GIS method for characterizing fire flow capacity

Martin M. Kaufman\textsuperscript{a*}, Troy Rosencrans\textsuperscript{b}

\textsuperscript{a} Department of Earth and Resource Science, 516 Murcie, University of Michigan-Flint, Flint, MI 48502-1950, USA
\textsuperscript{b} GIS Center, 504 Murcie, University of Michigan-Flint, Flint, MI 48502-1950, USA

\textbf{ARTICLE INFO}

Article history:
Received 22 September 2014
Received in revised form
20 January 2015
Accepted 1 February 2015

Keywords:
Geographic information systems
Historical fire incidences
Fire flow analysis
Hydrant availability
Fire infrastructure assessment

\textbf{ABSTRACT}

There are numerous methods currently used to calculate required water flow rates for sprinklered and non-sprinklered buildings. The aim of this study is to provide a flexible automated procedure for identifying locations lacking adequate fire flow. To accomplish this objective, this research uses a GIS procedure to determine the spatial relationships between fire hydrants and historical fire incidences, and integrates the recommended hydrant spacing and building type specifications from the International Fire Code. This method was tested in two communities in eastcentral Michigan, USA. The results indicate an ability to define clusters of fires, determine the availability of hydrants, and assess the suitability of the available fire flow, including areas of potential extra capacity. Using these same data, additional GIS analyses can optimize hydrant location, ascertain the frequencies of different categories of fires, and identify the patterns of building types prone to fires.

\textbf{1. Introduction}

The water requirements for firefighting include the rate of flow, the residual pressure required at that flow, the flow duration, and the total quantity of water required. Specifically, fire flow is defined as "the rate of water flow, at a residual pressure of 20 psi and for a specified duration that is necessary to control a major fire in a specific structure." [2,30]. Determining the correct fire flow is necessary to achieve successful fire control efforts. If the fire flow is over-calculated, there could be a negative impact on the water distribution system; under-calculating of the fire flow may result in the loss of the building or lives [4,16].

Several recognized methods are currently used to determine the required fire flow for a building [5,10]. These methods can be broken down into two general categories: those for building planning (building and/or fire code requirements), and those for on-scene fire service use. The building planning methods account for a range of variables in determining fire flow, such as building construction, occupancy, and fire size. This method allows for building and community planners to assess current or future buildings against the existing or planned water supply and adjust accordingly. The on-scene fire flow calculation methods consist of one equation with one variable used to determine the fire flow, which allows the firefighters on scene to assess whether they need more hose lines or apparatus to fight the fire [5].

\textbf{1.1. GIS and fire science}

Geographic Information Systems (GIS) have been broadly applied to natural disasters in the areas of risk reduction and risk response [8]. With the increasing sophistication of spatial analytic tools, GIS has been combined with spatial statistics to investigate fire incidence [19]. For example, Asgary et al. [3] analyzed temporal and spatial dimensions of structural fires in Toronto, Canada. Using a classification scheme of fire types, their study found clear spatial and temporal patterns of fire for the different types of fires. In another study using GIS, Schacterle et al. [26] were able to find a significant association between vacant housing and fire risk. Other researchers, such as Corcoran et al. [9] have been able to find linkages between socioeconomic characteristics with fire risk and specific types of incidents in space.

On the infrastructure side of fire analysis, GIS has been used to study fire station location and response. An analysis of fire stations in California, USA demonstrated that short and long term costs can be saved by optimizing station location with a systematic approach that includes GIS [21]. Other approaches to fire station siting have been developed from an operations research perspective, and recent investigations have incorporated GIS into their models [1,11]. One limitation of existing GIS-related research on urban fire infrastructure has been the relative lack of studies addressing fire hydrant location and the implications for providing adequate fire flow. Here, there is the opportunity to combine the
temporal characteristics of fire incidence (fire history) with the existing spatial patterns of hydrants to ascertain whether adequate fire flow is available. Thus, an a priori risk assessment can be made by fire departments to identify locations within their coverage area that may lack adequate fire flow. This research is designed to provide fire personnel the ability to make a risk assessment about fire flow capacity at specific locations, with the added ability to identify fire clusters for further investigation from the maps produced. Fire flow capacities available for each land parcel within the study areas are also investigated to help identify locations where potential fire flow deficiencies may occur when no historical fire data exists.

The research hypothesis asserts that fire flow capacity is not sufficient in all cases within a fire department's coverage area. This hypothesis is tested in two communities in east-central Michigan, USA with a flexible automated GIS-based procedure for identifying locations lacking adequate fire flow. Through standard GIS operations, the spatial relationships between fire hydrants and historical fire incidences are constructed and integrated with the recommended hydrant spacing and building type specifications from the International Fire Code [17]. This method is thus compatible with the building planning methods used to determine fire flow requirements.

2. Methods

A multiple-method case-study approach is employed to investigate fire flow capability in the study areas. In a case study, a primary objective is to assess the ability to transfer theory, principles, or techniques existing at the geographic scale of the case to other areas or "cases" [31]. The methods used to characterize fire flow capacity in this study include map analysis, GIS modeling, and field observation. Being largely data-driven, the use of a GIS procedure mandates a specific sequence of tasks [15–25]. With respect to this research, the flow of work included study area selection, data collection, GIS map layer preparation and projection, development of the GIS procedure (model) for integrating the necessary data and arriving at a solution, and field verification of the results.

2.1. Study area selection

The study area for this research encompasses the two communities of Grand Blanc and Flint Township located within Genesee County, Michigan (Fig. 1). These communities were selected based upon the availability of hydrant data in digital format and the desire of the fire chiefs to participate in the study. Both communities contain a variety of land uses ranging from highly urbanized to semi-rural, and thus contain different patterns of hydrant spacing and density.

2.2. Data collection

GIS data consist of map layers containing spatial and attribute data. In vector-based GIS systems, spatial data are the points, lines, or polygon features constituting the visible map; attribute data are linked to each spatial feature to provide descriptive and analytical information. For instance a spatial data point feature might represent a fire hydrant, and the attribute data associated with that hydrant might include its part number, flow rate, and operational status. To perform the tasks of this research, the following data were collected for each community: fire hydrant locations and their flow rates, 3-year fire history from 2010 to 2013, land parcels, digital street maps, the International Fire Code standards for fire flow (Table 1), and hydrant requirements based on fire flow (Table 2).

Referring to Table 1, the columns under the heading “Fire Flow Calculation Area” represent a range of building types. The building types are derived from the International Building Code and are based on their construction materials, occupancy, and height; with subtypes denoted by the letters A and B to indicate relative fire resistance [18]. For the sake of brevity, only the construction materials will be presented here. Types I and II buildings are constructed of noncombustible materials. Type III has exterior walls made of noncombustible materials and the interior building elements are of any material permitted by the code. Type IV consists of heavy timber, with the exterior walls having noncombustible

Please cite this article as: M.M. Kaufman, T. Rosencrants, GIS method for characterizing fire flow capacity, Fire Safety J (2015), http://dx.doi.org/10.1016/j.firesaf.2015.02.001

Fig. 1. Study area.
Table 2
Number and distribution of fire hydrants [17].

<table>
<thead>
<tr>
<th>Fire-flow requirement (gpm)</th>
<th>Minimum number of hydrants</th>
<th>Average spacing between hydrants (feet)</th>
<th>Maximum distance from any point on street or road frontage to a hydrant</th>
</tr>
</thead>
<tbody>
<tr>
<td>1750 or less</td>
<td>1</td>
<td>500</td>
<td>250</td>
</tr>
<tr>
<td>2000-2250</td>
<td>2</td>
<td>450</td>
<td>225</td>
</tr>
<tr>
<td>2500</td>
<td>3</td>
<td>400</td>
<td>200</td>
</tr>
<tr>
<td>3000</td>
<td>4</td>
<td>350</td>
<td>180</td>
</tr>
<tr>
<td>3500-4000</td>
<td>5</td>
<td>300</td>
<td>150</td>
</tr>
<tr>
<td>4000-5000</td>
<td>6</td>
<td>250</td>
<td>120</td>
</tr>
<tr>
<td>4500-5000</td>
<td>7</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td>5000</td>
<td></td>
<td>150</td>
<td>90</td>
</tr>
<tr>
<td>6000</td>
<td></td>
<td>100</td>
<td>60</td>
</tr>
<tr>
<td>6500-7000</td>
<td></td>
<td>80</td>
<td>40</td>
</tr>
<tr>
<td>7500 or more</td>
<td></td>
<td>60</td>
<td>30</td>
</tr>
</tbody>
</table>

2.3. GIS map layer preparation and projection

For a specified geographic extent (study area), all of the GIS layers must have internal consistency and the ability to overlay on each other with an acceptable amount of spatial error. Internal consistency refers to the correct correspondence between the spatial features and their attribute data. For example, each flow rate assigned to a hydrant should represent its actual flow. The ability to overlay layers is dependent upon several factors, including: cartographic errors in map preparation, incorrect projection methods, and data compiled from multiple sources having different spatial resolutions [29]. To minimize attribute error, statistical range checks were performed to help detect data entry errors in the hydrant flow data, as these values were derived from paper maps. After their entry, the hydrant flow data were displayed and compared to the paper source maps for accuracy. Cartographic errors were minimized through consistent map projection, which are attempts to portray the surface of the earth or a portion of the earth on a flat surface. Some distortions of conformity, distance, direction, scale, and area always result from this process. Conformality refers to the preservation of scale in any direction, with the lines of latitude and longitude intersecting at right angles. Some projections minimize distortions in some of these properties at the expense of maximizing errors in others, whereas other projections attempt to only moderately distort all of these properties [24]. For this application, a State Plane projection was applied for all map layers to facilitate spatial overlay operations [27]. Fire history data were geocoded and added as a point layer to the GIS application. Geocoding is the process of transforming a description of a location such as an address to a location on the earth’s surface [12]. In this application, the address of each fire in the 3-year history file was matched to street reference files containing geographic centerline coordinates, street numbers, street names and postal codes. The 3-year histories were compiled from the fire incident reports input to the National Fire Incident Reporting System [23]. Data available from these fire incident reports also enables fire flow characterization for specific categories of fire, such as those related to hazardous materials or vehicles. In this application, the only types of fires investigated are building fires. Land parcels, streets, and hydrants were obtained in digital format and comprised the remaining three layers of data in the GIS. Boundaries were inspected for consistency and alignment after each layer was projected and overlaid on the others.
2.4. Model development

Models are descriptions of systems, where systems consist of discrete and interacting components with inputs and outputs, a sequence of processes, and feedback mechanisms [5]. A GIS has these elements, with feedback pertaining to the human actions taken in response to the solution presented. Given this definition, GIS models specify the operations performed on each data layer to produce the desired output [20]. Fig. 2 depicts the sequence of operations required to characterize fire flow capacity.

Starting on the left side of the model, the fire history locations and hydrants are input into a spatial join. A spatial join creates a joined table in which fields from two layers’ attribute tables are merged based on the relative locations of the features in those layers. In a spatial join, the option is available to have statistics performed on the fields, along with the ability to delete any unnecessary fields. For this case, the flow of each hydrant within the search radius is summed. The search radius can be determined from the building type in Table 1; however, building types are not explicitly input on the Fire Incident Report [23], so the largest average spacing between hydrants is used (500 ft or 152.4 m; Table 2). Employing the maximum radius of 152.4 m is the most robust way to test the model, since the use of shorter distances might miss hydrants that should be included and yield a false positive for deficient fire flow.

After the spatial join, the minimum required fire flow is calculated in row 1 on the right side of the model based on the fire flow requirement shown in column 1 of Table 2. If the building type or area is not available, the lowest amount of required fire flow (1500 gal/min) is input from Table 2. Once again, this is the most robust way to test the model, since any deficiency discovered using the least amount of required fire flow indicates deficiencies are more likely to exist for all other building types and square footages. In row 2, a threshold for potential excess fire flow capacity is calculated by doubling the minimum required fire flow for any building type, and the authors recognize this is somewhat arbitrary. Since there is no precedent for defining excess fire flow, we selected double the lowest flow rate that would apply to large radii correlate well to the fire deficiencies identified. Within “A” there were 19 hydrants with a combined fire flow capacity of 20,400 gallons per minute. Hydrants here were within a search radius of a historical fire 52 times, with 8 instances of 4 or more hydrants in the same search radius of a fire. The absence of hydrants in the southern portion of circle “A” accounts for the majority of deficient fire flows. In circled area “B”, where there were more fire flow deficiencies, there are 29 hydrants with a fire flow capacity of 35,200 gallons per minute, yet a hydrant was within
the search radius of a fire only 7 times. The absence of hydrants in the northeast quadrant of circle “B” accounts for this result. Fig. 4a indicates no areas of fire flow deficiency in Grand Blanc. This outcome, however, demonstrates the capability of the model to identify areas with a potential excess of fire flow capacity and unneeded hydrants. In many urbanized regions—especially those with an industrial legacy—vacant land parcels (brownfields) may occupy significant portions of the total land area [22]. For example, in nearby industrialized Flint, Michigan, 19 percent of the land is categorized as vacant brownfield [13]. A land parcel layer with the vacancy status of each parcel can be incorporated within the model to help identify areas with excess fire infrastructure, as demonstrated in Fig. 4b.

As shown in Fig. 4b, there are some areas within Grand Blanc potentially having excess capacity, despite vacant parcels occupying only a small percentage of the land area (9 percent). The definition of excess capacity is problematic, since fire situations vary over time due to property development and variations in building size and use, so an excess of fire flow today may become a deficiency tomorrow. The objective here is to allow for the investigation of the possibility there may be excess capacity and infrastructure in certain areas. Within this framework, excess fire

Please cite this article as: M.M. Kaufman, T. Rosencrants, GIS method for characterizing fire flow capacity, Fire Safety J (2015), http://dx.doi.org/10.1016/j.firesaf.2015.02.001
flow capacity was defined in Section 2.4 as one or more hydrants within a 152 m search radius of a historical fire that create an available fire flow over twice the minimum value of 1500 gal/min. Fire professionals should evaluate each potential case of excess capacity, with a more rigorous analysis made possible by the addition of tenure data available from the U.S. Census Bureau at the block level [28] and current utility usage.

Points A, B, and C in Fig. 4b refer to fire locations where there is a potential excess in fire-flow. Point A has a fire flow rating within the search radius of 29,500 gallons per minute. Point B has a fire flow rating within the search radius of 20,000 gallons per minute and point C had a fire flow of 24,000 gallons per minute. All three points were significantly higher than the 3000 gallons per minute that was set as the threshold.

3.1. Parcel-based fire flow analysis

The coding of the GIS model shown in Fig. 2 was revised to perform a parcel-level fire flow assessment. In the interests of brevity this analysis is shown for only one of the study communities. Fig. 5a depicts the fire flow deficiencies for Flint Township at the parcel-level, and Fig. 5b illustrates the difference between these areas and those depicted by the historical fire flow deficiency map in Fig. 3a.

This difference map shows those areas within Flint Township that did not have historical fires, but may possess a potential deficiency in fire flow. As indicated by this figure, there are some clusters (especially in the northern part of the township) of potential fire flow deficiency not revealed by the historical fire data. In urban areas where there has been new development and little history of fire, using the parcel-based GIS model can help fire personnel identify areas of potential inadequate (or excess) fire flow capacities.

3.2. Future implications of this research

With this GIS model, the existing spatial and attribute data can enable additional GIS analyses. For instance, future hydrant locations can be optimized by simulating the required distances and correlating these to the anticipated land uses and building types. It

Please cite this article as: M.M. Kaufman, T. Rosencrants, GIS method for characterizing fire flow capacity, Fire Safety J (2015), http://dx.doi.org/10.1016/j.firesaf.2015.02.001
is also possible to ascertain the frequencies of different categories of fires such as hazardous materials available from the fire codes available in the attribute table, and to identify the patterns of building types prone to fires.

The temporal aspects of fire flow availability can also be investigated. If the times of fire occurrence are input from the fire incidence report, inclusion of these data would allow for the assessment of current fire flow availability. Since water usage varies widely in urban areas, the quantity of water and system pressure available for fire flow varies with the existing demand on the water supply system [14]. Integration of fire temporal data into Supervisory Control and Data Acquisition, or SCADA systems would permit a real-time (instantaneous) transfer of available water to a fire scene. SCADA systems are specialized computer networks and devices that work in concert to monitor and control key processes involved in the management of machinery, equipment and facilities. Measurements taken from a variety of sensors (e.g., temperature, pressure, flow) are used to make decisions, for example, to open a valve and release water from a tank when it fills up [7].

Please cite this article as: M.M. Kaufman, T. Rosencrants, GIS method for characterizing fire flow capacity, Fire Safety J (2015), http://dx.doi.org/10.1016/j.firesaf.2015.02.001
4. Conclusions

The main hypothesis was confirmed by the model test; fire flow capacity is not sufficient in all cases within a fire department's coverage area. Moreover, the converse is also true, this model has the capability to identify areas where excess fire infrastructure might exist. As a result, the efficacy of the model is likely to increase when a land parcel layer is included and applied to larger urban areas having significant percentages of vacant land. Given the coding mechanism used to identify fire types in fire incident reports, this model also has the ability to characterize fire flow capacity for specific classes of fire, such as those associated with hazardous substances. This aspect of the model's flexibility may be of some benefit when deciding on the purchase and use of firefighting foams and the equipment needed for their application. The inclusion of building type on the fire incident reports would increase the power of this GIS application by enabling an easier spatial characterization of fire incidences by building type. In addition to the identification of the spatial patterns related to fire events, fire flow, and building types, perhaps the most promising use of the model will come with its application to fire's temporal aspects. Here, the model might provide a variety of results ranging from basic frequency information about the incidences of specific categories of fire type, to providing input into real-time SCADA systems for fire flow assessment and water transfers before fire crews arrive on site.

This research contributes to the fire science literature by providing a flexible method for the assessment of deficient, adequate, and surplus fire flows. Using this model with historical fire flows also enables further analysis of fire clusters by specific fire types; whereas running the model at the parcel-based scale can identify areas of potential fire flow deficiency (or surplus) where no historical fires have occurred. The primary objective of case study research is accomplished, as this model is applicable to any urban area or fire district. Additional research is needed that investigates the clusters of fires and their correlation with various fire flow capacities and local socio-demographic characteristics. Using GIS to merge fire response times to specific fire flow capacities may also help fire districts evaluate their current and future fire station locations.

Acknowledgments

Content of this publication is based upon work supported by the Research and Creative Activity funding from the University of Michigan–Flint's Office of Research and Sponsored Programs. The authors would like to thank John Ringwelski and James Harmes, Fire Chiefs of Flint Township and Grand Blanc, respectively, for their assistance with fire data, and the Genesee County staff; specifically, Jennifer Boyer (Emergancy Management) and Ken Koleda (GIS) for granting access to their data and information. We also thank Sergeant Dan Kelly of the Flint Township Fire Department who provided water flow data for their hydrants, Matt Wurtz and Matt Gilbert of Grand Blanc for their digital hydrant location and flow data, and Karyn Miller, Flint Township Supervisor for her efforts in securing data.

References


Please cite this article as: M.M. Kaufman, T. Rosencrants, GIS method for characterizing fire flow capacity, Fire Safety J (2015), http://dx. doi.org/10.1016/j.firesaf.2015.02.001