FIRE STATION SITE SELECTION IN RURAL AREAS:
A CASE STUDY OF DICKINSON COUNTY, KANSAS

A THESIS PRESENTED TO
THE DEPARTMENT OF GEOLOGY AND GEOGRAPHY
IN CANDIDACY FOR THE DEGREE OF
MASTER OF SCIENCE

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MARYVILLE, MISSOURI
JUNE 2011
FIRE STATION SITE SELECTION IN RURAL AREAS

Fire Station Site Selection in Rural Areas:

A Case Study of Dickinson County, Kansas

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Abstract

This study examines a methodology for rural fire station site selection with a case study of Dickinson County, Kansas. The primary research question centers on finding the optimal site to place a new fire station within the study area to address unmet need. The question is a planar form of the Maximal Covering Location Problem where potential sites are represented by address points and potential building sites by a continuous plane. Current fire services are accounted for by evaluating the effective service areas of existing stations. The evaluation uses network analysis based on the county’s “all-weather” road network and response standard established by the National Fire Protection Association and Insurance Services Offices, Inc. guidelines. Unmet need is identified as the address points that lie outside those service areas. Local concerns such as adhering to building site restrictions from the county’s Comprehensive Plan are taken into consideration as well. Simple enumeration of total demand points covered by potential building sites is used to calculate the optimal solution. Application of the methodology resulted in a small contiguous region of appropriate building sites that would address the maximum amount of unmet need.

This study also evaluated the impedance of fire district boundaries on the effectiveness of existing fire stations. The potential service area of each station was
compared to its actual response area. The effective range of every fire station in the study area was shown to be limited by district boundaries.
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Acknowledgements

At base, this thesis and the classes and projects that preceded it have been focused on finding ways to use geographic information systems at the local government level to the benefit of all citizens. Local government is often the creator and maintainer of the basic data layers that fuel GIS projects everywhere. Everyone seems to want that data because it is generally considered to be the most accurate and up-to-date thing available. In many jurisdictions, though, local officials are often mystified as to why so many people are so interested. State and national initiatives have told them it is valuable, that they are obliged to do it as caretakers of the public trust. Somebody is always saying that GIS will save them money and time. “How?” was the question of one county commissioner at a conference I attended a couple of years ago, echoing the thoughts of many more in the room and around the country. The answer from the speaker, said as they packed up their things and left the room, was “Lots of ways.” Training in how to use software is easy to come by. Training in when and why it is beneficial is scarce. For them GIS and the investment in money and effort that it represents can be a leap of faith.

The officials of Dickinson County, Kansas made that leap, opening a GIS department in 2006 and entrusting me as its coordinator. Since then, we have managed to build a robust system that aids in workflows and decision making at every level of our organization. But it would not have happened without that blind leap. For that, for the data, equipment and assistance they provided to this study and for their continued support, I would like to thank the Dickinson County Board of Commissioners, County Administrator Brad Homman, Emergency Manager Chancy Smith, Road and Bridge
Supervisor Martin Tannahill and all the other officials and employees of Dickinson County.

I would also like to thank two agencies that not only helped with this project but have also spearheaded GIS efforts in the state of Kansas and made my job much more enjoyable. Ken Nelson and his staff at the Data Access and Support Center are invaluable for the service they provide as the state’s GIS data clearinghouse. This study and I personally have benefitted from their technical assistance and moral support. Additionally, I would like to thank Jessica Frye and her staff at the Kansas Adjutant General’s GIS office. Their work has helped get software, hardware, training and direction in making use of it all to local jurisdictions across the state. Jessica directly contributed to the study with information about response standards, and her efforts to make sure that emergency managers see GIS as a tool to solve some of their problems helped inspire the original research question.
Chapter 1: Introduction

Providing fire coverage is one of the basic responsibilities of a local government. Citizens expect adequate fire coverage whether they live on the 40th floor of an apartment building or a mile from their nearest neighbor. Many variables, including staffing, training and equipment, are considered in determining whether coverage is adequate (NFPA 2010). One of the most crucial variables is response time, specifically the time it takes to get from the fire station to the fire (NFPA 2010). Ideally, officials would place a fully staffed and equipped fire station on every corner. However, it is impossible because of limited resources so there is a need to assess and address inadequacies in fire coverage with available resources. When an opportunity arises to build a new fire station, it is critical to place that station in the location that best addresses local need.

1.1 Fire Service

Determining that best location starts with an examination of current service to determine where additional coverage is needed. In many rural jurisdictions, including the study area Dickinson County, fire response is handled by several different departments that are each responsible for a specific geographic area. Each of those departments has one or more fire stations from which its crews and equipment respond when fires are reported. There are two widely accepted standards for what area is covered by each individual fire station. Both standards are distances from the station that were set as a function of time using the average response speed of 35 mph for a fire truck using lights and sirens (ISO 2009, NFPA 2010). That speed was identified in a series of studies by the RAND Corporation in the 1970s and reviewed recently by Insurance Services
Offices, Inc (ISO) where it was found to be a valid predictor of response times (ISO 2009). The National Fire Protection Association (NFPA) provides consensus standards for fire response with the goal of lessening the impact on quality of life posed by fire and other hazards (NFPA 2010). The NFPA standard lists stations as adequately covering properties within fourteen minutes or eight miles as measured along existing roads (NFPA 2010). That standard is less strict than ISO’s, which is used to determine property insurance rates. The ISO standard is within nine minutes or five road miles and further specifies that the roads must be classified as “all-weather” roads (ISO 2009). If the roads are impassable in inclement weather such as heavy rains, they cannot be used in a determination of adequate coverage.

A second requirement within both standards allows only those stations on the initial page to be considered. The initial page is the first notification made to fire units by the emergency call-taker. In other words, only those stations notified when the fire at a given location is first reported can be considered to cover that location. When a call is received by the local public safety answering point (PSAP), the call-taker determines the fire district within which the incident is taking place and notifies the firefighters of that district, usually through a radio paging system of some kind (Smith 2010). If a particular station is within five road miles of a location but in a different fire district, then it cannot be considered as it will not be part of the initial page and thus will not meet the requirement. If a station is closer than five miles to the boundary of its fire district, then part of its effective range is truncated. To address this issue, fire departments can enter into mutual aid contracts, agreeing to share resources across boundary lines. However, in
order for them to be considered in evaluation of effective response, those contracts must be “automatic” and both departments be paged to every incident (NFPA 2010).

1.2 Station Siting

Once current service is determined by applying the appropriate standard and accounting for impedance by district boundaries, anything outside those service areas becomes demand to be considered in placing a new station. From there, various site selection approaches can differ on what additional information they require and what primary need they address (Plastria 2001). Some methods test specific potential station sites (Church and ReVelle 1974), others are designed to place the stations within a continuous plane (Murray and Tong 2007). Some are designed to minimize system congestion (Liu et al. 2006). There are methodologies designed to place a limited number of stations (Church and Revelle 1974), and others designed to place whatever number of stations necessary to address all demand (Plastria 2001).

While a great deal of research has been done on the most effective ways to place fire stations, it has primarily focused on urban areas. For example, Ball and Lin (1993) studied emergency service vehicle location, Liu et al. (2006) evaluated fire stating siting and Toregas et al. (1971) examined emergency service facility locations. However, all these studies dealt exclusively with urban areas, and there is little research on fire station site selection in rural areas. The circumstances that affect proper station siting in such areas are quite different. First, the road network is sparse and inconsistent. Second, the number of fire stations is small. Third, the population is neither evenly spaced nor concentrated into specific areas, but rather it can be widely scattered with large tracts left unpopulated. Fourth, the funding mechanisms for rural fire departments can create
arbitrary district boundaries, like Public Land Survey System (PLSS) township borders, that impose artificial barriers to response. Conversely, some difficulties faced by researchers looking at urban fire response are not issues in rural areas. For instance, traffic and system congestion do not generally need to be considered. In addition, the large number of demand points and complex road network in urban areas can limit the approaches available to researchers because of processing time, but that is not usually the case in rural areas. Fire station site selection in rural areas is simply a different question than it is in more densely populated environments.

While it has not received much attention in research, the specific examination of site selection for rural stations is certainly important. Over eighty percent of the more than 30,000 fire departments in the United States serve populations less than 25,000. More than forty percent serve populations less than 2,500 (USFA 2009). What is more, those communities of less than 2,500 people have a fire death rate that is twice the national average (Gamache et al. 2007). Put simply, rural fire departments are less likely to meet national response guidelines because of scattered populations and long travel times (Gamache et al. 2007). Therefore it is crucial to utilize effective site selection for the placement of any new station.

1.3 Research Objectives

The overall goal of this research is to address a problem voiced by Dickinson County’s Emergency Manager, Chancy Smith (2010), while reviewing the application for a grant to fund the construction of a new fire station. If there is funding for a new station, which will be managed directly by the county so that it could ignore district boundaries, where should it be built and how could the expected benefit be quantified to a potential
funding organization? With that in mind, this research proposes a method for fire station site selection in rural areas. For the purposes of this study, the term “rural” refers to areas sparsely populated (averaging fewer than 50 people per square mile) and largely unincorporated. The proposed method is applied in a case study at Dickinson County, Kansas. The two distance standards for determining current service coverage, NFPA and ISO, are examined, as is a comparative analysis of the impact of district boundaries. Maximizing demand covered at the NFPA standard is the primary goal with the amount of demand covered at the ISO standard used to select between optimal NFPA solutions. The actual facility siting is addressed as a planar variant of the Maximal Covering Location Problem (MCLP) where demand is represented by points and potential facility sites by a continuous plane. The methodology considers circumstances specific to rural regions as well as those variables unique to the study area.

1.4 Study Area

Dickinson County, Kansas was founded in 1857. It lies in central Kansas in the third tier of counties from the northern border of the state and covers 852 mi² (Figure 1). It has nine incorporated towns and a total population of 19,300 in 2000 (Dickinson County 2010). The county is bisected by Interstate 70 and the Smoky Hill River. It is perhaps best known for the county seat of Abilene, which was a major cow town in the 1800s (Dingler 1999). Abilene was also the home of President Dwight D. Eisenhower and hosts the Eisenhower Presidential Library and Museum (Dickinson County 2010).

The entire study area contains 1,821 miles of roads, 1,700 miles of which are in the unincorporated areas. This includes 395 miles of pavement, 815 miles of gravel roads and 490 miles of dirt roads (GIS Department of Dickinson County 2010). The paved and
Figure 1. Study area with incorporated towns labeled
graveled roads are considered to be all-weather roads, where the dirt roads are considered impassable in inclement weather (Bowers 2007).

The study area is served by thirteen fire departments with a total of 21 fire stations. Eleven of these departments are staffed entirely by volunteers while two have some full-time personnel but are staffed primarily by volunteers. Three departments (Abilene, Chapman and Enterprise) operate only in their respective city limit boundaries, leaving ten fire departments with a total of 18 stations to cover the remaining 845 mi² of the county (Figure 2). The rural district boundaries largely coincide with PLSS township boundaries. The few boundaries that do not match PLSS have been set to account for geographic features like a busy state highway. The stations in most rural districts were placed as land and facilities were donated by citizens (Smith 2010). In the cases of the Hope, Herington and Solomon Fire Departments the stations are in the largest community in the district, centering coverage on the primary population, and leaving large tracts of the districts without adequate coverage by the accepted standards. Most of the departments have mutual aid contracts with bordering districts. Because of the cost involved in deploying unnecessary equipment, the contracts, like those in many rural areas, are not “automatic,” and cross-district aid is given only on specific request usually after the first trucks have arrived (Smith 2010).

In selecting a location for a new station from a continuous plane, there is potential for the site that provides the best coverage of unmet need to be inappropriate for building, particularly in rural areas where access to basic services such as electricity and well maintained roads is not consistent. While these circumstances will vary greatly from place to place, many communities have an official Comprehensive Plan, a document to
Figure 2. District boundaries and stations of Dickinson County's rural fire departments
guide the future growth of a community, particularly in terms of physical development (Goodman and Freund 1968).

According to Dickinson County’s Comprehensive Plan (2007) new construction is ideally limited to an area within ½ mile of existing paved roads (Figure 3). This area is targeted in the plan because it best utilizes current infrastructure. It also helps protect water quality and preserves agricultural land (Dickinson County 2007). Using this guideline in the final step of site selection will not only assure the new station fits in with the interests of the community, but also assure that it is placed well to cover future need.
Figure 3. Area designated as "preferred development" in 2007 Comprehensive Plan
Chapter 2: Literature Review

2.1 Location Problems

Selecting fire station sites for maximum efficiency is a type of location problem known as a covering problem. In covering problems, each facility covers demand within a defined proximity, such as the distance standards used in this study. There are many variants of the covering problem depending on the specific objectives. The Set Covering Location Problem (SCLP) involves covering all demand with the minimum number of facilities while the objective of the Maximal Covering Location Problem (MCLP) is to use a limited number of facilities to cover the maximum amount of demand (Marianov and Serra 2001). Other location problems account for different scenarios, like the Maximum Available Location Problem, which attempts to account for “system congestion” or simultaneous calls to the same station (Ball 1993).

2.2 Location Models

Models to optimize fire station site selection have been frequent research topics. Toregas et al. (1971) introduced the Set Covering Location Model (SCLM), a solution to the SCLP for the location of emergency facilities such as fire stations. In their model, one set of points represents demand locations and another set represents potential facilities. A maximum distance or time from the station determines how many demand points are covered by each potential facility site, and the optimal solution is determined using linear programming and inequalities (Toregas et al. 1971). According to Ball and Lin (1993), most fire station siting studies include some form of the SCLM.
Public facility location in general and fire station location in particular are usually examined as maximal covering problems (Marianov and Serra 2001). Church and ReVelle (1974, p. 102) first defined the MCLP as maximizing “coverage (population covered) within a desired service distance \( S \) by locating a fixed number of facilities.” They examined both heuristic algorithms and linear programming similar to the SCLM as potential solutions to the MCLP (Church and ReVelle 1974). In their models both demand and potential facility sites were represented as sets of points, as they were in studies by Galvão and ReVelle (1996) and Rosing (1997). Other researchers proposed models with demand set as continuous throughout a region (Murray et al. 2008) and varying demand with point, line and polygon representation (Murray and Tong 2007).

Of specific interest in this study is the planar version of the MCLP where demand is represented by discrete points but potential facility sites are represented by a continuous plane. Potential facility sites can be identified with circular disks having a radius equal to the effective range of a facility or a radius of \( R \) and centered on the point of demand (Church 1984, Meherez and Stulman 1982). The calculations for placing one facility or many facilities to provide maximum coverage of demand begin the same way. Meherez and Stulman (1982) proved that given a circle of radius \( R \) covering \( N \) points of demand, there must be a circle covering the same points with one of them being on the perimeter of the circle. They extended this to multiple points, stating that if a single facility can cover \( N \) points, then it can be placed at the point of intersection of the perimeters of two of the circles and still over the same \( N \) points, thus showing that an optimal solution can be found within the finite set of intersection points. For a single facility, the point or points that maximize demand covered are optimal solutions. For
multiple facilities, a simple iteration can be undertaken through the intersection points
starting with the one covering the highest number of demand points and ending either
when available facilities run out or when all demand is covered (Meherez and Stulman
1982). Church (1984) took that a step further limiting the set of intersection points
through the use of a dominance test. His approach began by assuming two intersection
points, one covering a set of demand points and second covering the all same points and
possibly more and thus being the dominant point. A smaller set of potential sites which
still contains the optimal solution can then be calculated by eliminating all dominated
points (Church 1984).

2.3 Service Areas

For studies like this one with existing stations to consider, defining demand
begins with an assessment of the effective response area for each of those stations,
usually by using time or distance limits. Most researchers chose to create the response
area as a straight-line or Euclidean buffer rather than a network buffer because of
computation time (Liu et al. 2006) or because the necessary network data was unavailable
(Murray and Tong 2009). In a thorough comparison of the two methods, Euclidean
buffers were found to over-estimate service areas (Gutierrez and Garcia-Palomares
2008). This was especially true in locations with a low density of stations or with sparse
road networks, situations common to rural environments. In attempts to address this
issue, some researchers have focused on non-circular service areas. For example,
Matisziw and Murray (2009) studied the Planar MCLP with continuous demand and
irregular service areas based on road networks. Their study focused exclusively on urban
environments, however.
2.4 Urban vs. Rural Studies

In fact, for some reasons, there are very few studies that consider fire station siting in rural areas. Firstly, the presence of available data often makes it easier to study urban areas than rural ones. Secondly, the greater resources to build or move stations as well as the higher density of population mean that urban studies are more likely to impact a large number of people. The prevalence of research into urban areas is so strong that a 1990 study found all research to that date was urban-centered and that rural station location had been “neglected” (Richard et al. 1990). Both Richard et al. (1990) and Murray and Tong (2009) mentioned the need to account for variables unique to rural settings. A sparse road network with segments impassable by emergency vehicles and very low density of existing stations are two examples. An evaluation of station siting in the country of Luxembourg identified several qualities of rural areas that suggested the need for study independent of urban areas, including the ability to accurately identify specific demand points and greatly reduced need to consider system or traffic congestion as factors in analysis (Richard et al. 1990). Finally, location/allocation methods used in studies focused on urban areas are often limited by computer processing capabilities or access time (Liu et al. 2006). A study focused on rural areas has a much lower density of data features to analyze and does not face the same processing limitations.
Chapter 3: Conceptual Framework and Methodology

In essence, this case study breaks down to the examination of four questions. Which demand locations in the study area do not receive adequate coverage from existing fire stations? How is coverage impacted by fire district boundaries? Where are the optimal locations for placing an additional facility to address unmet need? Which of those locations are appropriate building sites within the needs of the County?

3.1 Description of Data

All data in this study are provided by Dickinson County’s GIS Department. The coordinate system of these data is Kansas State Plane Coordinate System North, NAD83. The unit is US feet.

3.1.1 Dickinson County Address Points

The address point dataset obtained from the GIS Department of Dickinson County (2010) contains a point centered on each addressed structure within the county, including residential, commercial, industrial and agricultural sites as well as utility structures like cellular towers and oil wells.

3.1.2 Dickinson County Street Centerlines

The dataset includes lines representing every public and private named road within Dickinson County. Included in the attribution is the surface type delineated as paved, gravel, dirt or “platted,” which is used for roads that are planned but not yet built (GIS Department of Dickinson County 2010). The topology and connectivity of the lines has been confirmed to assure accurate network analysis.
3.1.3 Dickinson County Fire Districts and Fire Stations

The fire district dataset contains a polygon representing each of the ten districts that are part of this evaluation as well as the three districts coincident with city limit boundaries, which are not part of this study. The fire station layer contains a point centered on each fire station in the county, but only the 18 that respond outside city limit boundaries have been used in this evaluation.

3.1.4 Preferred Development Area

This dataset represents the area of preferred development outlined in the county’s 2007 Comprehensive Plan. There is a single polygon encompassing all areas in the county that are within one-half mile of a paved road.

3.1.5 Cartographic Data

To create complete and accurate maps, several datasets were obtained for purposes of display. The color orthophotography, city limit boundaries and the county boundary were obtained from the GIS Department of Dickinson County. The orthophotography has a resolution of one-foot and was flown in March of 2007. The statewide county boundary layer was obtained from the Data Access and Support Center, the GIS data clearinghouse for the state of Kansas.
3.2 Methodology

3.2.1 Identifying Unmet Demand

Demand in this evaluation was represented by the county’s address point layer. To determine which of those points represented unmet demand, the actual service area of each existing fire station had to be determined (Figure 4, Section 1). By the NFPA (2010) standard, each station covers an area of eight miles along all-weather roads. To create these service areas as polygons, a network dataset was created using ESRI’s ArcGIS 9.3.1 with the Network Analyst extension. Segments from the county’s road centerline feature class that did not represent all-weather roads were removed from the layer (Figure 5). Specifically that included roads with surface types of “dirt” and “platted.” A new field was added to represent segment length in miles and then calculated for each record. Since traffic congestion is not a concern in rural area like Dickson County, this study aims to meet the road mile not time requirement set by ISO and NFPA. The network dataset was created with the reduced roads layer and the new [Miles] field as the distance impedance for the network. Then service area polygons were calculated with the fire station points as “facilities” and the service areas set to eight miles away from each facility with u-turns allowed at junctions. Polygons from different facilities were allowed to overlap. The resulting polygons were then used to identify those demand points not covered by existing stations.
Figure 4. Diagram of site selection methodology
Figure 5. Dickinson county road centerlines with all-weather roads emphasized
3.2.2 The Impact of Fire District Boundaries on Coverage

Since only the stations in the same fire district as a particular demand point will be notified of an incident on the initial call, the actual coverage area of each station is truncated by the boundaries of its fire district. To represent this in the evaluation, the service area polygons were processed together with the fire district polygons for geometric intersection. This resulted in a polygon layer with separate features for each unique combination of station and district allowing inappropriate combinations, like a Grant Township fire station responding in the Solomon Fire District, to be removed. The same result could have been obtained by converting the fire department polygons to lines and using those lines as barriers in the initial service area calculation. However, as one of the objectives of the study was to evaluate the impact of boundaries on adequate response, both the potential service areas and the actual service areas for each station were needed. The remaining polygons representing the actual service area of each station were then used as the first set had been to identify unmet demand. As they represent the real-world response of each station, this larger set of demand points was used for the remainder of the evaluation.

3.2.3 Calculating Optimal Sites to Address Unmet Demand

Following Church’s (1984) work, service area polygons were created with the unmet demand points as “facilities” and the remaining variables unchanged from the earlier geoprocessing (Figure 4, Section 2). The polygon created around each demand point represents the area in which a station could be built to address that demand. Although several studies (Meherez and Stulman 1982, Church 1984) determined that any
optimal solution found inside the polygon could also be found on the perimeter, this
evaluation accounts for criteria other than demand, specifically the county’s “preferred
development” region. Since one optimal solution derived using only demand may be
inside that region while another is not, potential sites were not limited to polygon
perimeters or intersection points.

A full county grid was created with a cell fabric across the entire county with cells
approximately eight acres or 700’ by 500’. Those dimensions are approximately double
the minimum lot size for new construction within rural areas of the county (Dickinson
County 2007). The size was set at double the minimum to account for cells which would
be divided by roads, leaving a site appropriate for building even if the road divided the
cell directly in half. Then the demand area polygons were joined to each cell in the grid
layer that they intersected with the “Spatial Join” function. The output polygon layer was
a grid with an attribute for each cell representing the count of demand area polygons that
intersect it. In other words, the resulting dataset was a grid with a value for each cell
describing the number of demand points that would be covered by a station built at that
location.

3.2.4 Building Site Restrictions

The grid layer was then restricted to the county’s “preferred development” area
(Figure 4, Section 3). The final result was a feature class with potential building sites
ranked by the amount of unmet demand a station built there would address.
3.2.5 Re-evaluation and Comparison

The same evaluation was then completed using the five-mile service areas corresponding to the ISO (2009) standard for rural departments. In case the NFPA-based evaluation was to result in more than one optimal solution, the ISO-based evaluation could be used to help select from those sites the one that would address the most economic need.
Chapter 4: Analysis Results and Discussion

4.1 Fire Station Response Areas and Unmet Demand

Using a network dataset based on the all-weather roads from the county’s road centerline data, service areas for each of the 18 rural fire stations were calculated using the eight-mile and five-mile standards. Those polygons were then processed with the district boundaries and the portions of each station’s service area polygon that lay outside its district boundary were removed. The results were four polygon layers: eight-mile service areas with and without district consideration and five-mile service areas with and without district consideration. In the eight-mile service areas without district consideration, the total area covered by the rural stations was 800 mi² or 93.9% of the land area in the county. Once fire districts were considered, the total area covered dropped to 764 mi² or 89.9% of the county (Figure 5). The five-mile service areas showed a larger drop from 63.9% of the county covered without district consideration to 58.7% when districts were considered or from 544 mi² to 500 mi² (Figure 6).

Among the 3,586 demand points in the rural areas of the county, points outside each of the service area polygons were selected. In the eight-mile evaluation, 2% of total demand or 72 demand points were outside the coverage area before district boundaries were applied. Four percent of total demand or 144 demand points were outside the coverage area after district boundaries were applied (Figure 8). For the five-mile service area evaluation, 23.7% of total demand or 850 demand points were outside the coverage area before the district boundaries were applied and 27.2% or 975 demand points after (Figure 9). Unmet demand increased 14.7% in the five-mile evaluation and 100% in the eight-mile evaluation because of the impedance of district boundaries (Table 1).
Figure 6. Eight-mile service area polygons for each rural fire station
Figure 7. Five-mile service area polygons for each rural fire station
Figure 8. Unmet demand from eight-mile service areas
Figure 9. Unmet demand from five-mile service areas
Table 1. Impact of fire district boundaries on unmet demand

<table>
<thead>
<tr>
<th></th>
<th>Unmet Demand</th>
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<th></th>
<th></th>
<th>Increase</th>
</tr>
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<tr>
<td></td>
<td>Without Boundaries</td>
<td>With Boundaries</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>% of total demand</td>
<td>Total</td>
<td>% of total demand</td>
<td></td>
</tr>
<tr>
<td>NFPA Standard</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eight-mile service areas</td>
<td>72</td>
<td>2%</td>
<td>144</td>
<td>4%</td>
<td>100%</td>
</tr>
<tr>
<td>ISO Standard</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Five-mile service areas</td>
<td>850</td>
<td>23.7%</td>
<td>975</td>
<td>27.2%</td>
<td>14.7%</td>
</tr>
</tbody>
</table>

4.2 Site Selection

Using the unmet demand points from the eight-mile evaluation with district consideration, a set of service area polygons was calculated with the demand points as facilities. The first of these was run with an output of generalized polygons, which produced service areas with large tracts that were unreasonable for building because they contained no road features. The service areas were produced a second time with the output set to trim the outer edges of the service areas to within 200 meters of existing features. The second run produced results of more practical value and seemed to be much better suited to selecting a building site on a sparse network (Figure 10). Because of that, the service areas created from the five-mile demand points were only done with the resulting polygons trimmed to existing features.

The count of overlapping polygons at each location represented the number of unmet demand points that would be served by a station at that location. The eight-mile evaluation resulted in sites that covered a range of one to 63 demand points (Figure 11). The potential sites were then limited to the county’s “preferred development” region. This reduction in area did not remove any of the optimal (63) or near-optimal (60-62) cells.
Figure 10. Service areas with trimmed polygons better reflect practical building sites
Figure 11. Eight-mile count results
All cells representing sites that would address 60 or more points of demand were contiguous, located in along a two-mile stretch of road. The twelve cells representing optimal solutions, those covering 63 demand points, were also contiguous and located along both sides of a half-mile length of road (Figure 12). Because of the sparseness of the road network and the size of land parcels in the area, this effectively resulted in a single optimal solution to the original research question. The best place to build a new station to address need in Dickinson County according to the NFPA Standard was determined to be anywhere in the northern half of the 1200 block of State Highway 15, including the intersection of 1300 Ave and State Highway 15 (Figure 13).

Although the practical result of the eight-mile evaluation was a single site, it did produce twelve individual cells that could cover the optimal number of demand points. Those twelve optimal cells were ranked by the effectiveness of a new station at addressing unmet demand based on the five-mile ISO standard. The number of five-mile demand points covered by these sites ranged from 92 to 106. The ideal potential site is a few hundred feet south of a bridge over a small unnamed waterway (Figure 14).

Taken independently, the five-mile evaluation produced a range of demand points covered from one to 182 points with a single optimal site that could cover 182 demand points (Figure 15). If the goal had been to place a station to best address economic development, then that site would have been the optimal solution. By placing a station within the ISO standard range, those 182 properties and any future construction within that service area would have reduced insurance rates for which they would not otherwise qualify.
Figure 12. Count of eight-mile demand limited to “preferred development” region
Figure 13. Optimal building site for new fire station
Figure 14. Optimal sites with covering totals for five-mile demand points
Figure 15. Count of five-mile demand limited to “preferred development” region
4.3 The Impact of Fire District Boundaries

As discovered in the initial identification of unmet demand, fire district boundaries provided noticeable impedance to the efficacy of existing fire stations in Dickinson County. The number of unmet demand points in the evaluation of the more generous eight-mile standard doubled from 72 to 144 when station service areas were stopped at the district boundaries. In the more strict five-mile standard, by which more than 23% of the county’s rural demand was already unmet, the restriction to district boundaries raised the number of unmet demand points by 125, an increase of more than 14%. In fact, in the five-mile evaluation, every existing fire station site was also calculated to be a potential building site for a new station that would address unmet demand (Table 2). The sole fire station for the Grant Township Fire Department was found to have the greatest reduction in efficiency. Grant Township contains the county’s most populated town, Abilene. The rural areas within two miles of the Abilene city limits both in and out of Grant Township represent the greatest rural population density and property value in the county. Since the only rural fire station within either standard distance of that region stops at its district boundary, many citizens, valuable property and prime building sites are without adequate coverage (Figure 16).

The optimal sites identified in this study are another illustration of this situation. As the original research question stipulated that the new station would be operated by the county rather than an individual fire department, the new station would not be subject to the restrictions of district boundaries. The optimal solution in the eight-mile evaluation is on the border between two districts and just over one mile away from the common corner
Table 2. Demand abandoned by district boundaries per fire station

<table>
<thead>
<tr>
<th>Fire Station</th>
<th>ISO Demand</th>
<th>NFPA Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grant Township</td>
<td>87</td>
<td>42</td>
</tr>
<tr>
<td>DKCO Dist 1 Station #3</td>
<td>22</td>
<td>7</td>
</tr>
<tr>
<td>Hope</td>
<td>17</td>
<td>3</td>
</tr>
<tr>
<td>DK Dist 1Station # 2</td>
<td>17</td>
<td>26</td>
</tr>
<tr>
<td>Sherman Fragrant Hill</td>
<td>14</td>
<td>0</td>
</tr>
<tr>
<td>SACO Dist 1Garfield Station</td>
<td>12</td>
<td>25</td>
</tr>
<tr>
<td>Solomon</td>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>Herington #2</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>SACO Dist 1 Carlton Station</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>Woodbine</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Longford Talmage Manchester Station</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Herington #1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Navarre</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>DKCO Dist1 Station #4</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Fragrant Hill</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Longford Talmage-Talmage Station</td>
<td>2</td>
<td>5</td>
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<tr>
<td>DKCO Dist 1 Station #1</td>
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<td>0</td>
</tr>
</tbody>
</table>
Figure 16. Service area and unmet demand for the Grant Township fire station
of three districts. The optimal solution in the five-mile evaluation is even more telling, however. It sits at the corner of three different districts (Figure 17). If the new station were subject to the impedance of district boundaries, the location of the optimal solution would likely move to the corner of a district where the new station would cover one of the clusters of unmet demand, but would also be severely limited in its efficiency.

Figure 17. Optimal and near-optimal sites on the border of three fire districts
Chapter 5: Conclusion

The focus of this case study has been to answer a question posed by Dickinson County’s Emergency Manager: What is the optimal site to build a new fire station in Dickinson County that is not limited by district boundaries, and how can the potential effectiveness of that station be expressed to a funding organization? At its base, this is one of the simplest location problems, a maximal covering location problem with only one site to place. Solving that problem requires calculating the effectiveness of potential building sites in addressing unmet demand, a subject that has been the target of research for several decades. The basic methods involved have been tested, proven and expanded on to accommodate a wide variety of situations. However, it is also one of the most important location problems to local government, being the spatial version of getting the “biggest bang for your buck.” Applying it to a real-world situation requires great consideration in identifying the inputs. There must be unmet demand, and there must be potential building sites. How they are defined has great impact on the resulting solution and its viability for practical application. For this question, in Dickinson County, Kansas, unmet demand was defined by both national standards and local jurisdictional concerns. Potential building sites were limited to those areas that would best benefit the local community. With these inputs and a primary goal of increasing the number of properties covered by the NFPA standard, a single optimal solution was found. The best place to build a new fire station in Dickinson County under the assigned parameters is on either side of the road in the 1200 block of State Highway 15, a few hundred feet south of a bridge over a small waterway. A new station built at this location would cover 63 existing properties that do not currently have coverage at the NFPA standard and 106 that
do not have coverage at the ISO standard. If the primary concern had been to maximize demand covered at the ISO standard, the optimal solution would have been different. A new station built at the intersection of Fair Road and 2500 Avenue would provide coverage meeting the ISO standard to 182 existing properties that are not currently covered. However, it would provide coverage to only five existing properties that do not have coverage meeting the NFPA standard. Since maximizing coverage at the NFPA standard was the focus of this study, this site cannot be considered optimal.

With the identification of an optimal site comes the data necessary to quantifiably express the effect of the new station. It would provide coverage meeting the NFPA standard to 476 existing properties including 63 that are not currently covered. Additionally, it would provide coverage meeting the ISO standard to 132 existing properties including 106 that are not currently covered. It would provide new coverage at the ISO standard to more than 15 mi² of potential building sites in areas where development is encouraged in the county’s 2007 Comprehensive Plan. This would directly impact economic development by lowering potential insurance rates. Each of these effects could be used to make a case for funding in a grant application or by officials to support an informed budget decision.

The overall goal of the thesis was to establish a general methodology for site selection in rural areas. Three specific hurdles to effective site selection in rural areas were identified by earlier researchers: sparse road networks; roads that are not able to support emergency vehicle traffic; and a low density of existing stations. By using network buffers, or service areas, based on the county’s roads instead of Euclidean measurements, sites were placed within true driving distances along existing roads, no
matter how sparse they were in the study area. Basing that network analysis on the subset of the road network that met the definition of “all-weather” roads allowed the evaluation to bypass those roads not able to support the traffic of emergency vehicles. Finally, the low density of existing stations was accounted for by calculating the service areas for those stations and using those to identify unmet need. Although much depends on the quality of data used as input, the methodology addressed the identified concerns in rural site selection and could be used in a variety of location problems in rural areas.

5.2 Case Study Issues

Perhaps because they do not introduce new methods or address new questions, published case studies applying location models to real-world situations are rare (Current et al. 2001). The eventual goal of research is to have the formulated methodology applied to solve a problem, and this study is an example of doing just that. However, there are fundamental differences between a theoretical problem and a real-world problem that can complicate the process of finding a solution.

In this case study, the first of those issues was defining demand. Since there were existing fire stations, as there would be in nearly any practical situation, demand could not be defined as simply any location that could possibly need a fire truck. For a realistic answer to the Emergency Manager’s question, demand had to be defined as any location that could possibly need a fire truck and did not have one within the accepted standard distance that was also in the same fire district as the location itself. Other variables could have come into play as well, depending on the circumstances. For example, in this case study every demand point had the same weight, but that may not be reasonable if one of
the demand points represents a school or factory while the others represent unoccupied utility sheds or barns.

The second issue that had to be addressed was defining potential fire station sites. Since the County had no potential sites in mind, they were represented by a continuous plane, but it is unreasonable to define that plane as everything inside the county boundaries. Some areas are more and less suitable for building, and there is nothing “optimal” about a site that covers all unmet demand but requires millions of dollars of new infrastructure before it is viable. By using building site recommendations from the county’s comprehensive plan, reaching an optimal solution that was also viable was simplified. If it had not been available, the introduction of several variables may have been required to produce a practical solution.

Other issues could have come up that did not. For this study to produce a result congruent with existing standards, network analysis was the only choice. Euclidean buffers would have dramatically overestimated response areas given the nature of the road network in the region. That required the road layer to be in good condition with consistent and accurate topology. It was, but if it had not been, the solution would have been questionable from the outset, if it could have even been determined at all. Along that same line is the ambiguity of the term “all-weather road.” A consensus definition was found from ISO and the local and state transportation authorities, but finding it was one of the most taxing research tasks of the study. It is not that clear-cut in every jurisdiction, and including or excluding the wrong segments would have drastically affected the accuracy of the solution. While these issues do not impact the viability of the methodology, the point is to produce as accurate a solution as possible. Decisions
affecting people’s lives and property might be made relying on studies like this one, so
the accuracy and appropriateness of every part of the study needs to be considered, not
just the chosen statistical model.

5.3 Future Applications

Within the sphere of local government, applications for this method of single
facility site selection are abundant. With maintenance history to define demand, it could
be used to optimally site an equipment storage facility. With voting records, it could be
used to locate a new polling station. Getting the greatest utility out of every tax dollar
spent is a primary focus, and this type of study can help assure that focus is satisfied. The
new version of ESRI’s Network Analyst extension to ArcGIS software has built-in
models for solving location/allocation problems, including the maximal covering problem
(ESRI 2010). However, it requires potential facility sites to be input as points rather than
a continuous plane. For public sector problems the question of where to place something
within an entire jurisdiction is as frequently or more frequently asked than which of a few
discrete sites is best (Marianov and Serra 2001). To make certain that this type of
evaluation is accessible to agencies with limited experience in advanced geoprocessing,
the methodology could be organized into a model that takes a road network, existing
facility points, demand points and district boundary polygons as inputs and returns site
recommendations.

When datasets are very small, which is often the case in rural areas like Dickinson
County, heuristics are not always necessary to solve location problems. Simple
enumeration, as was used in this study, can return an answer in moments. Removing the
newly met demand and re-running the evaluation for a second or even third site takes
little time and effort and can produce a reasonable result. However, even in areas with sparse road networks and few demand points, placing a large number of sites requires a more robust approach. A proposed project to place GPS base-stations and 30-50 signal boosting antennae around the region may soon provide an opportunity to use one of the heuristic solutions to the planar MCLP within the study area.

5.4 Study Impact

If a station is built by Dickinson County at the optimal site, the direct impact of this study will be clear. In fact, quantifying the direct impact in order to express it to potential funding organizations was part of the goal. While less quantifiable, the indirect influence of the study may be more significant, however. Preliminary results provided to the Emergency Manager and fire department administrators have spurred dialogue about automatic mutual aid agreements and redistricting. For the Board of County Commissioners, the preliminary results have inspired discussions about other possible applications within the county like reducing road maintenance costs by optimally siting storage for equipment and materials.

There are also potential impacts for the larger GIS community. For local GIS personnel, the methodology presented can be duplicated by anyone with the appropriate data and software. Because the only statistical evaluations used are pre-packaged in software tools, neither advanced math skills nor programming knowledge are necessary. This leaves the methodology as a viable option for decision support to many agencies without the personnel or funding to implement more traditional location models. For GIS researchers whose goal is to develop methods of solving real-world problems, case studies put those methods to a practical test. This study showed the need to identify not
just the required data type for inputs, but also the standards of topological accuracy and attribution necessary to produce a reliable solution. Additional case studies like this one could help refine the existing models and show new paths for further research.
References


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