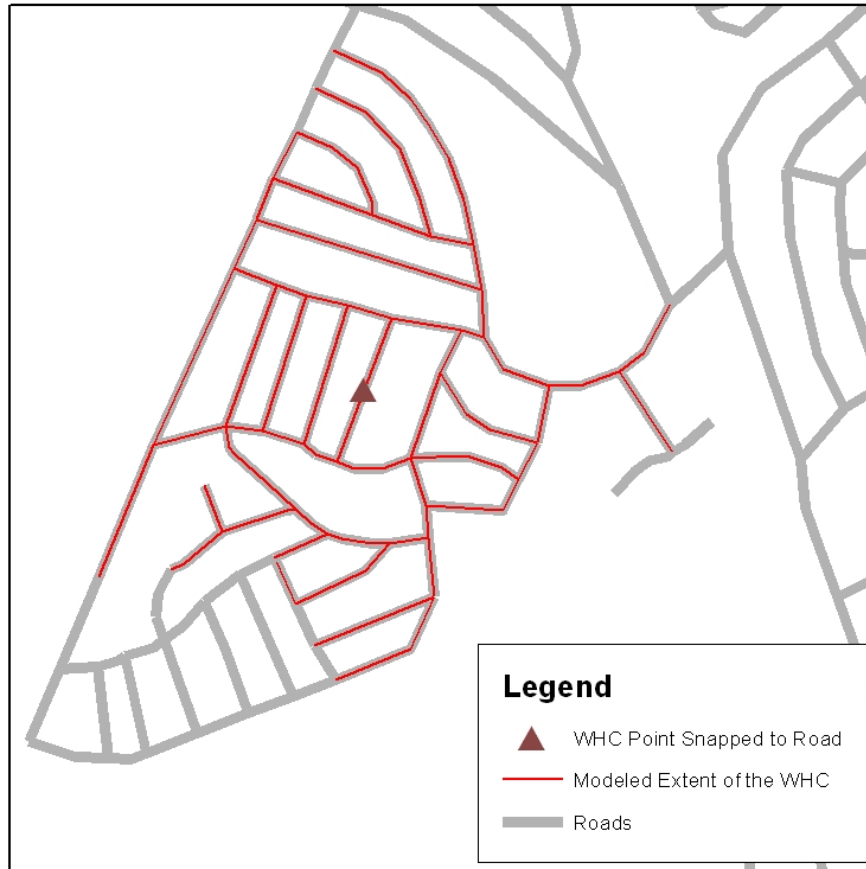
**Figure 3.8. Points from the initial assessment that representing the entire community and GPS points being gathered in the current WHC surveys.**

However, these detailed WHC assessments have been conducted in only a handful of counties thus far. Consequently, the original points representing an entire WHC must be used in this thesis, thus the ALLOCATION feature in ArcInfo was used to model the extent of each WHC.



### 3.4.5.1 Regression Model Overview

To model the extent of the WHCs, the WHC points were snapped to the nearest road. The roads were then split at these snapped points, thereby forcing the creation of a node when the road network was “built” using ArcInfo’s BUILD command. Each WHC point contained a numeric attribute representing the number of homes in the community. It was hypothesized that the extent of a WHC could be predicted using the number of homes in the community, the population density of the area in which the WHC is located, and the road density surrounding the WHC point. The reasoning behind using the number of homes was that WHCs with a large number of homes (e.g., 250 homes) would occupy more space than those with a smaller number of homes (e.g., 25 homes). It was also assumed that WHCs in densely populated areas would have smaller lot sizes and therefore impact the extent of the WHC, hence the inclusion of population density in the model. Finally, it was assumed that areas with greater road density would contain more homes and therefore influence the extent of each WHC as well. Therefore, the length of the all of the roads representing the community was the dependent variable in the regression model. The independent variables would then be the number of homes, population density and road density. The resulting regression equation could then be implemented in the ALLOCATE command to expand the WHC throughout the road network. For example, if the regression equation estimated that a WHC occupied 3.25 mile of roads, the ALLOCATE command could be used to “grow” outward from the WHC point until a total of 3.25 miles of roads had been traversed, as shown in the example below (Figure 3.9).



**Figure 3.9. A demonstration of using ALLOCATE to model a WHC’s extent.**

### 3.4.5.2 Obtaining a Sample for the Regression Model

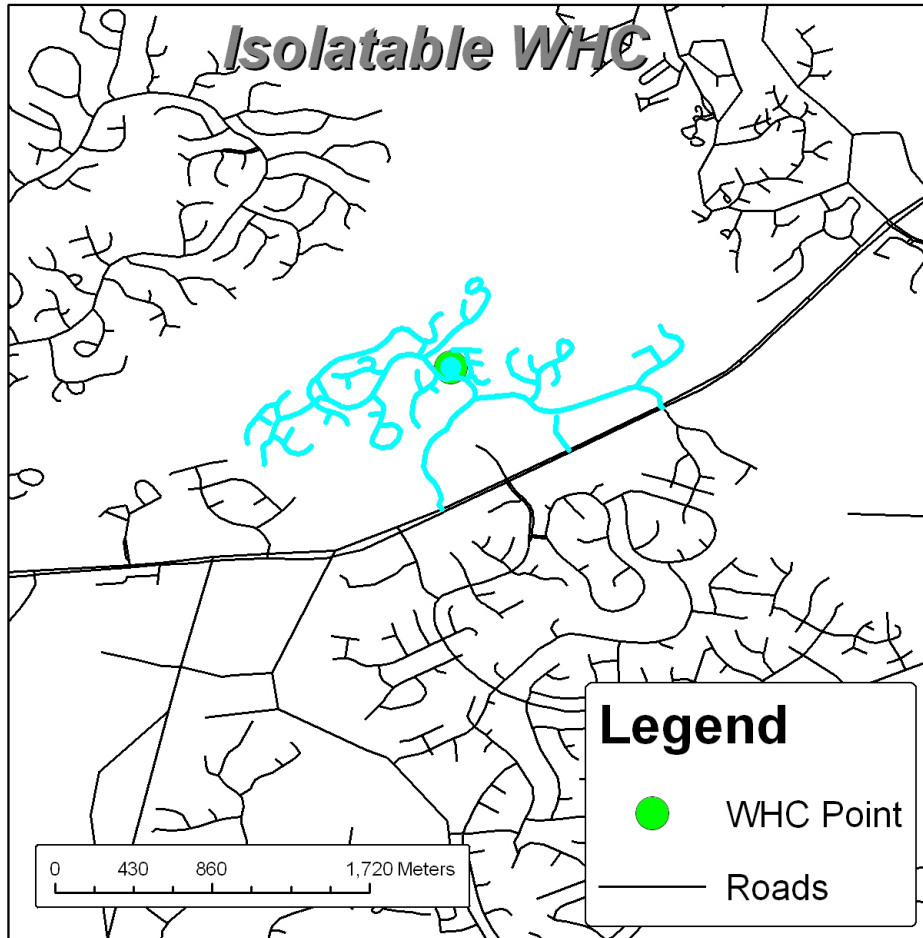
Because the number of homes in a WHC was thought to have the greatest impact on the geographic extent of the community, it was important to ensure that WHCs of various sizes were included in the sample used in the regression model. Hence, a stratified random sampling scheme was used to select the WHCs that would be used in the model. WHCs ranging in size from 10 homes to 500 homes were selected from the statewide database of WHCs. WHCs greater than 500 homes would not be modeled; they would later be mapped manually. The WHCs were then broken into 8 size classes with equal intervals of the number of homes found in each community, as shown in Table 3.2.

**Table 3.2. Size classes of the WHCs that were sampled.**

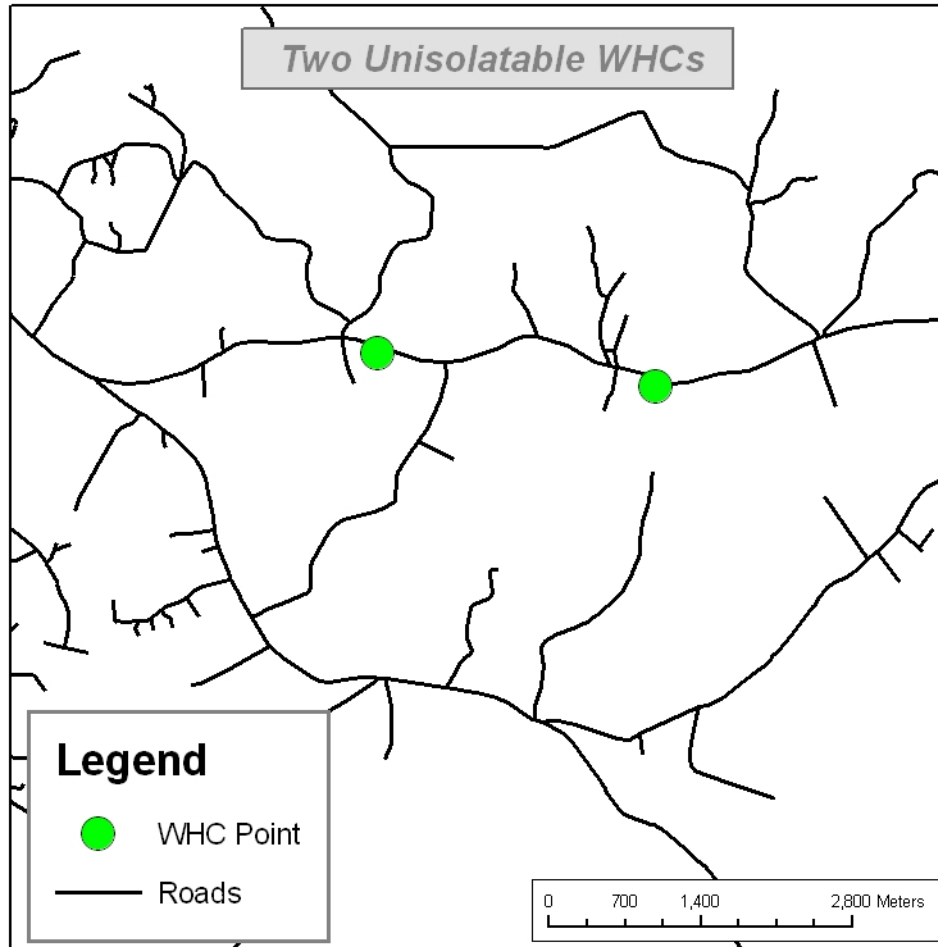
| Size Class | WHC Size (Number of Homes) | Number of WHCs used in the model |
|------------|----------------------------|----------------------------------|
| 1          | 10 - 70                    | 60                               |
| 2          | 71-131                     | 17                               |
| 3          | 132-193                    | 14                               |
| 4          | 194-254                    | 14                               |
| 5          | 255-316                    | 14                               |
| 6          | 317-377                    | 14                               |
| 7          | 378-439                    | 14                               |
| 8          | 440-500                    | 14                               |

However, a large majority of the WHCs in the eight study counties used in this thesis fell into the first two classes. Because of this distribution, it was decided that half of the sampled communities should come from the first two size classes and the rest from the six other classes. Hence, the sample was temporarily broken into two classes: small WHCs (10 –131 homes) and large WHCs (132 –500 homes). Approximately 75% of the WHCs in the small class had 10 –70 homes. Hence 60 WHCs were sampled from size class 1 and 17 WHCs were sample from size class 2. The appropriate number of homes in all eight size classes was then randomly selected from the statewide WHC database.

The extent of each WHC, expressed as the number of feet of road that the WHC occupied, was then recorded. However, the extent of some WHCs could not be determined by examining the road network pattern; some WHCs were not “isolatable”. Figure 3.10 shows an example of an isolatable WHC and Figure 3.11 shows an example of two WHCs that were not isolatable.



**Figure 3.10.** An example of a large, isolatable WHC.



**Figure 3.11. Two unisolatable WHCs. These WHCs are clusters of homes located on a through highway; it was impossible to surmise their extent by examining the road network.**

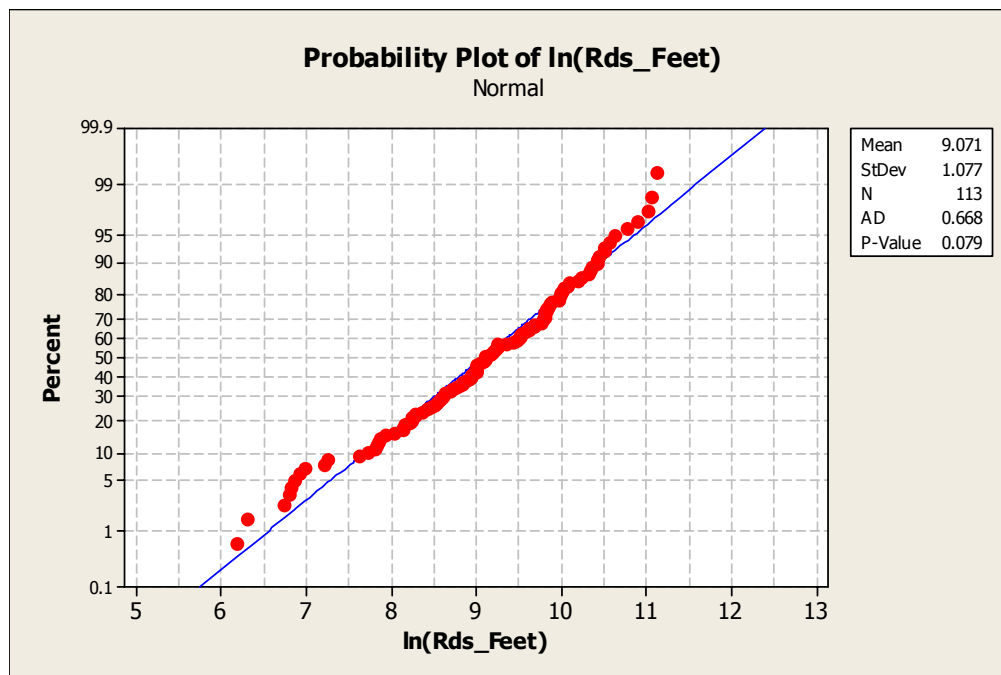
The length of the roads (in feet) of each isolatable community were summed and stored in the WHC point attribute table. Fifty-three unisolatable WHCs were encountered during this process and they were removed from the sample, resulting in a usable sample of 113 WHCs.

These WHC points were then spatially joined to census blocks to record the population density of the area surrounding each WHC point. The same process was executed with a continuous road density raster. Hence, the WHC sample point attribute table then contained all four variables: length of roads in feet (dependent variable),

number of homes, population density, and road density. The attribute table was then exported to a Microsoft Excel spreadsheet.

### 3.4.5.3 Executing Regression Models and Results

To run the model, the Excel spreadsheet was imported into Minitab statistical software. This software reported that the dependent variable (Rds\_feet) was not normally distributed. However, a natural log transformation on this variable (now labeled as “ln(Rds\_Feet)”) did produce a normal distribution, as shown in the probably plot below (Figure 3.12).



**Figure 3.12. Probability plot of the natural log transformed dependent variable. Note that the P-value exceeded 0.005, indicating that the ln(Rds\_Feet) was in fact normally distributed.**

It was thought that the population density and road density variables would exhibit high covariance and therefore cause multicollinearity problems in the subsequent multiple regression model. However, the Pearson correlation coefficient between the two variables was only 0.485 (p-value = 0.000). Hence, it was deemed safe to use the two variables together in a multiple regression analysis.

A best subsets multiple regression model was then executed using all three independent variables; the Minitab output is shown below (“PplSqMile” is the population

density variable – People per square mile, the “Rd Density” variable is the road density, and the “Num Homes” variable is the number of homes).

**Table 3.3. Results of Best Subsets Regressions.**

**Best Subsets Regression: ln(Rds\_Feet) versus PplSqMile, Rd Density, Number Homes**

Response is ln(Rds\_Feet)

| Model Num. | Vars | R-Sq | R-Sq (adj) | C-p  | S       | R<br>P d N<br>p u<br>l D m<br>S e<br>q n H<br>M s o<br>i i m<br>l t e<br>S e y s |
|------------|------|------|------------|------|---------|--|
| 1          | 1    | 42.9 | 42.4       | 6.7  | 0.81721 | X  |
| 2          | 1    | 9.1  | 8.3        | 75.3 | 1.0315  | X  |
| 3          | 2    | 46.2 | 45.2       | 2.2  | 0.79742 | X X  |
| 4          | 2    | 43.7 | 42.7       | 7.2  | 0.81550 | X X  |
| 5          | 3    | 46.2 | 44.8       | 4.0  | 0.80046 | X X X  |

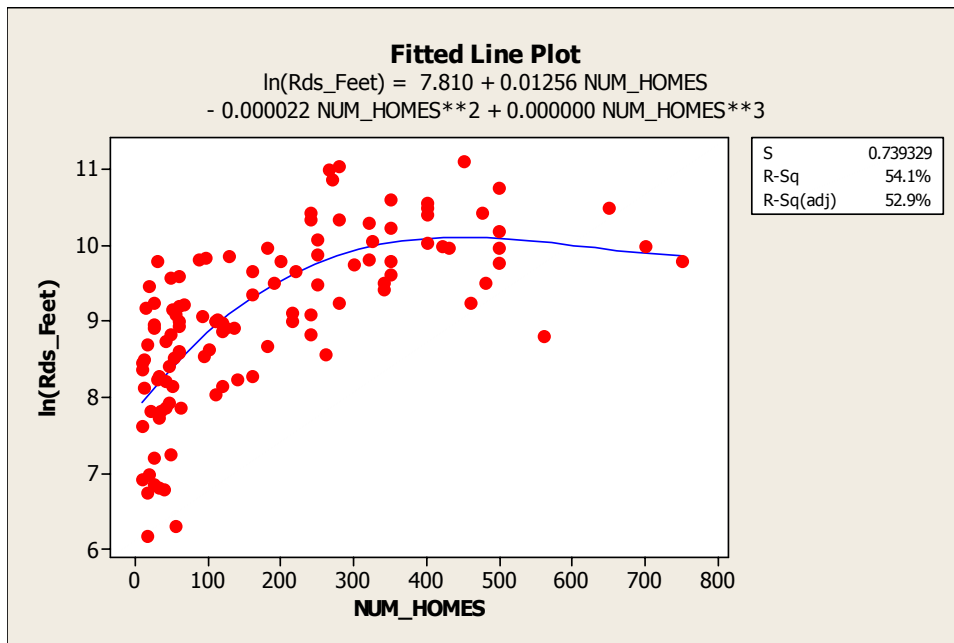
With the exception on the road density variable used by itself (model 2), all of the combinations of variables produced very similar  $R^2$  values. The combination of the road density and population density independent variables (model 3) produced the highest adjusted  $R^2$  value of 45.2%.

All of the models, with the exception of road density used alone (model 2), were run through individual multiple regressions. All of these individual models produced significant p-values of 0.001. With the exception model where all three independent variables were included (model 5), the residuals produced in the models were all normally distributed. Consequently, model 5 was eliminated. Table 3.4 below shows the equation resulting from the regression models.

**Table 3.4. The multiple regression model equations from the four models.**

| Model Number | Multiple Regression Equation  |
|--------------|---|
| 1            | $\ln(\text{Rds\_Feet}) = 8.32 + 0.00406 \text{ Num Homes}$  |
| 3            | $\ln(\text{Rds\_Feet}) = 8.68 + 0.00505 \text{ Num Homes} - 98.4 \text{ Rd Density}$                              |
| 4            | $\ln(\text{Rds\_Feet}) = 8.35 + 0.00428 \text{ Num Homes} - 0.000033 \text{ PplSqMile}$                           |
| 5            | $\ln(\text{Rds\_Feet}) = 8.67 - 0.000012 \text{ PplSqMile} - 92.9 \text{ Rd Density} + 0.00507 \text{ Num Homes}$ |

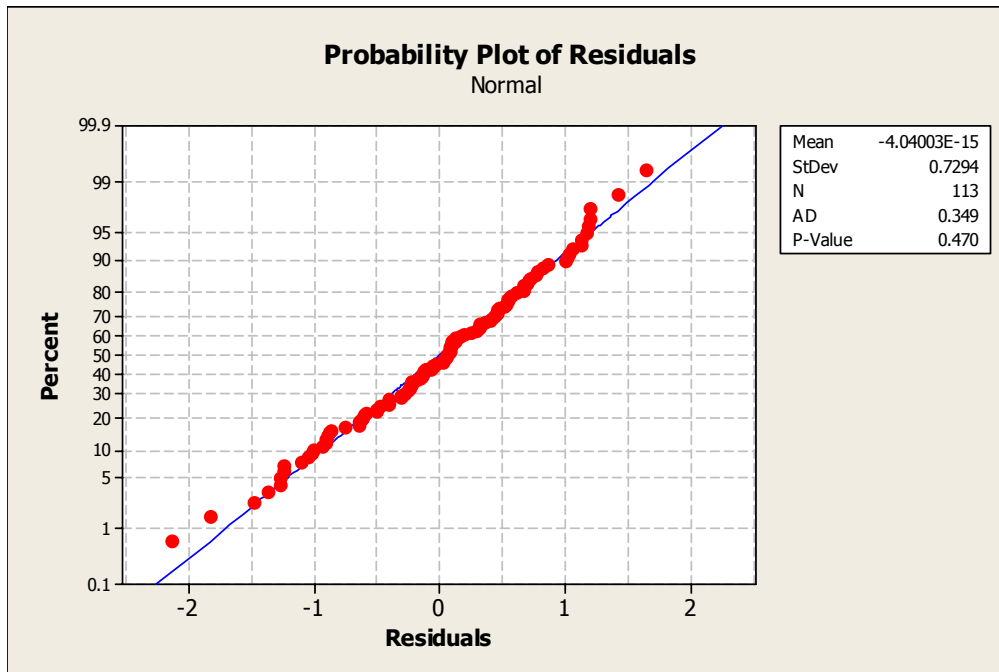
A third-order polynomial regression was also run on the ‘ln(Rds\_Feet)’ and ‘Num Homes’ variable. It produced an adjusted R<sup>2</sup> value of 52.9%, which was significantly higher than the highest adjusted R<sup>2</sup> produced by model 3 above (Figure 3.13).



**Figure 3.13. Results of the third-order polynomial regression equation using the number of homes are the independent variable.**

Furthermore, this regression model produced a p-value of 0.000 and normally distributed residuals (Figure 3.14).





**Figure 3.14. Probability plot of the residuals resulting from the polynomial regression model.**

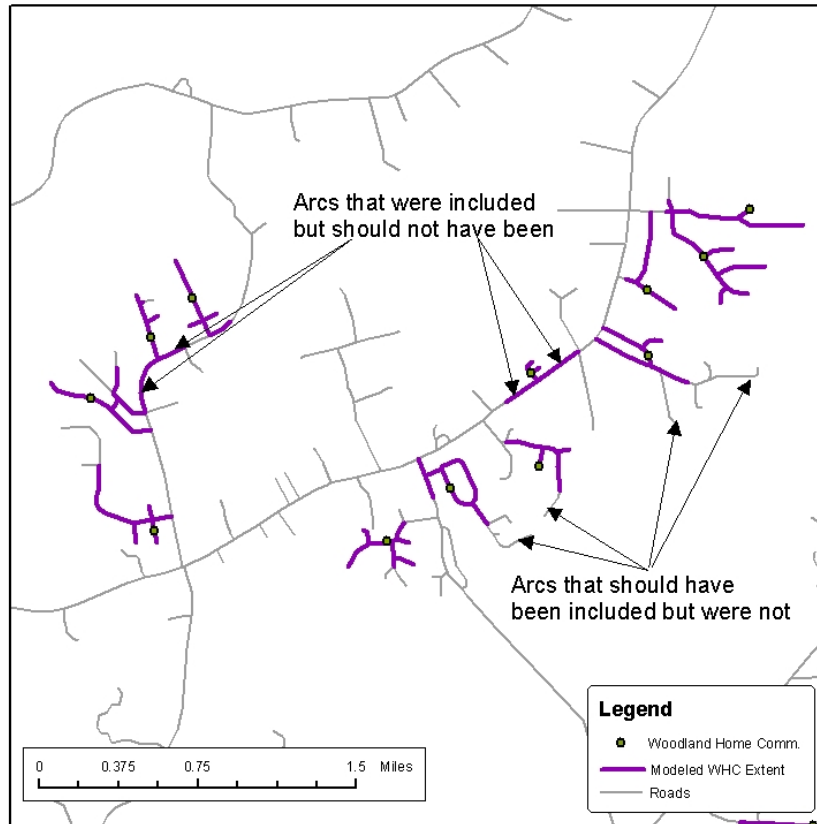
Because the polynomial regression produced the highest adjusted  $R^2$  value and because its residuals were normally distributed, it was selected as the model on which to base the ALLOCATE command

#### **3.4.5.4 Implementing the Regression Model using the ALLOCATE command**

To implement these equations using the ALLOCATE command, all of the WHC points in the eight study counties were spatially joined to the same census blocks and continuous road density raster surface as the sampled WHC points. Hence, all of the WHC points contained all three independent variables in its attribute table. WHC point attributes values were then transferred to the corresponding nodes in the ArcInfo coverage using a spatial join. The polynomial regression model was then applied to every WHC node. To take the “anti-natural log” of equation results, the “exp()” function was used to give the number of miles of road that were represented by each WHC node (the field/item was titled “whcfeet”). The ALLOCATE command was then executed on every WHC node in the study counties using the following ArcInfo Arc Macro Language (AML) script:

```
netcover northroads whc init          (1)
centers whc.cen # # whcfeet          (2)
demand feet #                          (3)
allocate out centers connected         (4)
```

Line 1 of code implements the “NETCOVER” ArcInfo command, which specifies the coverage to use and the name of the output allocation routes (whc). Line 2 specifies the INFO table that contains a list of the nodes that represent the WHC and the field that contains the amount of “supply” (whcfeet) that each center (WHC node) possesses. Line 3 specifies that the “feet” field as the demand or impedance field/item in the arc attribute table. The final line executes the ALLOCATE command. The “out” parameter specifies that arcs should be allocated outward from the WHC node (the “centers”). The last parameter in this line specifies that the arcs must be allocated outward in a connected fashion and prevents them from become “disjointed”. The results of implementing the polynomial regression equation in ArcInfo are exemplified in Figure 3.15 below.



**Figure 3.15. The arc allocations resulting from the polynomial regression equation. “Overshoots” (arcs that were included in a WHC, but should not have been) and “Undershoots” (arcs that should have been included, but were not) are shown.**

Figure 3.15 shows many WHCs. Several county highways traverse the area shown in the figure. All of these WHCs are likely to be “neighborhoods” that are located on dead-end roads or several roads that all dead-end (‘no outlet’ situations). If the regression model had accurately modeled the extent of each WHC, then all of the roads in the ‘no outlet’ situations would have been included in the WHC extent. These are the ‘undershoots’ in Figure 3.13. Furthermore, the WHC extents should not have “spilled over” into the county highways. These are the ‘overshoots’ in Figure 3.15.

Due to the obvious errors resulting from this process (the “overshoots” and “undershoots”), it is reiterated that these modeled WHC extents will not be used when VDOF implements these methods. The modeled WHCs are used here only because the true extent of WHCs have yet to be documented using GPS data in a handful of counties.

Recall that nodes in a road network data model occur at every intersection, dead ends or where the nature of a road changes. Additional nodes were created when

establishing existing hydrant locations, candidate sites, and the initial WHC points. Furthermore, the attribute table of these WHC points specified the number of homes represented at each point. The modeled WHC extents, as shown in purple in Figure 3.15 will hereafter be referred to as ‘WHC routes’. To establish the number of homes represented at each node, the number of homes represented by each initial WHC point was divided by the number of nodes that intersected the WHC routes. As an example, say an initial WHC point (shown in green in Figure 3.15) represented 20 individual homes. If the corresponding WHC route intersected 5 nodes, then the number of individual homes assigned to each of these nodes would be 4. In the subsequent portions of this thesis, when the phrase ‘number of homes’ is used, it refers to the individual homes assigned to each node (4 in the example immediately above).

### **3.5 Testing the MCLP – LAM’s Flexibility in the VDOF Context**

#### **3.5.1. Overview**

This section of Chapter Three introduces and discusses several methods and concepts. To test the flexibility of the MCLP LAM, three different demand-weighting schemes will be applied to the road network nodes and the model then executed on each of these demand weighting scenarios. Because the process of executing the LAM in ArcInfo has not been discussed so far, it is discussed in detail after applying the first weighting scheme. Furthermore, the output generated by ArcInfo will be introduced and discussed in detail as well.

#### **3.5.2. The First Demand Weighting Scheme**

This section discusses the first demand weighting scheme used to test the flexibility of the MCLP model. WHCs, VDOF’s primary concern, are given a very high priority in distributing demand for dry hydrants. Therefore, the number of homes at each WHC node will receive high demand values. VDOF’s second criterion in placing hydrants is the wildfire risk assessment. If five candidate hydrant sites could serve the same two WHCs, but one particular site could also serve high fire risk areas outside of these WHCs, then it should be selected as the more effective hydrant location. Hence, nodes intersecting high wildfire risk zones should receive more weight than those located

in moderate and low risk zones, but be weighted far lower than nodes representing homes within a WHC.

### **3.5.2.1. Assigning Demand to the Road Network Nodes**

During initial trials of the location-allocation process, it was discovered that one hydrant in Montgomery County could serve 224 nodes that included no WHCs. Furthermore, a WHC of 10 homes was represented by 11 nodes, resulting in a 'NumHomes' value of 0.909. Hence, if the location-allocation process is to select first hydrant locations that would serve WHCs, the demand values of nodes outside of WHCs would have to be significantly lower than 0.909. Dividing the 0.909 'HumHomes' value by the 244 non-WHC nodes suggests that non-WHC nodes should receive a value of roughly 0.004 to influence the model to place hydrants near WHCs first. But because not all of these 224 nodes were located in high risk zones, it was deemed safe to assign a value of 0.009 to high wildfire risk assessment nodes (represented in the 'WRA' column in Table 3.5). To test the location-allocation's ability to distinguish high-risk areas from moderate-risk areas, nodes in moderate risk zones were assigned a value of 0.001 – a difference of a factor of 9.

Nodes in low risk zones were assigned a value of zero for three reasons. First, the number of hydrants necessary to serve WHCs, high fire risk areas, and moderate fire risk areas is likely to be high, especially when considering the fact that VDOF operates on a statewide scale. Consequently, installing hydrants in low fire risk zones is likely to be a low priority, even in the long term. Second, low fire risk areas are often found in urban areas, where there are existing pressurized hydrants and low amounts of wildland fuels (and therefore few WHCs). Third, to reduce computation time the software documentation recommends that the number of demand and supply nodes be kept to a minimum. So to follow this recommendation, all low risk nodes were assigned values of zero, causing the software to completely disregard those nodes.

To establish a total demand, the NumHomes field was added to the WRA (Wildfire Risk Assessment) field. Finally, all nodes that were within six minutes of an existing pressurized or dry hydrant, including WHC nodes, were set to a value of zero

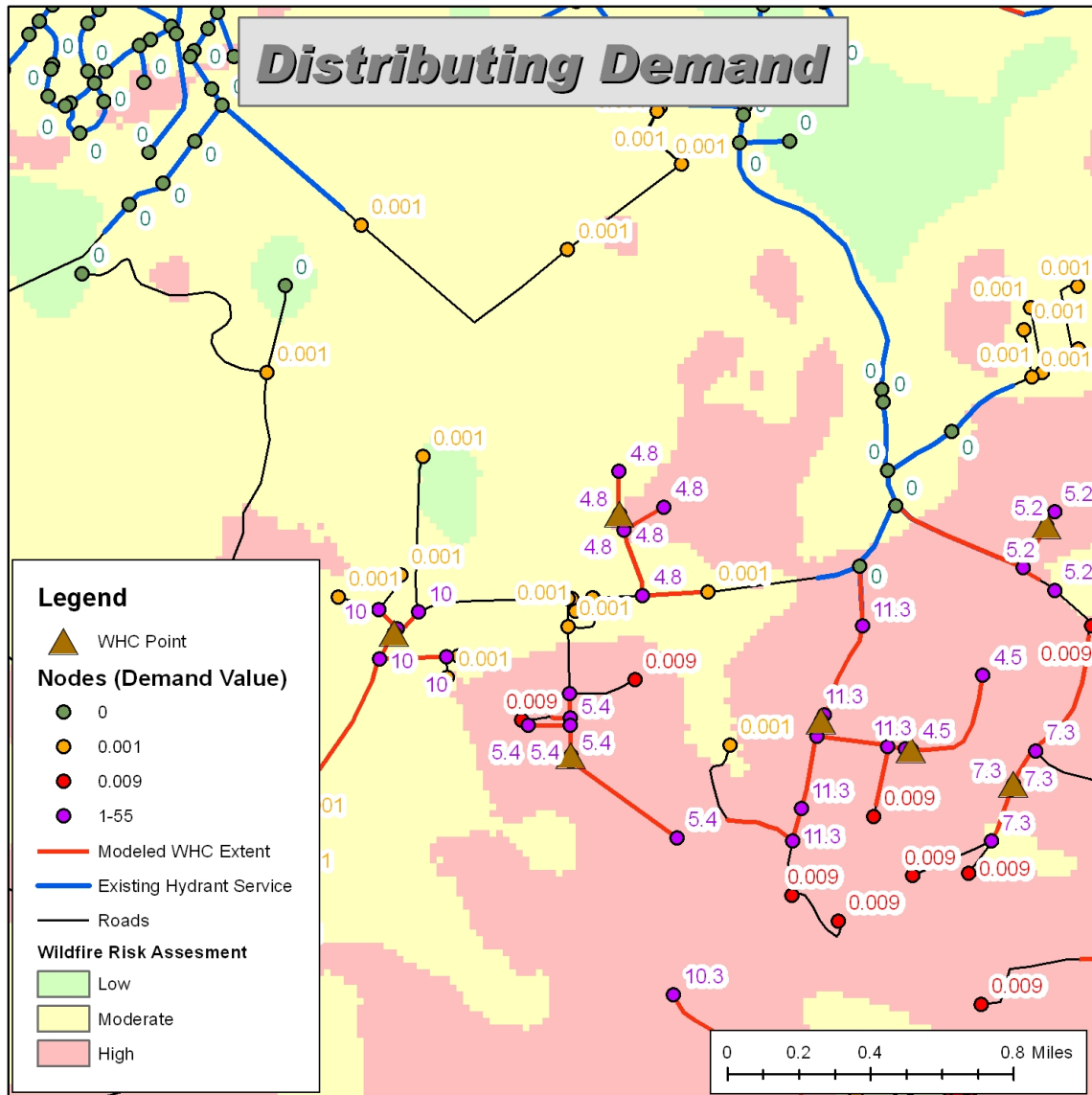
since they are already served. Table 3.5 is an example of the node attribute table after the final weighting scheme was applied.

**Table 3.5. An example of the node attribute table after the weighting scheme was implemented.**

| NodeID | NumHomes | WRA   | WHC Type  | Demand |
|--------|----------|-------|-----------|--------|
| 1      | 16.325   | 0.009 | Exposed   | 16.334 |
| 2      | 0.909    | 0.001 | Exposed   | 0.910  |
| 3      | 0        | 0.009 | N/A       | 0.009  |
| 4      | 0        | 0.001 | N/A       | 0.001  |
| 5      | 0        | 0     | N/A       | 0      |
| 6      | 10.0     | 0     | Unexposed | 0      |

The first two rows (NodeID 1 and 2) represent nodes at which exposed WHC homes were located. NodeID 1 was located in a high risk zone and NodeID 2 was located in a moderate risk zone. The next two rows (NodeID 3 and 4) represent nodes at which no WHC homes are located. NodeID 5 represents a node in a low risk zone, and hence the WRA value of zero. NodeID 6 represents a node at which 10 WHC homes were located, but was

within six minutes of an existing hydrant; hence, the demand value of 0. In subsequent portions of this chapter, these values will be manipulated to test the effect of assigning various demand values. Figure 3.16 shows this method of distributing demand to the nodes.



**Figure 3.16.** The demand values assigned to the road network nodes.

### 3.6. Executing the Location Allocation Model

Two individual road networks were prepared – one for the northern study and one for the southern study area. Although these two road networks represented four counties, the location allocation model (LAM) was executed on individual counties. To facilitate this process, an additional field named ‘TempWt’ (temporary weight) was added to the node attribute table. All of the nodes intersecting a particular county were selected and then the values from the ‘Demand’ field were transferred to the ‘TempWt’ field using the ArcMap field calculator. ArcInfo requires that nodes representing candidate locations be

represented in a ‘centers’ INFO table. All candidate site nodes intersecting a given county were exported to an INFO table and given the name candsites.cen.

The following AML code was used to set up the location-allocation environment and execute the location-allocation process 50 times.

```
arcplot (1)
netcover roads outroutes (2)
demand # TempWt (3)
impedance minutes minutes (4)
centers candsites.cen (5)
locatecandidates clear (6)
locatecandidates centers (7)
locatecriteria maxcover 6 (8)
&DO index := 1 &to 50 (9)
  locateallocate allmaxcov%index% cenmaxcov%index% glomaxcov %index% TEITZBART (10)
&END (11)
```

Line 1 initiates the ArcPlot module of ArcInfo that contains the network analysis and LAM algorithms. Line 2 specifies the road network coverage to be used, in this case the ‘roads’ coverage. Although no routes are generated in the location-allocation process, the software user must still specify an output routes name as the third argument in line 2. Line 3 specifies the field in the node attribute table that contains the demand values (‘TempWt’ in this case). Line 4 specifies the field in the arc attribute table that contains the impedance values. The first argument specifies the impedance when traveling along an arc from the “from-node” to the “to-node and the third argument specifies the impedance when traveling in the reverse direction, identical values in this case. Line 5 specifies the INFO table that lists the candidate site nodes. Line 6 clears any candidate locations that may exist in memory from previous usage – a cautionary measure. Line 7 specifies that the INFO table included in line 5 be used to establish the candidate hydrant locations.

Line 8 specifies the location-allocation model to use. In this case, the maximal covering location problem (MCLP) is represented by the keyword ‘maxcover’. The second parameter in line 8 specifies that the maximum distance that a demand point is to travel, in impedance units (minutes), to the nearest supply center. The value of 6 in this line meets VDOF’s criterion that hydrants should be placed in location where they can reach WHC nodes within 6 minutes. Line 9 signifies the start of the ‘for loop’ and directs



the computer to execute the following line of code 50 times. During each iteration of the loop, the 'index' variable is incremented by one. Line 10 executes the location allocation process and specifies the name of the output tables. Thus, on the third iteration of the loop, the command sent to the ArcInfo Network Module would read:

```
locateallocate allocmaxcov3 cenmaxcov3 glomaxcov 3 teitzbart
```

This command would specify that the output allocation, centers and global tables be named 'allocmaxcov3', cenmaxcov3 glomaxcov respectively (the contents of these output tables are discussed below). Because a different name is not specified for the global table, the single record produced during each iteration is appended to the existing global table. The next argument ('3') specifies the number of centers (hydrants) to be established. Because this line occurs within the loop, one hydrant is placed in the first iteration. Two hydrants are placed in the second iteration, then three hydrants and so on until 50. Hence, 50 *individual* MCLP models are run in each county.

The final argument in line 10 specifies that the Teitz and Bart (TAB) heuristic be used, rather than the Global Regional Interchange Algorithm (GRIA) heuristic, both of which were discussed in Chapter Two. The ESRI documentation states that GRIA requires less computation time than TAB. ESRI then notes that GRIA sometimes produces results that are slightly inferior to those produced by TAB. But the documentation points out that sometimes the opposite is the case. However, the software documentation then states that "when candidate locations are different than demand locations, TAB may do better than GRIA. This is because the regional phase of GRIA only evaluates those candidates that are also demand locations". In the case of establishing hydrant sites, it very possible and probably likely that one or more candidate sites with a demand value of zero will be selected as a recommended hydrant site. For example, the closest candidate site to a WHC may be located in a low risk zone (demand value of zero). Additionally, a candidate site that is within 6 minutes of an existing hydrant (demand value 0) may be the only site that could serve a particular WHC. Consequently, the TAB heuristic was used, as shown in the last parameter of line 10. The final line of code (line 11) signifies the end of the code that should be executed within the loop, which in this case, is only line 10.

### 3.7. Interpreting Output from the Location-Allocation Process

#### 3.7.1. Tabular Output

As discussed above, the location-allocation process produces three INFO tables as its output for each iteration. Relevant fields (columns) from these tables are shown below.

##### 3.7.1.1. The Output Allocation Table.

The output allocation table lists every demand node that has a value that is greater than zero (Table 3.6).

**Table 3.6. An example of an output allocation table. The Roads# column is the NodeID.**

| ROADS# | SITE1 | DISTANCE1 | DEMAND | SITE2 | DISTANCE2 |
|--------|-------|-----------|--------|-------|-----------|
| 25     | 2568  | 4.89      | 14.629 | 6956  | 14.25     |
| 26     | 2568  | 5.25      | 0.009  | 6956  | 15.26     |
| 27     | 2568  | 12.32     | 0.001  | 6956  | 17.28     |
| ....   | ....  | .....     | .....  | ..... | .....     |
| 639    | 6587  | 0.12      | 11.231 | 2365  | 18.69     |
| 640    | 6587  | 2.36      | 0.001  | 2365  | 21.56     |
| 641    | 6587  | 14.23     | 0.009  | 2365  | 22.36     |

The ‘ROADS#’ column in this output table corresponds with the ‘ROADS#’ column in the node attribute table. This table then specifies the center to which each demand point was assigned in the ‘Site1’ field. This field also corresponds to a specific node in the node attribute table. Although many nodes were beyond the 6 minute cut-off specified in the LOCATECRITERIA line of code, they are still assigned to the closest center. The distance between the demand node and the closest hydrant in impedance units (minutes in this case) is given in the ‘Distance1’ field. The amount of demand found at each node is given in the ‘Demand’ field. The ‘Site2’ and ‘Distance2’ fields list the second closest facility (hydrant) and the distance to that facility in impedance units, respectively. In this example, nodes 25, 26, and 27 were assigned to the hydrant placed at node 2568. Node 25 had a weight of 14.629 and was 4.89 minutes to the hydrant placed at node 2568. The second closest hydrant was placed at node 6956, which was 14.25 minutes away. Nodes 639, 640 and 641 were closest to the hydrant located at node 6587.

### 3.7.1.2. The Output Centers Table.

The output centers table lists statistics for each of the hydrants established. On the first iteration of the loop, this table would only have one record since only one hydrant was placed. On the 50<sup>th</sup> iteration, this table would have fifty records. Unlike the allocation tables, these centers tables list statistics that apply only to the demand locations that were within the 6 minute cut-off specified in the LOCATECRITERIA command. But like the allocation table, the centers tables list only those features where the demand was greater than zero (shown below in Table 3.7).

**Table 3.7. An example of a centers output table.**

| ROADS# | TOTFEATURE | TOTDEMAND | TOTDIST  | AVGDIST | FURTHDIST | FURTHEST |
|--------|------------|-----------|----------|---------|-----------|----------|
| 2568   | 70         | 158.540   | 183.911  | 3.753   | 5.869     | 26087    |
| 6587   | 96         | 242.866   | 404.891  | 4.132   | 5.700     | 23328    |
| 7499   | 362        | 315.876   | 512.120  | 3.766   | 5.999     | 25767    |
| 8947   | 74         | 353.456   | 671.055  | 3.749   | 5.913     | 26757    |
| ....   | ....       | ....      | ....     | ....    | ....      | ....     |
| 9957   | 94         | 398.486   | 1014.980 | 2.697   | 5.929     | 28987    |

The ROADS# column refers to the node at which the center (hydrant) was placed. This table lists the total number of demand nodes served by each center (TotFeatures), the sum of the demand found at all of these nodes (TotDemand), the total distance in minutes between every allocated demand node and the nearest center (TotDist), the average distance traveled from each demand node to the center (AvgDist) and the distance traveled from the furthest demand node to the center node (FurthDist).

### 3.7.1.3. The Output Global Table

The output global table lists statistics for each individual location allocation iteration. Only the relevant columns are shown in Table 3.8.

**Table 3.8. An example of the output global table from Stafford County. Only the first 30 of 50 total records are shown.**

| NUM_CENTER | TOTDIST  | AVGDIST | TOTDEMAND | Marginal Demand Served |
|------------|----------|---------|-----------|------------------------|
| 1          | 183.911  | 3.753   | 158.540   | N/A                    |
| 2          | 404.891  | 4.132   | 242.866   | 84.326                 |
| 3          | 512.120  | 3.766   | 315.876   | 73.010                 |
| 4          | 671.055  | 3.749   | 353.456   | 37.580                 |
| 5          | 726.647  | 3.615   | 382.947   | 29.491                 |
| 6          | 792.766  | 3.555   | 395.676   | 12.729                 |
| 7          | 897.070  | 3.560   | 396.477   | 0.801                  |
| 8          | 957.875  | 3.458   | 396.996   | 0.519                  |
| 9          | 1045.280 | 3.361   | 397.366   | 0.370                  |
| 10         | 1103.060 | 3.384   | 397.697   | 0.331                  |
| 11         | 1108.540 | 3.349   | 397.866   | 0.169                  |
| 12         | 1121.610 | 3.348   | 398.026   | 0.160                  |
| 13         | 1096.870 | 3.274   | 398.026   | 0.000                  |
| 14         | 1052.350 | 3.095   | 398.076   | 0.050                  |
| 15         | 1093.540 | 3.170   | 398.126   | 0.050                  |
| 16         | 1100.350 | 3.171   | 398.206   | 0.080                  |
| 17         | 1114.640 | 3.185   | 398.266   | 0.060                  |
| 18         | 1117.480 | 3.148   | 398.316   | 0.050                  |
| 19         | 1074.080 | 2.992   | 398.357   | 0.041                  |
| 20         | 1079.140 | 3.006   | 398.357   | 0.000                  |
| 21         | 1058.110 | 2.939   | 398.396   | 0.039                  |
| 22         | 1063.740 | 2.947   | 398.436   | 0.040                  |
| 23         | 1067.850 | 2.934   | 398.466   | 0.030                  |
| 24         | 1009.250 | 2.765   | 398.477   | 0.011                  |
| 25         | 1014.980 | 2.773   | 398.486   | 0.009                  |
| 26         | 1003.570 | 2.742   | 398.486   | 0.000                  |
| 27         | 987.142  | 2.697   | 398.486   | 0.000                  |
| 28         | 987.142  | 2.697   | 398.486   | 0.000                  |
| 29         | 987.142  | 2.697   | 398.486   | 0.000                  |
| 30         | 987.142  | 2.697   | 398.486   | 0.000                  |

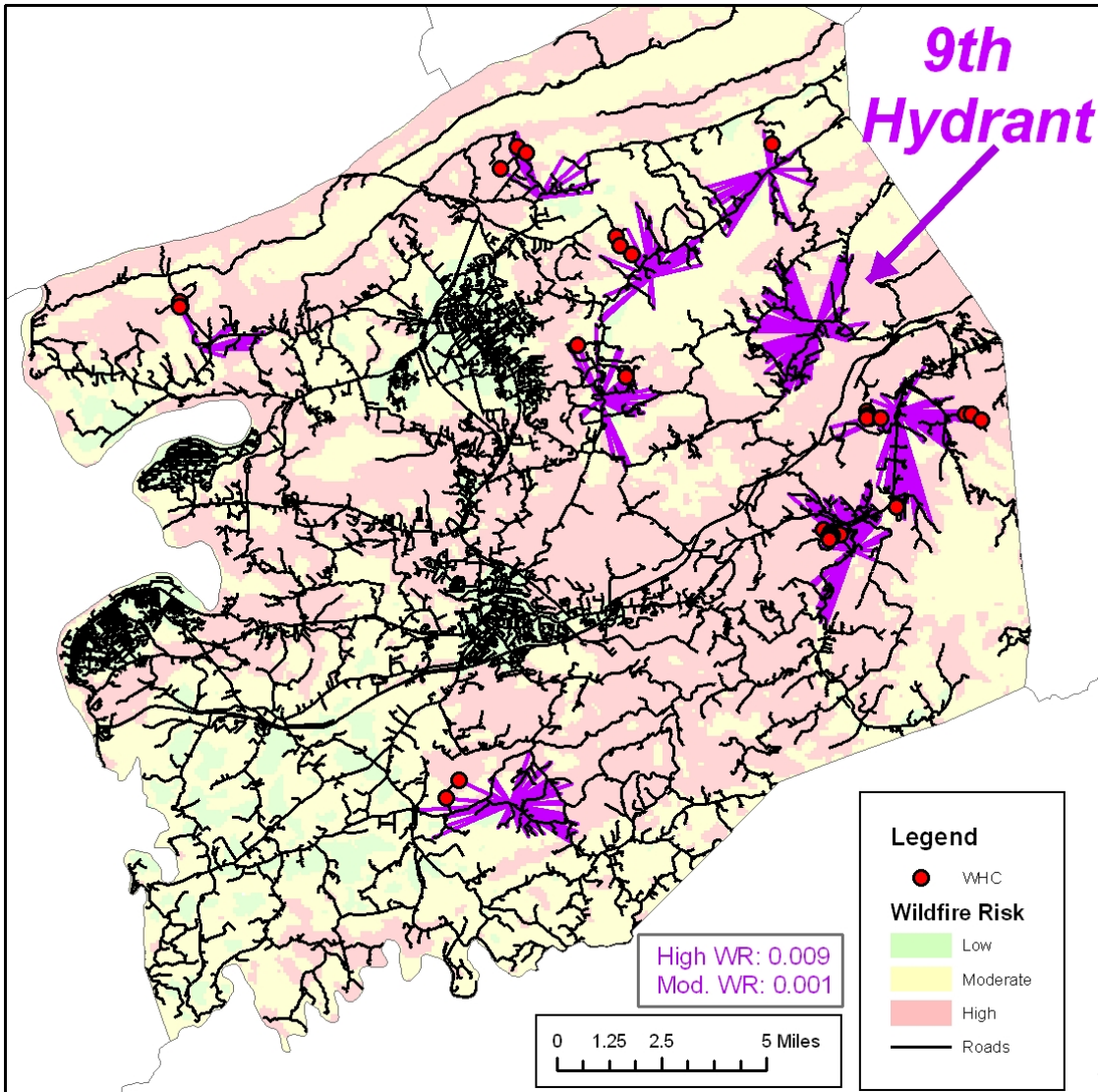
Like the centers table, the statistics listed here only summarize the demand nodes that were within the maximum distance of 6 minutes specified in the LOCATECRITERIA command. The Num\_Center column lists the number of centers (hydrants) placed during each iteration of the loop. TotDist and AvgDist list the total and average distances between the *all* of the demand nodes and the closest center, respectively. The TotDemand column lists the total amount of demand that was served by all hydrants.

The Marginal Demand Served column was added later using Microsoft Excel. It lists the added demand served by each additional hydrant. For example, the TotDemand value in row 1 was subtracted from row 2. Because MaxCover aims to cover the maximum amount of demand, the values in the Marginal Demand Served field should descend as the number of hydrants (Num\_Center) was increased. Overall, this trend occurs. This column is discussed in more detail in subsequent portions of this chapter.

This table also shows that all of the demand in Stafford County was fulfilled by 25 hydrants. As directed, the LAM continued to place up to 50 hydrants. But because 25 hydrants met the demand, the additional 25 hydrants were redundantly covering demand that could be met with fewer hydrants. This example shows that, if enough hydrants are placed, the MCLP LAM can also function as a ‘Covering Set’ LAM, as discussed in Chapter Two.

### **3.7.2. Cartographic Representation of the Output and Discussion of Results from First Demand Weighting Scheme**

The map in Figure 3.17 displays the location-allocation output.



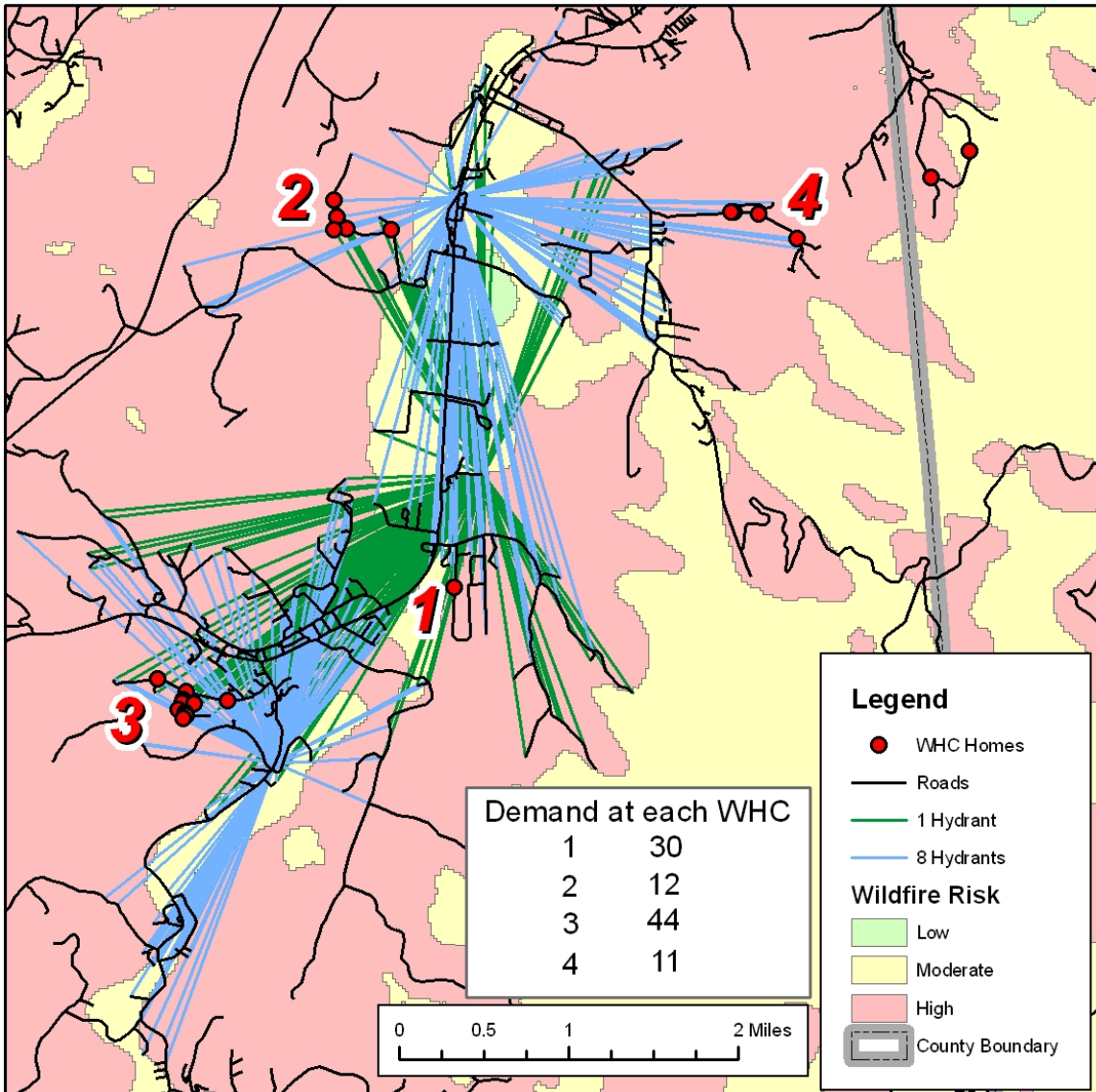
**Figure 3.17. Cartographic representation of LAM output with spider diagrams, Montgomery County.**

This map includes the ‘spider diagrams’ that show where the hydrants were placed by the LAM in Montgomery County. The lines radiating out from each selected hydrant location connect the hydrant site to all of the road network nodes that had a demand greater than zero and that were within 6 minutes from the hydrant.

As the map in Figure 3.17 shows, the first eight hydrants placed in the county covered all of the exposed WHCs. Recall that in this demand weighting scheme all non-WHC exposed nodes in high fire risk zones and moderate fire risk zones were assigned a weight value of 0.009 and 0.001, respectively. Nodes representing WHCs were given

significantly higher values. The output as shown in this map shows that this weighting scheme could be successful in meeting VDOF’s criteria that all WHCs should be served first. Once all of the WHCs were served by hydrants, the LAM algorithm then placed the ninth hydrant in an area with a large number of demand nodes in high fire risk zones.

The output from this weighting scheme demonstrates additional behavior of the MCLP LAM, as shown in Figure 3.18.



**Figure 3.18. The shift in hydrant configuration caused by additional hydrants.**

The first hydrant placed in the entire county was placed at the candidate location indicated by the green spider diagram. This hydrant site serves WHCs #1, #2, and #3, a

demand of 86, plus any demand values found at moderate and high fire risk zones outside of these communities. The next six hydrants were placed elsewhere in the county and served all but one remaining WHC (WHC #4). When the eighth hydrant was placed (blue spider diagrams), the hydrant configuration shifted. The eighth hydrant was able to serve WHCs #1, #2, and #4. Because these WHCs were served, the hydrant serving WHC #3 was shifted to the south where it could cover the otherwise exposed high fire risk nodes, hence maximizing the demand that could be fulfilled by eight hydrants.

**3.8. A Second Demand Weighting Scheme – Can the MCLP Model Differentiate between High and Moderate Wildfire Risk Zones?**

As discussed above, the intention in assigning the weight value of 0.009 to high risk nodes and 0.001 to moderate risk nodes was to influence the model to place hydrants in high risk zones before placing them in moderate risk zones. To test whether or not this non-uniform weighting of nodes in the two fire risk zones did in fact have the intended effect on the model, the weight in both zones was set to a uniform value of 0.001. The number of homes found at each exposed WHC was then added to these uniform wildfire risk weights. Table 3.9 below is the same table as Table 3.5 above, with the exception of the uniform wildfire risk values and the corresponding change to the demand values.

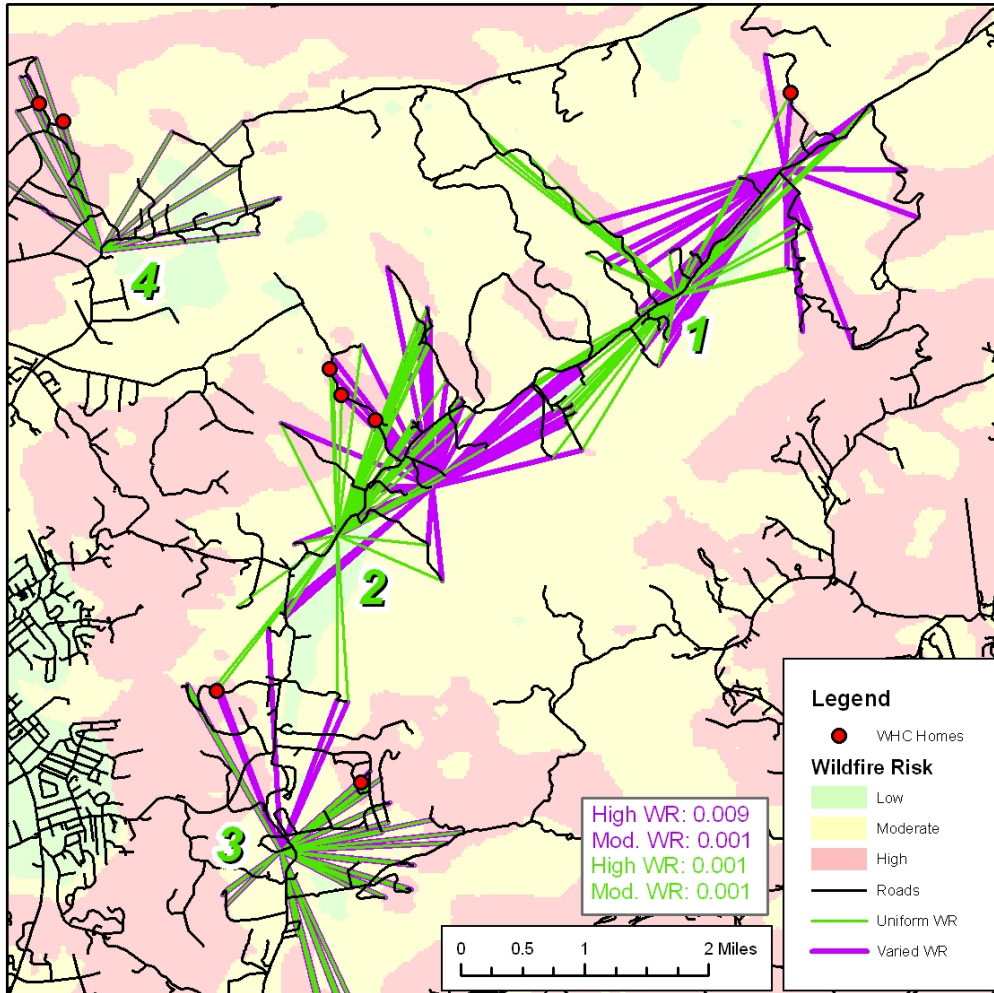
**Table 3.9. A revised version of Table 1 that reflects the uniform wildfire risk weighting**

| <b>NodeID</b> | <b>NumHomes</b> | <b>WRA</b> | <b>WHC Type</b> | <b>Demand</b> |
|---------------|-----------------|------------|-----------------|---------------|
| 1             | 16.325          | 0.001      | Exposed         | 16.326        |
| 2             | 0.909           | 0.001      | Exposed         | 0.910         |
| 3             | 0               | 0.001      | N/A             | 0.001         |
| 4             | 0               | 0.001      | N/A             | 0.001         |
| 5             | 0               | 0          | N/A             | 0             |
| 6             | 10.0            | 0          | Unexposed       | 0             |



Note that node 5 is located in a low risk zone, hence the final demand value of 0. Node six is located within six minutes of an existing hydrant; since it is already served it received a demand weight of zero.

Figure 3.19 demonstrates the effects of uniform and non-uniform WRA values. The purple spider diagrams represent the original, non-uniform weighting scheme; the green spider diagrams represent the uniform weighting scheme.

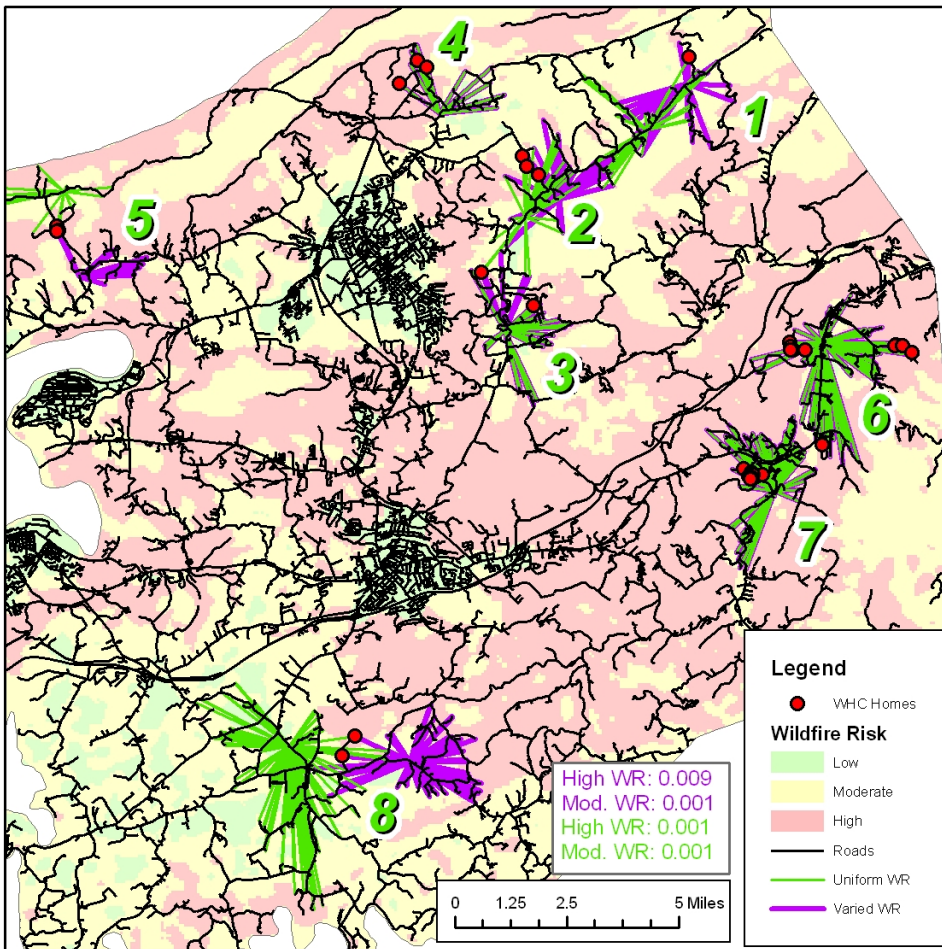


**Figure 3.19. A comparison between uniform and non-uniform weighting of the fire risk variables. Note that the green spider diagrams overlap some of the purple diagrams.**

As the figure shows, the non-uniform weighting affected the placement of 2 of the 4 hydrants. When subjected to the non-uniform weighting, hydrant 1 shifted to the northeast to cover the high risk nodes. Hydrant 2 also shifted to the northeast. But this shift did not necessarily occur as a result of the varying wildfire risk weights; it may have

shifted to cover the nodes that were exposed when hydrant 1 was relocated. Hydrant 3 did not shift. However, the relocation of hydrant 2 exposed one of the WHC nodes. But hydrant 3 was less than 6 minutes from this newly exposed WHC node and therefore hydrant 3 was able to compensate for the relocation of hydrant 2. Varying the wildfire risk variables did not affect the location of hydrant 4.

Figure 3.20 shows the same comparison as shown in Figure 4, but at a smaller scale.

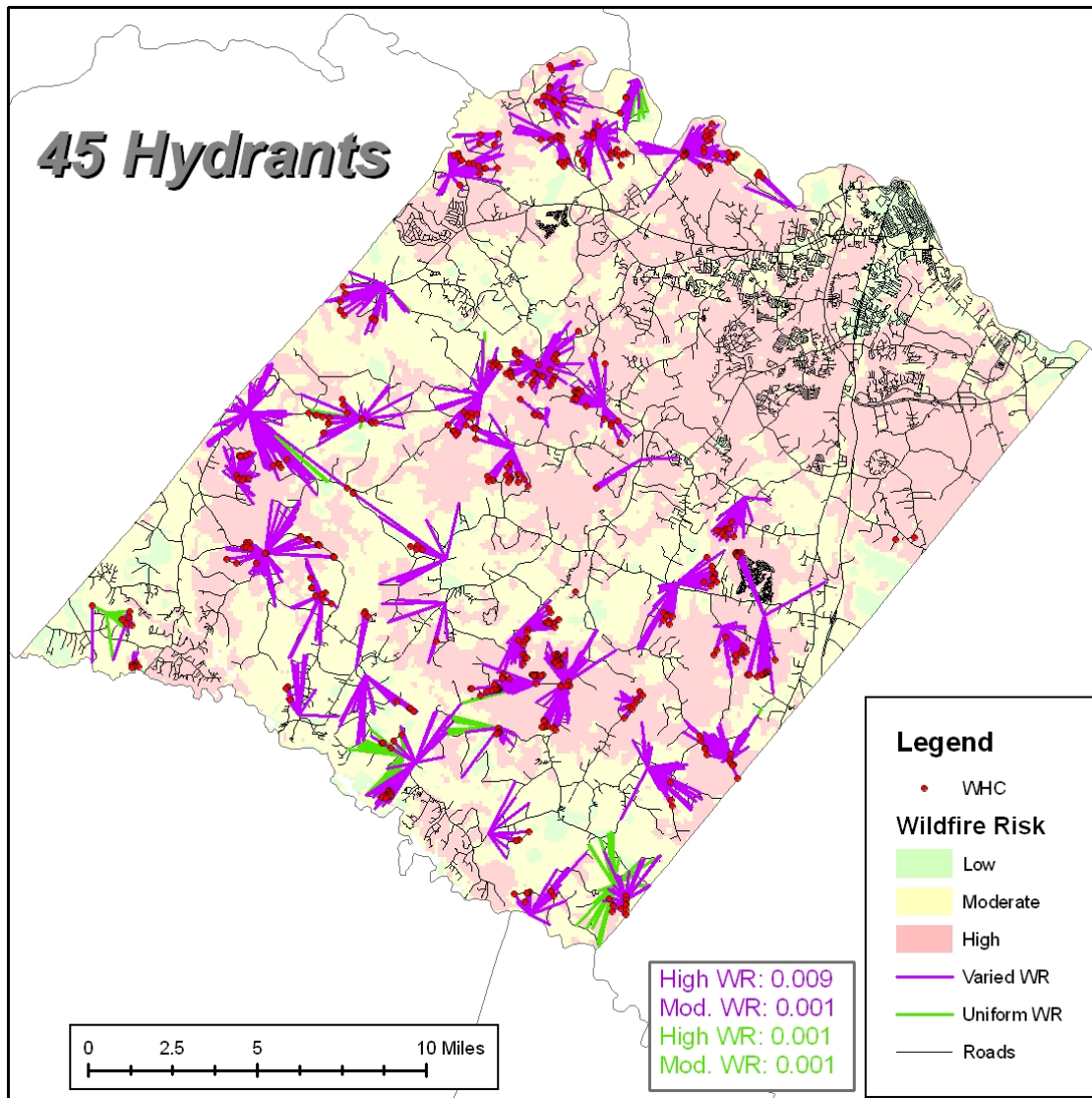


**Figure 3.20. The effects of varying wildfire risk weights. (Same results shown in Figure 3.19, but at a smaller scale).**

Hydrants 1, 2, 3 and 4 are the same hydrants that are shown in Figure 3.19. Varying the wildfire risk weight relocated hydrants 5 and 8 to cover high risk nodes, while still serving the same WHCs. Hydrants 6 and 7 were not affected by the non-uniform weighting scheme. This is likely due to the fact that most of the area they serve is a high

risk zone. In other words, the spatial variability surrounding these hydrants is low. In contrast, the WHC nodes covered by hydrant 8 lie on the border of a high risk zone and a moderate risk zone. The high-risk zone with the higher demand weight ‘attracted’ the hydrant westward to the location shown by the purple spider diagram.

In Spotsylvania County, the spatial variation of wildfire risk is significantly lower than in Montgomery County, particularly in the areas of the county where most of the WHCs are located (Figure 3.21).



**Figure 3.21. The effects of varying wildfire risk weighting scheme in Spotsylvania County. Also note that numerous hydrants are serving more than one WHC.**

This lower variation in wildfire risk did not, in most cases, affect the placement of the hydrants. In fact, only three of the 45 hydrants placed throughout the entire county shifted as a result of varying the demand values assigned to the two wildfire risk categories. This figure also demonstrates that the LAM placed many hydrants in locations that could individually serve multiple WHCs. In other words, many hydrants were placed in the centralized locations where they could maximize the amount of demand that they served.

### **3.9. A Third Demand Weighting Scheme – Increased Concern for Wildfire Risk Zones.**

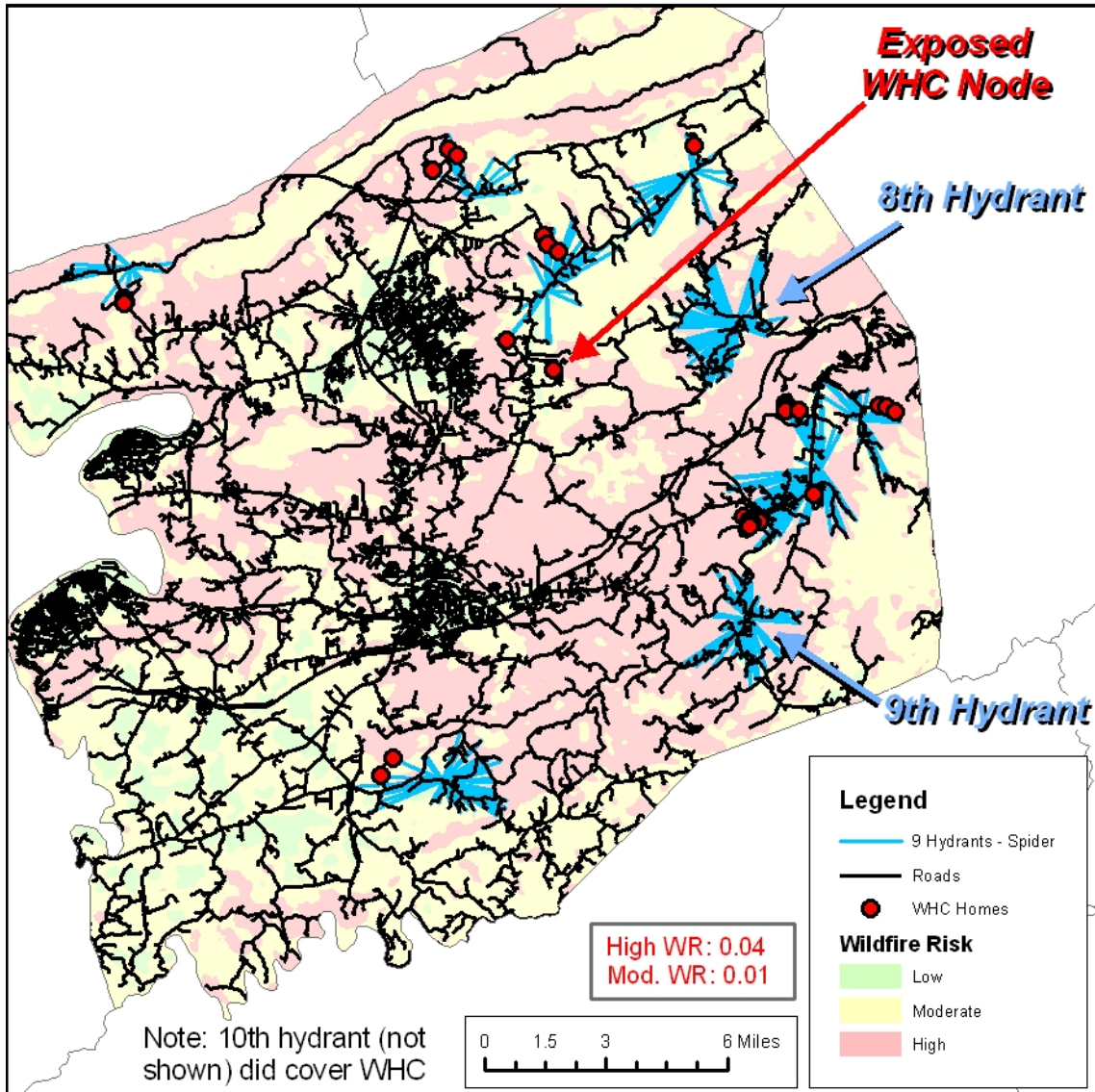
To further test the results of varying the demand node weighting scheme, a third treatment was applied to nodes. In the first treatment, the difference between the number of WHC homes and high fire risk nodes was rather large – a factor of roughly 100. In other words, 1 home represented at a single WHC node would “trump” 100 high risk nodes, that is 1 individual home in a WHC would take precedence over 100 high fire risk nodes in another location. One may argue that it would be foolish to allow a single, exposed home within a WHC to result in the neglect of an area with a large number of high risk nodes. To shrink this weighting gap between the number of homes and high wildfire risk nodes, high risk nodes were reassigned a value of 0.04, rather than 0.009. As mentioned before, one well-placed hydrant in Montgomery County could serve 224 non-WHC nodes, 142 of which are high risk nodes. With a value of 0.04 assigned to the high-risk nodes, 142 high risk nodes would “trump” a WHC node representing 5.68 homes ( $142 \times 0.04 = 5.68$ ).

Additionally, the moderate risk nodes were reassigned values of 0.01 rather than 0.001. Hence, moderate risk nodes (0.01) received  $\frac{1}{4}$  of the weight as high risk nodes (0.04). In the original weighting scheme, the moderate risk nodes (0.001) received  $\frac{1}{9}$  the weight of the high risk nodes (0.009). As a result, this new weighting scheme not only reduced the gap between the number of home and high risk nodes, but also reduced the gap between moderate risk nodes and high risk nodes. Table 3.10, which is a revised, updated version of tables 3.6 and 3.9, shows how this new weighting scheme affects the overall demand assigned to each node.

**Table 3.10. A revised and updated version of Table 1 and 5.**

| <b>NodeID</b> | <b>NumHomes</b> | <b>WRA</b> | <b>WHC Type</b> | <b>Demand</b> |
|---------------|-----------------|------------|-----------------|---------------|
| 1             | 16.325          | 0.04       | Exposed         | 16.365        |
| 2             | 0.909           | 0.01       | Exposed         | 1.009         |
| 3             | 0               | 0.04       | N/A             | 0.04          |
| 4             | 0               | 0.01       | N/A             | 0.01          |
| 5             | 0               | 0          | N/A             | 0             |
| 6             | 10.0            | 0.04       | Unexposed       | 0             |

Figure 3.22 demonstrates two different effects of this third weighting scheme.



**Figure 3.22. The effects of the third weighting scheme/treatment. Note that the 10th hydrant (not shown) did eventually cover the one exposed WHC node.**

Most prominently, this weighting scheme left one WHC node exposed. This WHC has 10 homes total and is represented by five nodes. Four of these five nodes are served by existing hydrants (resulting in a demand value of zero and as a result, they are not shown). Hence, this one exposed node only represents two individual, exposed homes within that WHC. Note that the 8<sup>th</sup> hydrant was placed in area with a large number of high risk nodes. The sum of these nodes was greater than 2 and therefore this high risk area received the hydrant, rather than the 2 WHC homes represented at the exposed WHC node. This “trumping” effect also resulted in the placement of the 9<sup>th</sup> hydrant in high risk

area that lacks WHCs. Although not shown in the figure, the 10<sup>th</sup> hydrant placed in the county finally covered the one exposed WHC node.

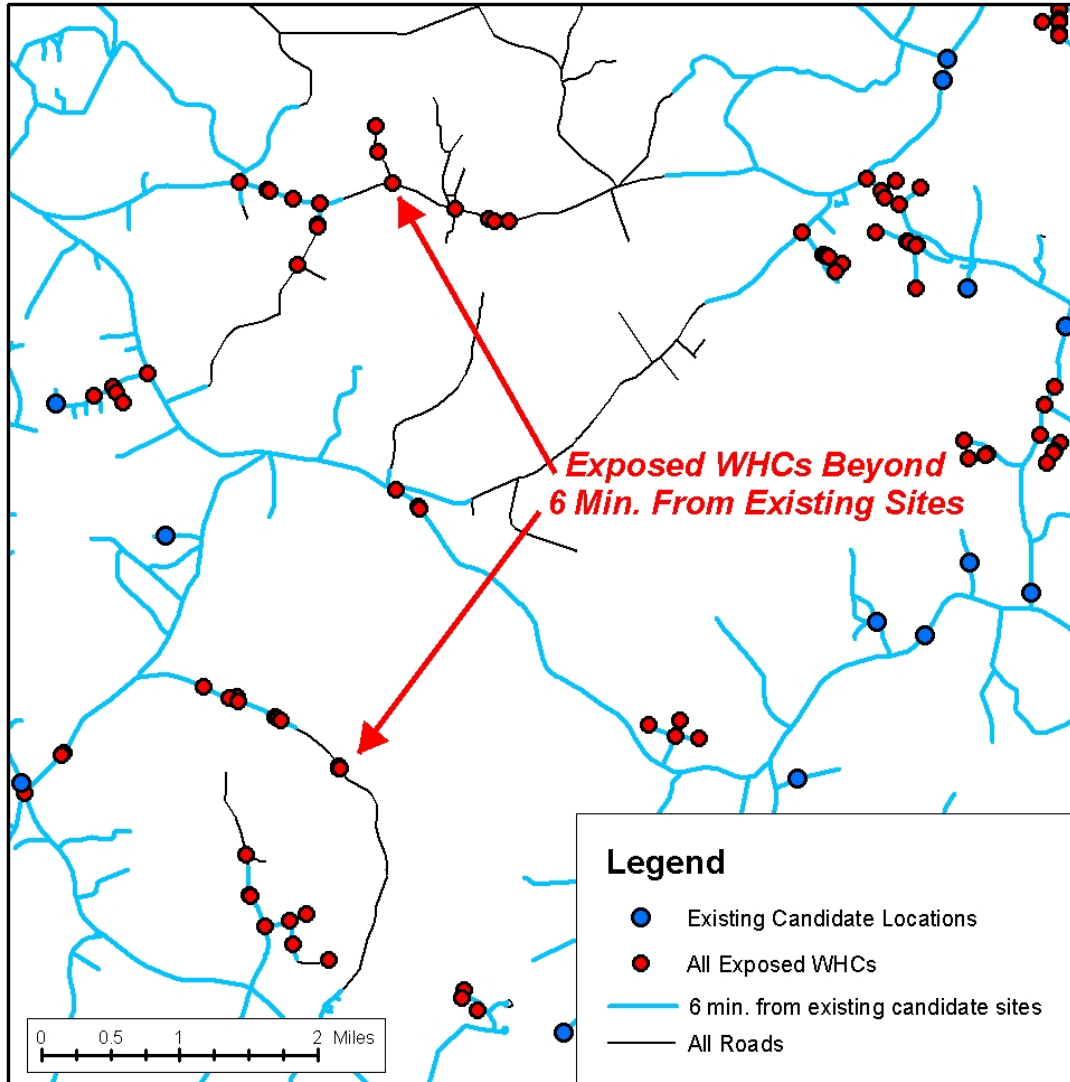
In Figure 3.20, the hydrant in the northwest portion of the county was shifted southward to cover a greater number high risk nodes. In that situation, the high risk nodes received a weight of 0.009 and the moderate risk zones received a value of 0.001, the factor of 9 discussed above. But in Figure 3.22, where the weighting gap between high risk nodes and moderate risk nodes was only a factor of 4, the hydrant didn't shift. In other words, the smaller weighting gap was not large enough to cause the hydrant to shift the area where there were a few more high risk nodes.

The three demand weighting schemes used here have shown that the MCLP LAM is capable of responding to detailed manipulation of the demand values. This responsiveness allows fire managers to finely adjust demand values to meet their particular management needs and concerns.

### **3.10. Accommodating WHCs Greater than Six Minutes From Existing Candidates Locations**

During some initial testing of the MCLP LAM, it was observed that some exposed WHCs were located beyond six minutes from the nearest existing candidate dry hydrant location (hereafter, these WHCs will be referred to as “unservable WHCs”). However, new, artificial water sources can be created to facilitate a dry hydrant, such as constructed ponds or water tanks. Doing so could be costly and should therefore be minimized. Below is a description of the process used to determine where to establish these new water sources in a manner that serves the otherwise unservable WHCs while minimizing the number of these sites. This would thereby minimize cost of installing these new water sources.

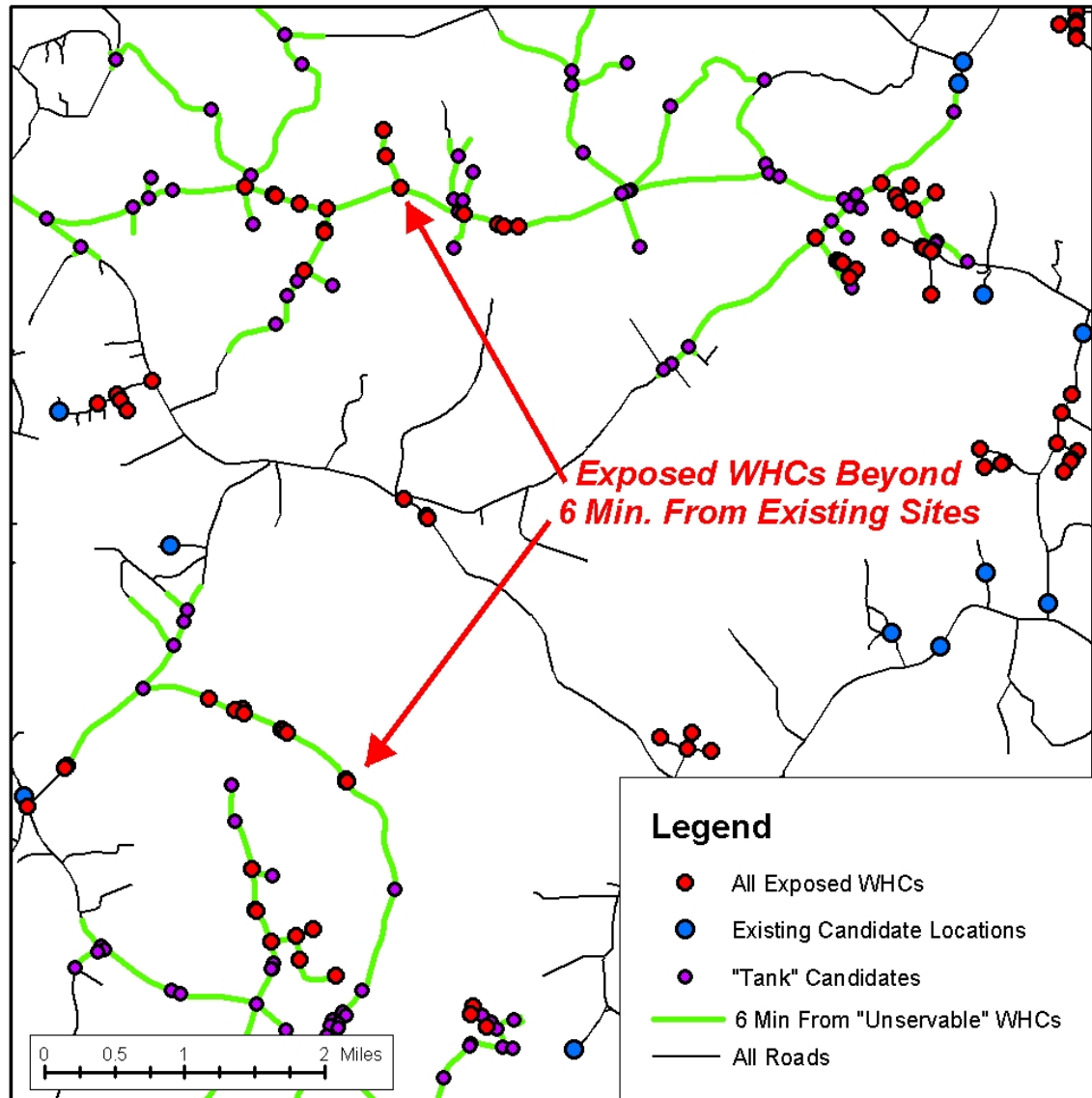
To identify the unservable WHCs, the ALLOCATE command in ArcInfo was used to determine the areas that are beyond 6 minutes from existing water sources, as shown in Figure 3.23.



**Figure 3.23. Six minutes routes from existing candidate locations**

The ALLOCATE command was used once again to generate routes that would identify all nodes within six minutes of these unservable WHCs, as shown in Figure 3.24.





**Figure 3.24. Six minute routes (in green) radiating outward from “unservable” WHCs. All nodes in the road network that intersect these routes (purple) would become candidates for new ponds or tanks.**

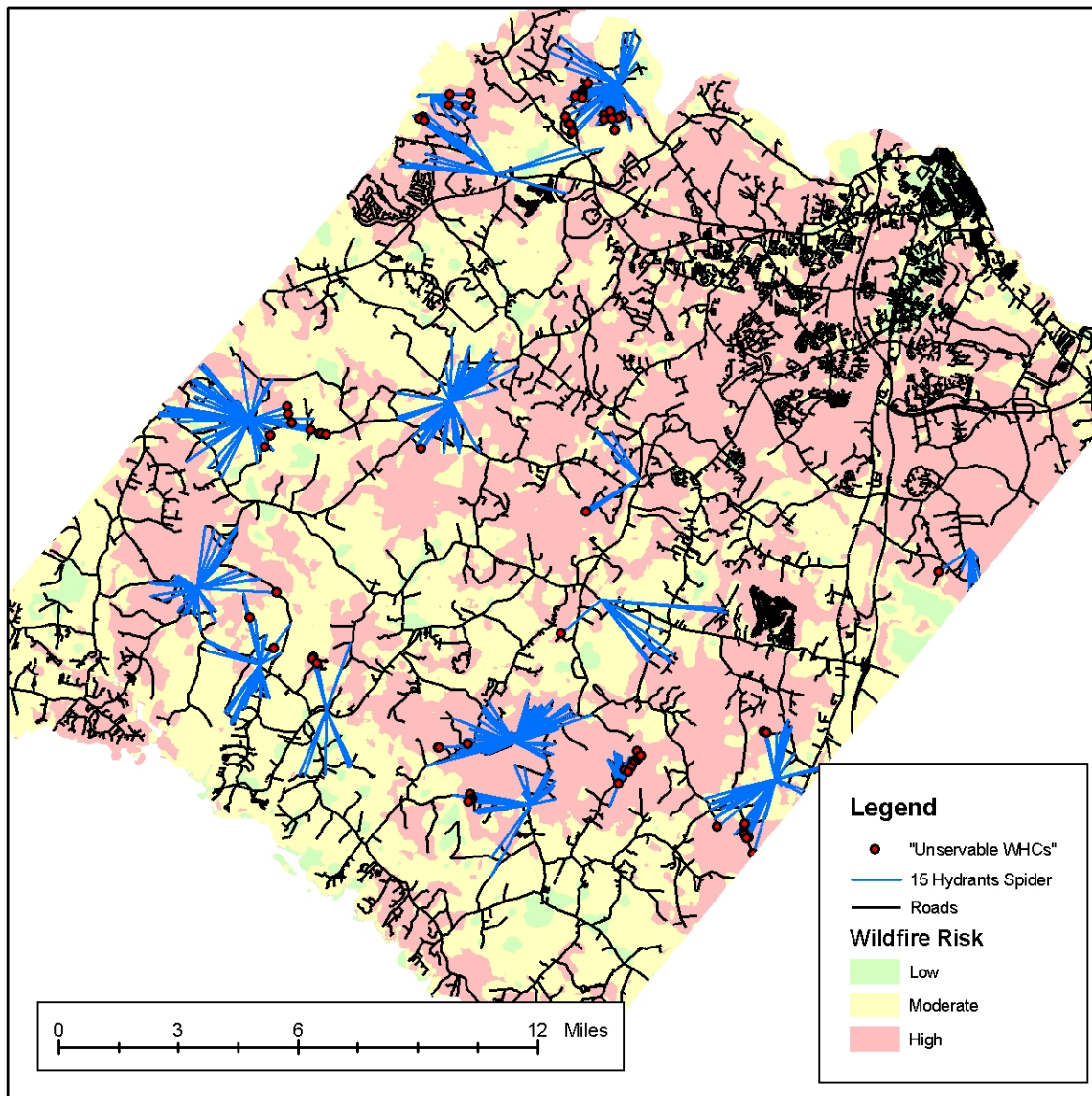
All of the nodes on the road network intersecting this second set of routes (shown in purple) would then become candidates for a new water source to serve the otherwise unservable WHCs. Using weighting set #1, all nodes not served by existing hydrants were assigned the same wildfire risk weights as before: high risk and moderate risk nodes were assigned values of 0.009 and 0.001, respectively. The number of homes represented at these unservable WHC nodes was then added to these wildfire risk values, as discussed

earlier and shown in Table 1. The same AML code executing the MCLP LAM was then applied to these nodes.

A table listing these unservable WHC nodes was exported to an ESRI “personal” geodatabase (hereafter, this table will be referred to as the WHCnodes table), along with the 50 output allocation tables. These geodatabases are essentially Microsoft Access databases, with a few added, auxiliary fields and tables that store and manage the spatial data. As a result, Visual Basic for Applications (VBA) and Structured Query Language (SQL), a programming language that excels in creating dynamic links and queries between two or more tables, could be used to determine the minimum number of new hydrant sites needed to serve these otherwise unservable WHCs. The VBA/SQL code used in this simple algorithm is provided in Appendix B. Cassel and Palmer (1999) provide succinct, yet thorough information about both the VBA and SQL programming languages.

This code loops through all of the output allocation tables in ascending order. Because the allocation tables list all of the nodes “assigned” to the selected center (or hydrant), including those beyond six minutes, each allocation table had to be queried for all records where DISTANCE1 was less than or equal to six. The results of this query are stored in a temporary table named “TempTable”. The TempTable is then joined to the WHC nodes table using an outer left join. The outer join causes all of the records in the WHCnodes table to be present after the join. If not enough records are in the current allocation table, then this outer join will produce records with null values. For example, in the first iteration of the loop, the allocation table from one hydrant being placed will likely not contain every unservable WHC node, indicating that 1 hydrant is not sufficient for covering all of the unservable WHCs. This will result in null records being present after the outer join. The loop continues until no null records are returned by the join, indicating that all unservable WHC nodes listed in the WHCnodes table have been served by a new water source. The number of hydrants needed to produce this condition is reported to the code user in a message box. This code assumes that MCLP LAM is successful at placing hydrants in locations that cover WHCs before those placing them in locations where they would reach no unservable WHCs, as was the case shown in Figure 17 above.

In Spotsylvania County, it was determined that 15 new hydrant sites would have to be established to cover these otherwise unservable WHCs, as shown in figure 3.25.



**Figure 3.25. The blue spider diagrams show where the 15 additional water sources were established.**

Note that, where possible, individual new water sources served multiple WHCs. Because the first demand weighting scheme (section 3.5.2) was used here, these 15 new water sources were also placed in locations where they would maximize the number of high and moderate wildfire risk nodes to be served as well.

A similar process was run in the other 7 study counties. Table 3.11 below lists the number of new water sources that would be necessary to serve the unservable WHCs in each county.

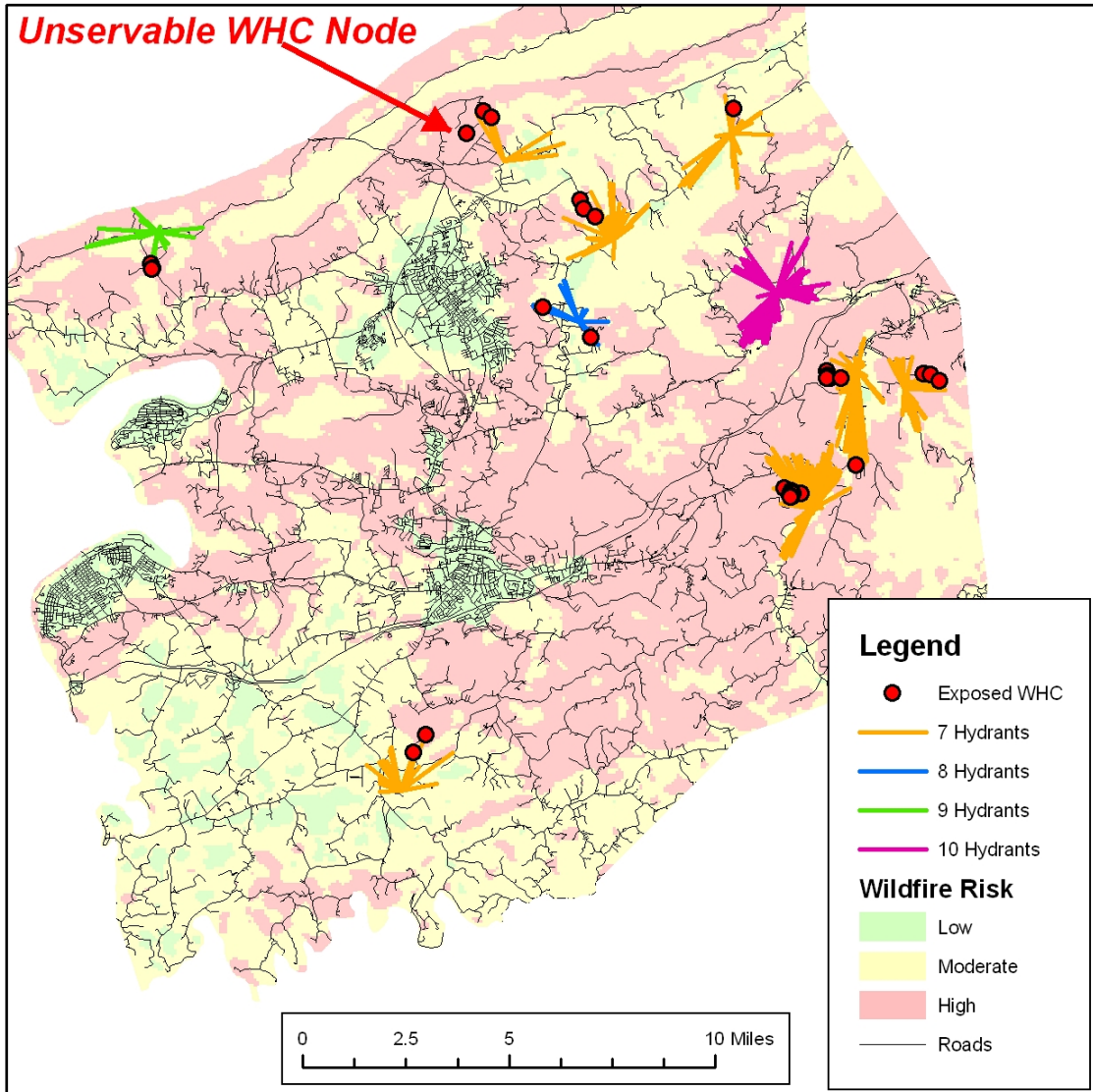
**Table 3.11. The number of new water sources established in all 8 counties.**

| <b>County</b> | <b>Number of new water sources established</b> |
|---------------|--|
| Spotsylvania  | 15   |
| King George   | 3  |
| Caroline      | 3  |
| Stafford      | 2  |
| Roanoke       | 2  |
| Montgomery    | 0  |
| Floyd         | 0  |
| Craig         | 0  |

These new water sources were then added to the candidate pool along with existing water sources, and were then used in the subsequent runs of the model.

### **3.11. The Effects of Using Different Fire Truck Travel Speeds**

To test the effects of reducing the fire truck travel speed as referred to in Section 3.3.4, the legal speed limits were multiplied by 0.75 and the ‘minutes’ impedance field in the arc attribute table was adjusted accordingly. In this analysis, the third weighting scheme, as depicted in Figure 3.22, was used. Reducing the travel speed did affect the placement of the hydrants in Montgomery County, as shown in Figure 3.12 below.



**Figure 3.26. Hydrant placement when fire truck travel speeds were reduced.**

Most notably, one WHC node was beyond 6 minutes from the nearest candidate hydrant location. As compared to Figure 3.22, three hydrants were required to cover the WHC nodes in the southeastern part of the county. Additionally, the hydrant in the southwestern part of the county shifted to the southwest because the hydrant location in Figure 3.22 would not have been out of range of the WHC. Furthermore, all WHCs were served before hydrants were placed elsewhere. This is because hydrant 8 was required to cover the WHC that was previously served by the hydrant to the northeast.

### **3.12. Running the Location-Allocation Model on All Eight Counties**

The location-allocation model was then run on all eight counties using the third weighting scheme, the scheme in which high risk nodes were assigned values of 0.04 and moderate risk nodes were assigned 0.01 (section 3.9). Of the three weighting schemes tested, the third scheme appeared to be a more ‘balanced approach’ since high fire risk areas were not neglected at the expense of a few homes at a single WHC node. This is not to say that VDOF or any other fire management agency should adopt this weighting scheme. It is up to VDOF and other agencies to determine what weighting schemes most appropriately suit their individual needs. But when running the models in all eight counties, the same weighting scheme had to be used so that the results in each county could be compared. The “new” water sources identified in section 3.10 were used. Furthermore, the posted speed limits, rather than the reduced were used here. Again, this is not to say that VDOF or other agencies should use the posted speed limits over the other approach. After closely examining the results discussed above, each agency should decide which approach is more appropriate. The output of these models are examined and discussed in Chapter Four of this thesis.