Using GIS and Asset Management to Understand Hydrant Damages and Required Maintenance

by

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To Lisa Matthies-Wiza: you introduced me to the world of GIS. Without you, this journey would have never begun.

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List of Abbreviations

AADT	Annual Average Daily Traffic
AWWA	American Water Works Association
EPA	Environmental Protection Agency
GCWW	Greater Cincinnati Water Works
GIScience	Geographic information science
GPS	Global Positioning System
I-190	Interstate 190
NOAA	National Oceanic and Atmospheric Administration
PRISM	Parameter-elevation Regression on Independent Slopes Model
Veolia	Veolia North America

Abstract

Throughout the United States, aging water infrastructure creates continuous challenges for safety and water quality. Maintaining infrastructure takes considerable organization and coordination. Hydrants are critical for maintaining high water quality and for safety-precautions such as firefighting and dust control in construction. This thesis project aims to determine what factors contribute to hydrant damages in Buffalo, NY through the use of spatial analysis with geographic information science (GIScience) and asset management. It is hypothesized that, due to weather patterns specific to north and south Buffalo, there will be significantly more hydrant damages reported for south Buffalo. Additionally, more hydrants will be damaged during severe winter weather in the locations where snow accumulation is greatest. This study utilized data on hydrants and corresponding hydrant maintenance and weather data at multiple scales to test these hypotheses. Hydrants and corresponding damages were analyzed based on spatial location and temporal (seasonal) scale. Hot spot analysis was used to determine areas where significant clusters of hydrants are located and where maintenance as a result of vehicle damage may be statistically significant. Hydrant failure and repair data were analyzed based on the frequency of occurrences each day, and in relation to weather patterns. In an additional analysis, weather data were analyzed on days when severe storms occurred, to determine if more hydrant repairs result from severe weather. As predicted, south Buffalo reported a greater rate of damaged hydrants than north Buffalo; however, contrary to the second hypothesis, hydrant damages were not consistently confined to areas of Buffalo with the greatest snow accumulation. Understanding how location and seasonal weather factors cause hydrant damage or increase maintenance will help Buffalo to identify highly susceptible areas. Buffalo can use the results from the analysis to strategically implement preventative maintenance and save city funds.

Chapter 1 Introduction

Throughout the United States, aging water infrastructure is reaching the end of its industry suggested life, potentially putting communities and individuals at risk. Due to aging infrastructure and an increase in demand as a result of population growth, restoring water systems in the United States is expected to cost more than 1 trillion dollars over the next 25 years (AWWA 2012). Municipalities serve the public and must maintain a high level of service while also delivering a high quality product, but managing water infrastructure is a growing challenge. Fire hydrants are critical for maintaining pipe quality, water quality, and safety practices in firefighting (Shah et al. 2001). Throughout the United States, aging water infrastructure is susceptible to failure and a decrease in water quality, creating challenging maintenance tasks (Booth and Rogers 2001). Understanding why assets fail and how preventative maintenance is performed is crucial for continued success in the water industry.

Located on the eastern end of Lake Erie, Buffalo, NY, referred to as Buffalo, (Figure 1) first began developing its municipal water distribution system in 1827 (French 1860). By 1913, Buffalo built a new water intake and consequently designed a new pumping plant, allowing Buffalo to expand their distribution lines even further. As trade and commerce increased, Buffalo continued to develop in the early and mid-1900s, resulting in much underground pipe infrastructure being placed for the water system around the 1930s (CW 2016). Many of these pipes from the 1930s remain in use today.

Figure 1. Map of study area. In the right map, Buffalo is divided into north and south districts.

Unfortunately, Buffalo's rapid growth came to a halt, and today it is what many would consider a "rust belt city." Rust belt cities were once thriving areas of commerce where manufacturing jobs were abundant and economy was booming. Over time, these cities underwent severe economic loss as jobs became scarce (Hobor 2012). Over only a few decades, the population decreased by half and manufacturing jobs, primarily in the steel industry, were nearly eliminated. Buffalo, like many rust belt cities, also suffers from economic loss. As a result, policy makers and planners struggle to provide adequate services and infrastructure improvements. Rust belt cities are quickly seeing the effects of aging water infrastructure and continue to suffer from lack of funding to assist with replacements and improvements (Hartley 2013).

Today, Buffalo Water, managed by Veolia North America (Veolia), serves a population of approximately 260,000 people through many of the same cast iron pipes placed in the 1930s. There are 806 miles of water mains and 7,940 fire hydrants documented at the time of this study. The vast infrastructure system continues to age, creating ongoing challenges for Veolia and Buffalo Water.

Numerous municipalities and private industries are adopting asset management systems to assist with asset maintenance, restoration, and critical data collection. Asset management systems are typically proprietary software systems that assist with understanding infrastructure and provide insight for maintenance management strategies (Baird 2010). Often, asset management system software includes a data tracking tool (such as a geodatabase), a scheduling module, and a criticality index. Additional tools may be included in software packages or incorporated through add-ons and attachments.

Asset management systems have the ability to track infrastructure assets and work orders while also maintaining information on staff performance and costs (Baird 2011a). Implementing an effective asset management system takes coordination between many individuals and a significant amount of time. Data must be inputted and maintained while the conditions of assets require continuous tracking and updating. Information and progress must be well documented (Hoskins et al. 1998). Asset management also integrates new technology, which may present many challenges; however, these systems have demonstrated great benefits such as cost savings and efficient scheduling. Understanding the advantages of asset management systems may assist with successful implementation of work order management, effective modeling, and condition monitoring. Furthermore, cost savings attributed to utilizing an asset management system provide increased data reliability and confidence in management techniques (Baird 2011b).

In addition to the aging infrastructure, weather poses a challenge to managing infrastructure in Buffalo. Strategic development and growth of Buffalo was in part a result of proximity to the Erie Canal, connecting Lake Erie to the Hudson River and ultimately the Atlantic Ocean. The unique location, to the east of Lake Erie, results in freezing winter temperatures and winds that blow east over the lake and into Buffalo. Throughout the winter season, these weather conditions combine and create harsh winter storms that are often concentrated in south Buffalo along what is considered the "snowbelt" (Nance 2006). As a result of the winds off the lake, south Buffalo will often experience a greater amount of winter precipitation during storm events than the neighboring north Buffalo area. These weather conditions pose issues that include frozen water mains, frozen hydrants, hydrants that are inaccessible due to being buried by snow, and vehicles that damage hydrants while driving. Due to the amount of snowfall, icy road conditions, and increased plow traffic in the winter, it is expected that vehicles will damage more hydrants during winter months than in summer months.

In Buffalo, the difference between north Buffalo and south Buffalo is typically defined by one of the major highways in the area, with land lying south of Interstate 190 (I-190) to be considered south Buffalo. For the purpose of this study, the south Buffalo delineation used is slightly north of the I-190, as using this more northern boundary line coincides with hydrant districts and Parameter-elevation Regressions on Independent Slopes Model (PRISM) weather data.

When Veolia began managing Buffalo Water in 2010, they brought in technology that would assist with implementing effective asset management systems. Underground asset management is possible through the use of InfoNet, an infrastructure management software developed by Innovyze. Implementing the comprehensive asset management system assists with data collection and management of these assets. Following thorough data collection, long-term goals include integration of asset management information with billing software, uniform work order management, utilizing criticality analysis to determine where capital work is most needed, and continuous monitoring and trending of flows. Information collected will also assist with modeling the distribution system and implementing effective business practices that change in line with technology.

Through scheduling and maintenance strategies developed for water mains, hydrants, and valves, Veolia has reduced costs on reactive maintenance by implementing proactive preventative maintenance and efficient scheduling. Ultimately, these proactive measures assist with reducing water loss and overall cost. Over the past five years, Veolia has successfully demonstrated that an effective asset management system can assist with reduction of water loss, even in years when the number of main breaks is high.

1.1 Motivation

Similar to underground water infrastructure, hydrants are highly susceptible to breakage, resulting in reduced level of service or complete asset failure. Although studies discuss the causes of water infrastructure failure, they often lack information on fire hydrants or do not mention fire hydrants at all (Arsenio et al. 2015; Hanson 2008; Livingston et al. 2008). Since fire hydrants are above ground, they are susceptible to additional factors that underground infrastructure may not be exposed to. Historically, hydrant damages are attributed simply to motor vehicles and weather, while it is well documented that underground infrastructure is also impacted by age (Brush 1920; Nelson 1976; Qureshi and Shah 2014). With this understanding, it is possible that hydrants experience additional failure due to factors related to age such as corrosion from environmental effects and use over time, as well as factors related to main connectivity, while also being susceptible to vandalism and vehicle damage.

Within Buffalo, managing the numerous pipes, hydrants, and valves is a challenge. After initial implementation of the asset management system, Veolia continues to demonstrate how uninterrupted data management is required to obtain the most accurate data for use in models and analysis. In Buffalo, work orders are tracked in the InfoNet database indicating the required maintenance along with specific information about the hydrant itself. Since 2011, 17,611 hydrant maintenance work orders have been created in the InfoNet database. Information within these work orders indicates why the maintenance was needed: routine use (such as by Buffalo Fire Department or Department of Public Works), damage (being struck by a car), or a failure to function properly identified during hydrant use (based on information from reports by City personnel or concerned citizens). After the hydrant is initially indicated as needing repair, the required maintenance (repair, replace, or seasonal maintenance) is documented prior to the work order being marked as completed in the system. Spatial analysis of these damages and the hydrant features may indicate what locational factors and physical characteristics impact damages and maintenance requirements.

Numerous studies and reports exist with information on the water industry, with many focusing on failing infrastructure, capital improvements, risk assessments, cost of improvements, public health issues, water quality, and asset management. The reports focus on asset conditions, system pressures, corrosion potential, and risk associated with the condition of the asset; however, few of these reports consider the geospatial distribution of assets and how pipe, hydrant, or valve failures may rely on physical properties and spatial location, both above and below ground (AWWA 2016; Livingston et al.; 2008 Nelson 1976). Therefore, this research adds to understanding why assets fail, potentially assisting with better maintenance scheduling.

1.2 Research Questions

The goal of this thesis is to determine whether or not spatial location is a factor that contributes to the need for fire hydrant maintenance. For the purpose of this study, only hydrants damaged by vehicles during winter months (November to March) will be included in all analysis. This project specifically aims to answer the following questions:

1. Is there a difference in the number of hydrants damaged by vehicles in north Buffalo versus south Buffalo?
2. Is the weather in Buffalo a factor that may result in required hydrant maintenance as a result of vehicle damage?

Ultimately, the answers to these questions will identify areas in Buffalo where additional maintenance may be required, or where techniques can be performed to prevent hydrants from failing before serious repair and replacement is required. Throughout this thesis, hydrant damages as a result of being struck by a motor vehicle will be assessed based on location and winter precipitation in that area. With information obtained about hydrant damage locations and corresponding weather data, it is possible that the most susceptible hydrants can be identified. This information will allow Veolia to develop and incorporate stricter maintenance management plans into a spatial geodatabase for Buffalo. By understanding where, when, and why the need for hydrant maintenance occurs, Buffalo can implement better preventative maintenance strategies that may potentially mitigate the need for repair work or hydrant replacement. Strategies may include sufficiently clearing snow from hydrants on a regular basis, installing hydrant marker flags on hydrants, installing bollards to block traffic, and in some cases, it may be necessary to move a hydrant a few feet from its current position.

1.3 Research Design

The research project begins with an overall data summary. Data are parsed based on occurrence during specific seasons (winter versus summer) and in various parts of Buffalo (north Buffalo versus south Buffalo) as defined in this thesis. Once the data are summarized, the focus of the project is on winter hydrant maintenance incidents, caused by vehicular damage. Hot spot analysis is utilized to determine the areas where hydrants are significantly clustered in Buffalo. Hydrant maintenance incidents attributed to vehicular damage are also analyzed via hot spot analysis to determine work order clusters. These two data outputs are then compared to determine if areas where hydrants are significantly clustered are the same areas where hydrant maintenance incidents are clustered. Additional hot spot analysis is performed on subsets of work orders, where data are parsed by year and analyzed using the same methods outlined above.

Following the initial data analysis, weather information is incorporated into the hydrant maintenance incident analysis. First, the hydrant work order analysis looks at days where numerous hydrant maintenance incidents occurred. Those specific days are compared to cumulative winter precipitation data in a visual analysis, using outputs to determine the likely associations between hydrant maintenance incidents and cumulative winter precipitation. The second analysis looks at dates where severe storm events were reported in or around Buffalo, NY. The hydrant maintenance incidents on those days are analyzed against cumulative precipitation data in a visual analysis. Data from both studies are used to examine overall hydrant maintenance incident distribution, from a north Buffalo versus south Buffalo perspective.

The first chapter provides a general introduction to asset management and the current state of water infrastructure. Chapter two provides the background of asset management in the water industry as well as other industries where similar techniques may be applicable. In this section, I discuss why incorporating GIS into asset management systems is crucial to fully utilize the data that are collected.

In chapter three, the methods used to analyze data from Buffalo Water, PRISM data from Oregon State University, and severe storm data from National Oceanic and Atmospheric Administration (NOAA) are described. Hot spot analysis determines areas where hydrants are located. These areas are subsequently compared to locations where hydrant damages occur. Visual analysis is used to determine if weather has an impact on the timing and location of hydrant damages by vehicles. Factors that are considered in this thesis are general locations of hydrants and hydrant damages as well as precipitation patterns in the area. The results of the analysis are presented in chapter four. The results, limitations, and future work are discussed in chapter five.

Chapter 2 Related Work

In Chapter 2, past work utilizing asset management is reviewed, emphasizing the need for comprehensive asset management in the water industry. Asset management with a GIS component is critical for future spatial analysis and research to assist with understanding what factors impact the quality of water infrastructure.

Understanding the current use of GIS and asset management in the water industry helps to identify benefits and uses of such systems. The various systems help provide a stable foundation for collecting data and tracking information, while also providing data that are necessary to schedule and create preventative maintenance programs. These programs could include leak detection identification, valve maintenance programs, and hydrant flushing. Incorporating GIS into asset management allows for critical data to be collected while also increasing the quality of water and the overall level of service to the end user.

In the water industry, asset management primarily focuses on infrastructure. Once developed, the asset management system is used to assist the public works department with overall decision support and data tracking. The priority of the asset management system is to help manage physical assets alongside economic and social values. Ultimately, asset management systems provide the basis for a decision support model, the information for criticality assessments, and information necessary for sustainable management and compliance (Baird 2011a).

2.1 Implementing a GIS and Asset Management

Prior to implementing a successful geospatial asset management system, georeferenced data must be collected and recorded. In a robust asset management system, this is a process that takes many years of planning and execution. At the Greater Cincinnati Water Works (GCWW), serving Cincinnati, OH, the utility spent years collecting data and uploading it to a geospatial database. Over time, the system has developed greatly and proves its valuable importance to Cincinnati through asset mapping and maintenance plans (Hanson 2008).

In addition to developing a comprehensive database of information, the physical locations of assets should also be collected. Geospatial data are beneficial for more than simple mapmaking. GIS allows users to catalogue, view, and analyze data quickly and efficiently (Baird 2010). Data upgrades from paper records are often inefficient and highly susceptible to errors. As a result, mobile GIS is a valuable tool for both strategic and tactical needs, allowing individuals to collect, update, and reference data in the field. The Global Positioning System (GPS) and various methods of data collection may be incorporated in the field during maintenance work to make strategic updates. Once data are collected and updated, the management process has endless possibilities (Shadin and Tahar 2015).

In the simplest form of asset management, the system is utilized as a data tracker, simply collecting information about assets while scheduling and tracking maintenance. Information about an asset is collected, and the current condition is analyzed. If repair is needed, corrective maintenance is scheduled through the asset management software (Schneider et al. 2006). Some utilities benefit greatly from scheduled routine maintenance and criticality analysis. GCWW considers 76 factors when analyzing and scheduling rehabilitation on pipes and these are all incorporated into the GIS. Using these factors as well as past experience, GCWW is able to perform relevant analysis and make qualified decisions (Hanson 2008).

Building a successful asset management system relies on incorporating known information along with effective management initiatives such as partnerships, long-term planning, leadership support, and broad thinking. Utilities must go above and beyond basic compliance, and they must consider sustainability, resiliency, and performance for both daily tasks and long-term planning (Santora and Wilson 2008). Not only must an asset management effectively demonstrate distribution system maintenance, but it must also provide the means for increased customer satisfaction and water quality improvement to achieve a high level of performance (Han et al. 2015; Imran et al. 2009). Once the organization of these factors comes together, information can be effectively tracked and undergo risk analysis. Using the information within an asset management software provides managers with a tool for budgeting time and money effectively, allowing utilities to meet short- and long-term goals (Booth and Rogers 2001).

2.2 Asset Management in Research and Industry

Incorporating components of GIS and asset management into the water industry has proved to be challenging in the United States, regardless of the known importance. Management of the distribution system and the high number of components would benefit from advantages of statistical analysis (Schneider et al. 2006). These various analyses may be integrated into models to determine factors that may impact the reliability of water infrastructure as well as predict future main break, hydrant repair locations, and various other types of distribution system maintenance (Wood et al. 2007).

Past research has focused heavily on risk assessment and reliability analysis. Asset management was introduced and implemented for everyday industry use later in the United States than it was in other areas of the world. Although not particularly beneficial, there was no lack of spatially relevant research occurring prior to the implementation of asset management in the United States. Reliability through condition assessment was the emphasis of much research, which considered reachability, connectivity, and demand. These components and observations led to the development of algorithms that demonstrate the capacity and reliability of water distribution systems (Quimpo and Wu 1997).

Although the water industry is often secluded to water treatment and distribution, it is important to recognize that an asset management system for one utility can ultimately affect parallel networks such as wastewater collection lines and transportation lanes. By performing a GIS-based risk assessment, Inanloo et al. (2015) developed a rating system that considers failure frequency, consequence of failure, and potential impacts to co-located linear systems. Probability of failure is determined based on information obtained from the Miami-Dade Water and Sewer Department. After developing the rating system and implementing it in a GIS, they are able to determine how a water main failure would also impact traffic. Buffer analysis is used to estimate the affect area, while Annual Average Daily Traffic (AADT) is used to estimate the impact that a failure event has on traffic. As a result, a methodology was developed that can be used as an aid to allocate maintenance efforts and coordinate events between collinear systems. Inanloo and colleagues only considered underground pipes; therefore above ground factors that may impact hydrants were not considered (Inanloo et al. 2015).

In addition to being used for decision making and planning in numerous utilities, asset management has also helped to save money in different scenarios. As a whole, asset management assists with cost savings by providing two solutions: developing an effective capital replacement program and also managing operations and maintenance effectively on a regular basis. Through planned maintenance and replacements, utilities often see a higher return on investment. Using asset management programs is a reliable method to effectively plan for these cost savings (Baird 2011b).

Various companies in the power industry are utilizing asset management to reduce power interruptions. By reducing power interruptions or promptly addressing issues, companies increase revenue and suffer less from economic loss (Penton 2015). The City of San Diego is implementing smart infrastructure as an asset management technique, replacing streetlights, installing a new traffic control system, installing solar panels, and developing state of the art water management programs. These strategies are ensuring cost savings for the City of San Diego while also providing customers with cost-effective and eco-friendly options (Callahan 2016).

2.3 Evolution in the Water Industry

Asset management has been utilized in the water industry since the late 1980s, and the benefits are continuously observed. The first asset management systems were implemented in Australia and New Zealand. The transition to using asset management systems has been slow to occur in the United States due to the high number of water providers, from private companies to municipalities; however, many United States companies are beginning to use best practice techniques along with sharing knowledge across industries to aid in water system management (Jones et al. 2014). According to the United States Environmental Protection Agency (EPA), best practice techniques include documenting the current state of assets, determining the required level of service, indicating what assets are critical to performance, defining the minimum life cycle costs, and implementing long-term funding strategies (EPA 2008).

It is apparent that asset management systems have evolved over time to assist with effective and efficient data tracking. In some communities, an asset management system has helped establish best practices, demonstrate the variability of different programs, and create long-term sustainability plans (Leitao et al. 2014). The information can be used to assist with understanding what causes pipes, hydrants, and valves to wear out and fail (Livingston et al. 2008). As a result, asset management and other such systems have helped with automating workflows and decision support (Arango et al. 2015; Kizito et al. 2009). Maintenance tasks, such as flushing, improve the quality of water and maintain distribution mains. Tasks like these can be scheduled, planned, and tracked in asset management systems (Deuerlein et al. 2014).

The current state of asset management in the water industry is evolving in the United States; however, there is limited incorporation of GIS throughout many municipalities. Buffalo Water has been working on developing a comprehensive geodatabase and asset management system, but the process takes several years to develop. Since 2010, under the instruction of Veolia, Buffalo Water has been collecting additional data that will assist with future analysis. The research here aids in determining important features and attributes to incorporate into the daily data entry collection that will further aid subsequent research.

2.4 Weather Data

Weather data are incorporated in this thesis due to the drastic seasonal changes and spatial variation that Buffalo experiences every year. In a typical year at Buffalo Water, the number of assets that require reactive repair and corrective maintenance is noticeably greater in the winter than in the summer. These repairs are often generalized as being related to freezing temperatures and accumulation of snow. In this thesis, weather data from two sources were used to determine total snow accumulation as well as dates where snow accumulation may have been greatest.

Total snow accumulation was determined using the PRISM dataset. PRISM data are available from Oregon State University at a 4km grid scale. Information within each grid is developed through interpolation of surrounding daily weather station data and uses a model that considers the effects of elevation, slope, and wind direction (Daly and Bryant 2013). PRISM data are utilized in this study due to the availability of daily information in the dataset. PRISM is cited in studies that use the dataset for seasonal patterns over several years as well as demonstrating climatological seasonal cycles at temporal scales as small as one day (Kim et al. 2016; Sawyer and Stephen 2014).

To determine specific dates where snow accumulation may have been the greatest, information on severe storms is extracted from the Storm Events Database managed by NOAA. The database includes information on storms that were considered a significant weather event. These events include blizzards, extreme cold or wind chill, heavy snow, lake effect snow, winter storms, and winter weather. NOAA data are used to determine dates when winter weather conditions were the most severe in the Buffalo area. Those specific dates will undergo further data analysis.

2.5 Geospatial Analysis Methods

GIS technology is an important component of the future of the water industry. Continued analysis will assist with managing infrastructure capital assets to ensure that budgets are met and resources are properly allocated. An asset management system allows municipalities to rank various assets based on conditions, helping to build a strong decision support model. These models often consider strategy, risk management, asset inventory, customer satisfaction, and asset condition, and incorporate a business model (Booth and Rogers 2001).

The current focus of water asset management is on underground water mains. Since much research focuses on underground water mains, there exists a lack of geospatial analysis on hydrants; therefore, it is relevant to observe how other industries manage their geospatial data for analysis. This is related to asset management in the water industry because various utilities track both above and below ground assets. For example, electric utility companies often have both above and below ground assets. Companies utilize data from asset management for condition monitoring and reliability analysis to determine where to allocate resources. Through processes such as smart grid technology and wireless sensors, these utilities are implementing an asset management system while collecting geospatial data through state-of-the-art technology (Bahramirad et al. 2015). In a similar way, these techniques can be utilized in water distribution systems by using wireless devices that can track information indicating where low pressure or leaks exist. Incorporating information like this into a geospatial database would provide valuable information to the water industry (Liu and Kleiner 2014).

Hot spot analysis has been performed in many fields, contributing to spatial analysis research on many topics such as crime, disease, traffic accidents, store locations, and environmental incidents (Herrmann 2015; Kumar et al. 2014; Lee and Lim 2008). Motor vehicle incidents have been extensively analyzed based on many factors that may contribute to each incident. Data may include detailed information such as location, date, time, vehicle type, cause, and severity of damage. In one specific study, spatial autocorrelation was performed for each type of traffic accident. The analysis demonstrated spatial and temporal variations in the hot spots when different parameters were considered (Prasannakumar et al. 2011). A similar technique could be used to further understand the need for fire hydrant maintenance; however, in this thesis, only hot spot analysis will be performed. Visual analysis will be used to determine the association of damaged hydrants with weather.

Chapter 3 Data and Methods

This chapter explores the data and methods used in this thesis project. Included is a review of the data collection and data cleanup process necessary to utilize the various datasets. This section includes a discussion on specific methods for working with City of Buffalo data, PRISM data, and NOAA data. Following the discussion of data, this chapter will explain the various analysis methods used to determine if there is a difference in the number of hydrant incidents in south Buffalo versus north Buffalo as well as if weather is a factor in the number of hydrant maintenance incidents.

In an effort to develop better preventative maintenance techniques, this study is necessary to determine what factors impact fire hydrant damage and maintenance, provide an increased level of service to the customer, high water quality, and ultimately to save money or allocate funds to areas where it is most needed. This study considers spatial and non-spatial parameters that have the potential to impact the results. Hot spot analysis is used to locate clusters of fire hydrants where maintenance is required. Hydrant damages are summarized based on predefined characteristics, and statistical techniques are used to determine whether or not these characteristics are significant. On dates when hydrant damages occur more often, weather is analyzed to determine if the weather potentially impacted the need for repairs. Likewise, on days where severe storms occurred, hydrant damages are assessed to determine whether there was an increase in damage frequency. Understanding and identifying susceptible areas and factors that contribute to hydrant damages may be the first step to develop effective maintenance management.

Chapter 3 is comprised of three sections. The first section includes a detailed discussion of the data that was needed for this study. The second section considers the research design and techniques used to obtain results. These techniques explain how hot spot analysis is used to focus on specific areas in Buffalo. This section also includes a discussion on correlation techniques. The third section includes a detailed description of techniques and procedures that are used to determine the outcomes.

3.1 Data Requirements and Sources

Data are required from several sources for this project. Hydrant asset information and maintenance information is obtained from Buffalo Water. Weather information is obtained from the PRISM Climate Dataset as well as NOAA. Background and basemap features are obtained from New York State Information Technology Services and Buffalo Water.

Veolia, managing Buffalo Water, has maintained data on hydrants, as well as hydrant damages and maintenance in Buffalo since 2010. The data corresponding to these assets and events are stored in a geodatabase. Data for hydrants are exported out of InfoNet to a shapefile, while data regarding hydrant maintenance and repair are exported as an excel document. Locations are assigned to hydrant maintenance based on the location of the hydrant asset that work order is associated with. Data for hydrants as well as hydrant maintenance were acquired on July 27, 2016. Data are updated daily, and were last updated on July 27, 2016.

Hydrant data were collected in NAD 1983 State Plane New York West. The original data were developed in CAD maps at a 1:300 scale, and then georeferenced to locations based on hydrant inspection districts. Currently, hydrants are mapped to within five feet of their physical locations. Hydrant data includes location, size of main (broken into three categories), and location description information. The size of the main the hydrant is off of is indicated based on the hydrant cap color. Red capped hydrants are off of a six or eight inch main, blue capped hydrants are off of a ten or twelve inch main, and white capped hydrants are off of a sixteen inch or greater main, with mains as large as sixty inches in Buffalo's distribution system (Figure 2). Some hydrant data includes date installed and manufacturer; however, this information was not documented on enough assets to include in the study.

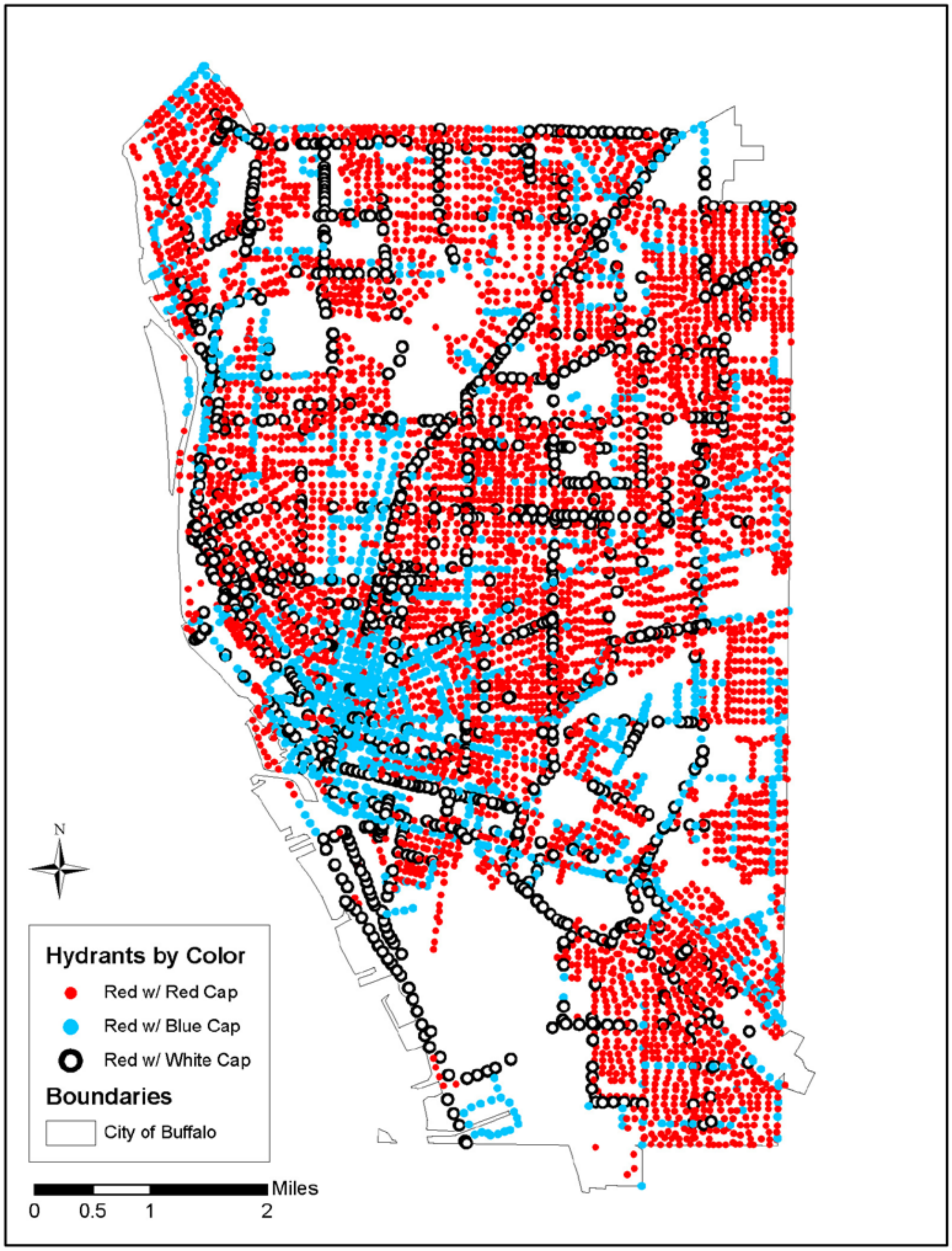

Figure 2. Hydrant distribution, represented by cap color. N = 7,940.

Maintenance information from July 1, 2011 to June 30, 2015 was used in this study, as the initial procedure for documenting data and collecting work order information was fully implemented by July 1, 2011. To maintain data in annual intervals of time, information beyond June 30, 2015 will not be used in this study. When Veolia implemented work order management for hydrant maintenance and repair, they required strict recording of data including date incident reported or repair started, date completed, type of repair, cause of incident, and verification of hydrant data such as location, cap color, and manufacturer. In summer, routine maintenance occurs when hydrants are greased and operated per scheduled inspection districts. In the winter, each hydrant in Buffalo is visited numerous times to inspect for water in the barrel. Water in the barrel must be pumped out so the hydrant does not freeze and remains operational. If a hydrant is found with frozen water in the barrel, a work order is created. Additionally, if a hydrant is found to be non-operational or malfunctioning at any time, the information is documented and a work order is created. Work order information, whether planned maintenance or reactive repair, is always associated with an asset and cannot stand alone.

Additional data obtained includes weather data from the PRISM dataset from Oregon State University and severe storm information from NOAA. To generate information on precipitation in Buffalo, PRISM data were summarized based on individual events. The weather data were used in conjunction with dates of hydrant maintenance to determine whether or not an increased quantity of hydrants required repair in areas where precipitation was higher. PRISM data were downloaded in BIL format, the raster format commonly used in climatology and the native format of the PRISM model. PRISM data are available at a 4km grid cell resolution in GCS North American 1983. PRISM data were obtained on July 27, 2016, and according to metadata, it is updated as needed, with no specific date of last update. The data contains daily precipitation in centimeters.

NOAA data were used to determine dates where severe storms were reported in the Buffalo area. NOAA severe storm information is reported at the county level, indicating whether or not the storm was in the northern or southern part of Erie County. NOAA data were first analyzed in this thesis for dates where events occurred in Buffalo and not just at the county level. The database was last updated in July 2016, and was obtained on July 5, 2016. On dates where severe storms occurred, PRISM data were utilized for precipitation totals.

The base maps generated include state and municipality boundaries obtained through the New York State GIS Clearinghouse, from New York State Information Technology Services GIS Program Office. Buffalo Water also provided hydrant district information, which was used in conjunction with PRISM data to assist with the north Buffalo / south Buffalo delineation.

All data were projected into NAD 1983 State Plant New York West for spatial analysis. Data are summarized in Table 1.

Table 1: Data Summary

Data	Date Acquired	Date Last Updated	Accuracy / Missing Data	Format
Hydrant Dataset	July 6, 2016	July 27, 2016	Missing information on date installed and model	Shapefile
Hydrant Work Orders	July 6, 2016	July 27, 2016	-	Excel
Hydrant Inspection Districts	July 5, 2016	July 5, 2016	-	Shapefile
PRISM Climate Dataset	July 27, 2016	Unknown	4 km grid cells	BIL (raster)
NOAA Storm Events	July 5, 2016	July 2016	-	Excel
NOAA Weather Stations	July 5, 2016	July 2016	-	Excel
City and Town Boundaries	May 3, 2016	Unknown	1:24,000-scale positional accuracy	Shapefile
New York State Shoreline Boundary	May 3, 2016	Unknown	1:24,000-scale positional accuracy	Shapefile

3.1.1. Dependent Variable

The dependent variable of this study is the likelihood that hydrant maintenance is required at any given hydrant or location. This information is currently available for documented hydrant maintenance that has already occurred. By using a summary of existing data and analyzing the independent variables, visual analysis was used to determine if there is a likely correlation for where hydrant damages exist.

To determine what maintenance was required, the work orders were analyzed based on three categories: hydrant replacement, hydrant repair, or routine maintenance. Finally, to explain what caused the required maintenance, the work order has information indicating if the hydrant was hit by a vehicle or if the maintenance was required due to failure to function properly upon operation or observation. There is also information indicating hydrants that are found frozen, and therefore non-operational in the winter, but this dataset is tracked by hydrant district and month.

Since the dataset does not contain specific locations of hydrants or dates the hydrants were found frozen, these numbers were not used for analysis in this study. Only the hydrants that have been repaired or replaced as a result of being hit by a vehicle are utilized in analysis that compares occurrence location to weather data. Data exclusions will be discussed further in section 3.2.

3.1.2. Independent Variables

The independent variables contributing to the likelihood that a hydrant will require maintenance includes information specific to the hydrant and the location of the asset. In this study, the following hydrant characteristics were considered: spatial location of hydrant, spatial location of hydrant damages, location in north or south Buffalo, severe storm information, and cumulative precipitation during storm events. Hydrant work orders were analyzed for additional data, including the date of the event, what maintenance is required, and what caused the required maintenance. The date of the event was simplified into the summer or winter season. Seasons are used to distinguish what type of preventative maintenance is occurring (summer or winter maintenance) as well as what is indicative of typical weather patterns. In Buffalo, parking restrictions to facilitate snow removal are put into effect from mid-November through the first of April. As a result, a similar time period of the first of November through the end of March is considered winter for this study.

3.1.3. Other data information

Results from the study were displayed on a map of Buffalo, using a fishnet grid that was developed to demonstrate where PRISM grids are located. The fishnet grid is comprised of 4km cells that were used to assist with generating this study's north Buffalo and south Buffalo boundaries. Displaying the final results on this map may indicate areas of Buffalo that lack hydrant maintenance programs or it may indicate an area that requires additional attention due to heightened risk of required maintenance.

3.2 Research Plan and Design

Determining what characteristics may contribute to hydrant maintenance relies heavily on information documented in the asset management system. When developing the research design for studying hydrant damages, it was apparent that seasonal attributes affect the quantity and location of work orders. Due to the large size of the data set, a subset of data was used. For the purpose of this study, hydrant repairs and replacement were summarized by season, and only winter hydrant maintenance as a result of vehicle damage was analyzed and compared to weather data.

3.2.1. Data Summary

Data were summarized based on predefined characteristics. These characteristics include specific location of the asset, general location of incident (north Buffalo or south Buffalo), type of incident, and date of incident. This summary is used to demonstrate differences between hydrant locations and where hydrant damages occurred. Hydrant damages are further parsed between seasons as well as locational differences between north Buffalo versus south Buffalo.

3.2.2. Hot Spot Analysis

Hot spot analysis was used to determine locations where hydrants are clustered as well as areas where hydrant maintenance incident rates are statistically significant for maintenance that resulted after a hydrant was struck and damaged by a vehicle. The hot spot analysis determines areas that have either high or low values of spatial clusters. Data points and their spatial relationship to neighboring features are evaluated in the hot spot analysis. Resultant hot spots based on overall hydrant locations as well as incidences that occurred in the winter as a result of vehicle damage were created.

3.3 Procedures and Analysis

Ultimately, the analysis performed will be used to determine whether or not specific weather-related events impact the likelihood that specific hydrants or hydrants in a designated area would be more likely to require maintenance or repairs. The analysis for this thesis project commenced with obtaining the necessary data on hydrant maintenance and weather-related events. Information was summarized and analyzed in several steps.

3.3.1. Visualization and Summary of Data

This thesis begins with an initial visualization and summary of data. The study area is defined as Buffalo, NY, located on the eastern shore of Lake Erie. The study area is mapped at a smaller scale to demonstrate the spatial relationship Buffalo has to Lake Erie, as this plays an important role in weather patterns (Figure 1). All hydrants were mapped out in the study area and visualized using hydrant cap color to demonstrate overall hydrant distribution within the study area (Figure 2).

Following initial visualization, data were summarized based on the total number of hydrants, total number of hydrant damages in the system and their general location in regards to north and south Buffalo. The distinction between north and south Buffalo was moved further north of what is typically considered to be south Buffalo due to the ability to distinguish between hydrant districts as well as PRISM grid data. The total number of hydrants that were located in north Buffalo and south Buffalo were compared to determine the difference in distribution throughout Buffalo. Hydrant damage occurrences were summarized based on frequency per day.

3.3.2. Parse Vehicle Damages and Seasonal Occurrences

After reviewing the total number of hydrant maintenance work orders, hydrant maintenance work order data in Excel data format was further parsed to indicate the number of repairs or replacements that result from a hydrant being struck by a vehicle. Both the total number of work orders and the work order repairs that result from vehicle damage were divided into two seasons: summer (April 1 to October 31) and winter (November 1 to March 31). Winter hydrant repairs that resulted from a hydrant being struck by a vehicle are then visualized with the north Buffalo and south Buffalo boundary lines.

3.3.3. Hot Spot Analysis

Hot spot analysis was executed using all hydrant locations. The input is the data file that included all 7,940 hydrants in the distribution system. The same analysis was performed on the hydrant damages that occurred in winter as a result of vehicle damage during the study period. Hot spot analysis was performed using a grid, normalized by hydrant count per grid. Only hydrant count per grid is a factor for normalization, and specific hydrant characteristics were not used to weight results. Hot spot analysis was also performed on annual subsets of hydrant damage data that occurred in winter as a result of vehicle damage. The outputs for each year were subsequently compared to each other to determine whether or not hot spots occur in similar areas during different years.

3.3.4. Acquire and Modify Weather Data

NOAA data for severe storm events are downloaded at a county-level scale. Data were then parsed for events that actually impacted Buffalo, and not the areas outside of the Buffalo boundary. Severe storm events are also selected for days where at least four hydrants were damaged. If fewer than four hydrants required repair after an event, it was difficult to observe spatial distribution during individual storm events.

PRISM data were downloaded as daily precipitation data for the time period of the study. PRISM data are only downloadable as a raster data set, with separate layers for each day that cover the contiguous United States of America. As a result, information was parsed out by days, based on the frequency of damages or severe storm event discussed below in section 3.3.6. After specific days were selected, PRISM data were converted from raster grid to point data. A grid outline of the PRISM data were developed to include all grids that fall within any part of Buffalo boundary limits. Clip analysis was performed on each individual date to limit the data to that of the study area. Following the clip, point data for each event period (events typically spanned multiple days) were added together for a cumulative precipitation total per event. Cumulative precipitation point data for each event period is spatially joined to the grid outline, creating several grid files that demonstrated cumulative precipitation. Finally, the resulting vector grid data for each layer was displayed using natural breaks.

Natural breaks were chosen to visualize the cumulative precipitation as a means to allow comparison of the high and low precipitation areas of each individual event, rather than comparing all events to each other. If all events were displayed with the same symbols, a severe event that produced between six and ten centimeters throughout Buffalo would appear as if very little snow as produced if it was compared to the worst storm, which produced nearly one hundred centimeters of snow. By using natural breaks, it is easy to observe what areas of Buffalo receive the most snow during each event.

3.3.5. Group Frequency and Weather Events

The frequency of hydrant damages was further analyzed and grouped into individual events. Frequencies of four or more damages were considered, and damages from consecutive days were combined into one event if separate events of four or more damages occurred within three days of each other. The three days have been selected based on the expected lag time between when snow falls and how long it may take for a hydrant damaged by a vehicle to be reported. Grouped events were then compared to cumulative PRISM data for the days of the event as well as three days prior.

The NOAA dataset was parsed for several severe weather occurrences. For the winter season, the following severe weather events were considered in analysis: blizzard, heavy snow, ice storm, lake-effect snow, winter storms, and winter weather. The Storm Events Database includes records where the storm was considered a significant meteorological event, when the event generated media attention for being a rare occurrence for that time and/or location, and events when the storm had a great enough intensity to cause loss of life, injuries, significant property damage, or caused a disruption to commerce. NOAA severe storms are grouped together in a similar way as the frequency events. If storms fall within three days of each other they are grouped into one event. Work orders were parsed based on event as well as three days following the end of the storm date. The three day lag time was again selected as a representation of the time it may take for an incident to be reported. These groups of work orders were then compared to cumulative PRISM data for the defined time period of each storm event.

3.3.6. Correlation of Cumulative Precipitation with Increased Frequency of Damages and Weather Events

The same method of visual analysis was used to compare for both results. The location of hydrant damages during each event was compared to the locations within Buffalo where the highest accumulation of snow was present. Visually, areas that appear red received the most snow during an event, while areas that appeared green received the least snow. The visual analysis observation was made to determine if the majority of damages appeared in areas that were red or dark orange. Due to the lack of data available for regression analysis, Spearman's Rank Correlation was used to determine significance between frequency and cumulative precipitation. The non-normality of the data required the use of Spearman's Rank Correlation instead of Pearson's r for this analysis.

Chapter 4 Results

This chapter reports the outputs of analysis performed to test the hypotheses that there is a difference in the number of hydrant damages incurred by result of a vehicle between north and south Buffalo and that these damages may be affected by weather. Section 4.1 considers analysis that was performed on general work order occurrences, analyzing the type of work order and general location (north Buffalo versus south Buffalo). Section 4.2 concentrates on hot spot analyses for various subsets of data. Sections 4.3 and 4.4 consider work orders in relation to PRISM and NOAA weather data. Section 4.3 focuses on the weather that occurred just prior to dates where the rate of hydrant replacement and repair as a result of vehicle damage is increased. Section 4.4 focuses on dates when NOAA reported severe winter storms, and compares the locations of high snow accumulation to work order occurrences at those locations.

4.1 Work Order Overview

Although work is required to repair hydrants all year, corrective maintenance (repair and replacement) tends to increase in the winter. Table 2 shows the occurrence of work orders, summarized by total number and seasonal occurrences. It is also broken down into the number of hydrant damages that were the result of being struck by a vehicle, as a total number as well as broken down by season.

Table 2: Total Number of Hydrant Repairs

	Total	Summer (April 1 through October 31)	Winter (November 1 through March 31)
Total Number of Hydrant Maintenance Work Orders	1392	747	645
Hydrants Repairs as a Result of Damages Incurred by Vehicles	875	381	494
Percent / Ratio of Vehicular Damages to All Repairs	63%	51%	77%

4.1.1. North Buffalo vs. south Buffalo Hydrants

Due to Buffalo's location on the east coast of Lake Erie, cold winter temperatures, and wind patterns, Buffalo is considered to be in the snowbelt. The snowbelt is essentially a weather pattern that helps distinguish the difference between north Buffalo and south Buffalo, creating climatically different locations within a couple miles of each other. During winter storms, south Buffalo often experiences greater snow accumulation than north Buffalo.

Using the north Buffalo / south Buffalo delineation developed for this thesis, there are 4,945 hydrants in north Buffalo while there are 2,995 in south Buffalo. In addition to having fewer hydrants, south Buffalo also has a smaller area. North Buffalo is approximately 25.2 square miles while south Buffalo is approximately 18.6 square miles. Of the 18.6 square miles in south Buffalo, about 2.6 square miles in the south west part of Buffalo are used by industrial companies. These companies are responsible for maintaining their own hydrants and therefore asset information, location, and maintenance is not collected by Buffalo Water or stored in the geodatabase.

4.1.2. North Buffalo vs. south Buffalo Work Order Occurrences

An analysis of the data indicates that 239 hydrants were damaged by vehicles in the winter in north Buffalo while 255 were damaged in south Buffalo (Figure 3). Not only were more hydrants damaged in the winter south Buffalo by number, but with fewer hydrants in the area, the rate of damage was much greater.

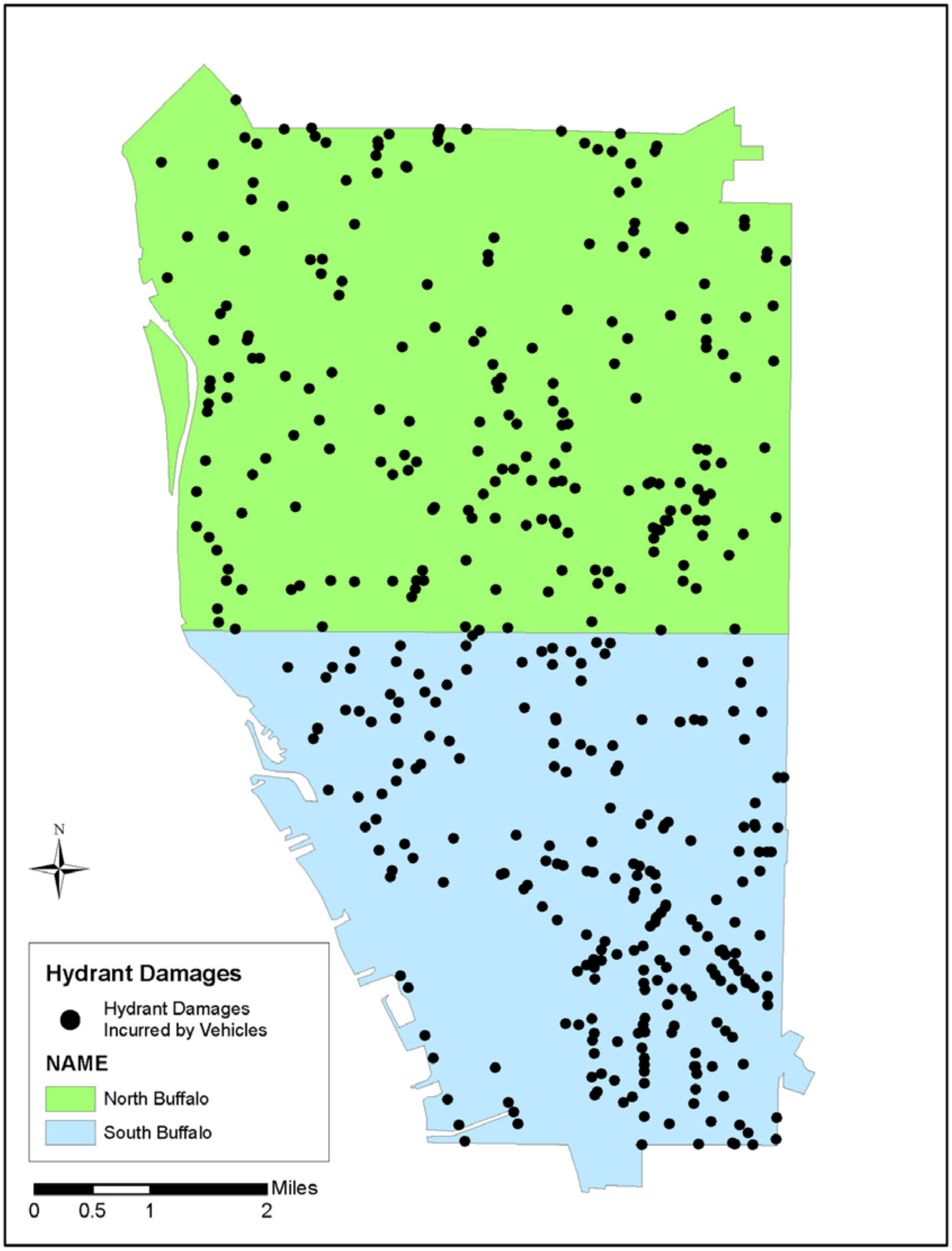

Figure 3. Hydrant damages incurred by vehicle visualized over north and south Buffalo, in winter months. N = 494.

4.2 Hot Spot Analysis

In addition to the general hydrant work order information, a hot spot analysis was performed on the entire hydrant dataset to obtain information on how the assets are distributed throughout the study area (Figure 4). Hot spot analysis demonstrated a large hot spot in the downtown Buffalo area that continued to extend east. The analysis also showed cold spots in south Buffalo, as well as a cold spot in the east part of Buffalo near the north-south border.

The large cold spot in south Buffalo has few hydrants because the land is primarily industrial complexes that maintain their own fire hydrants or have installed fire prevention mechanisms into buildings, such as internal emergency sprinkler systems. Additionally, on the western border of Buffalo, near Lake Erie, hydrants are scarce due to limited land use on the water. The small cold spot at the very northeastern part of Buffalo is not only on the municipal border, but also the location of a large college campus. Hydrants found in college campuses are not maintained by Buffalo Water, but by private management companies or property owners.

Hot spot analysis was performed on winter work orders that indicated hydrants were damaged by a vehicle for the duration of the study. The hot spot analysis was normalized based on the number of hydrants in each grid cell. Locations where there were no hydrants (and therefore no damages) are represented as empty (white) cells. There is a relatively large area with a hot spot in south Buffalo. This hot spot does not coincide with the significantly clustered hydrant distribution. Additionally, there was one small hot spot of damages in the north-central part of Buffalo. There are no hot spots present in the downtown area, and there are no cold spots (Figure 5).

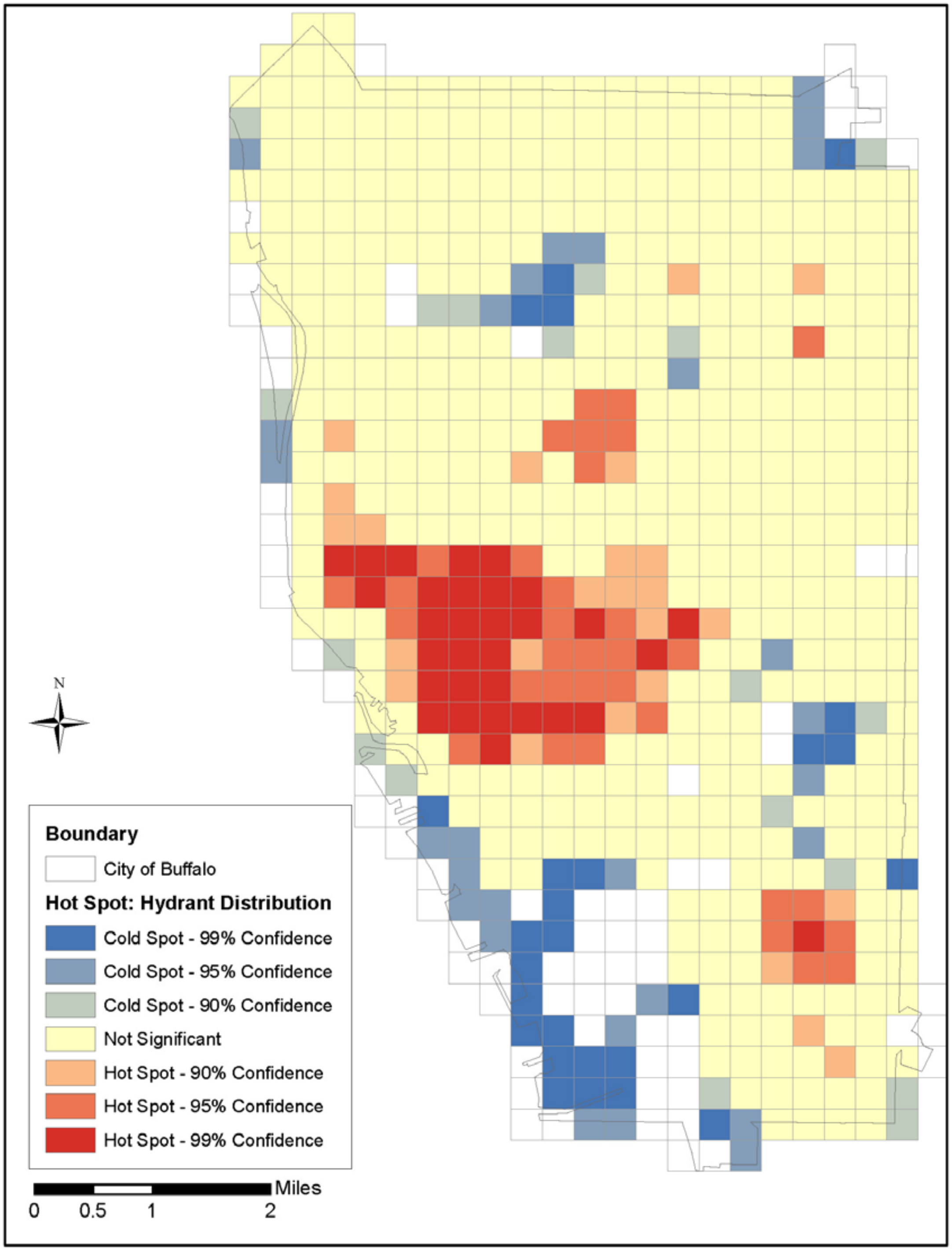

Figure 4. Hot spot map of hydrant locations in Buffalo, NY. N = 7,940.

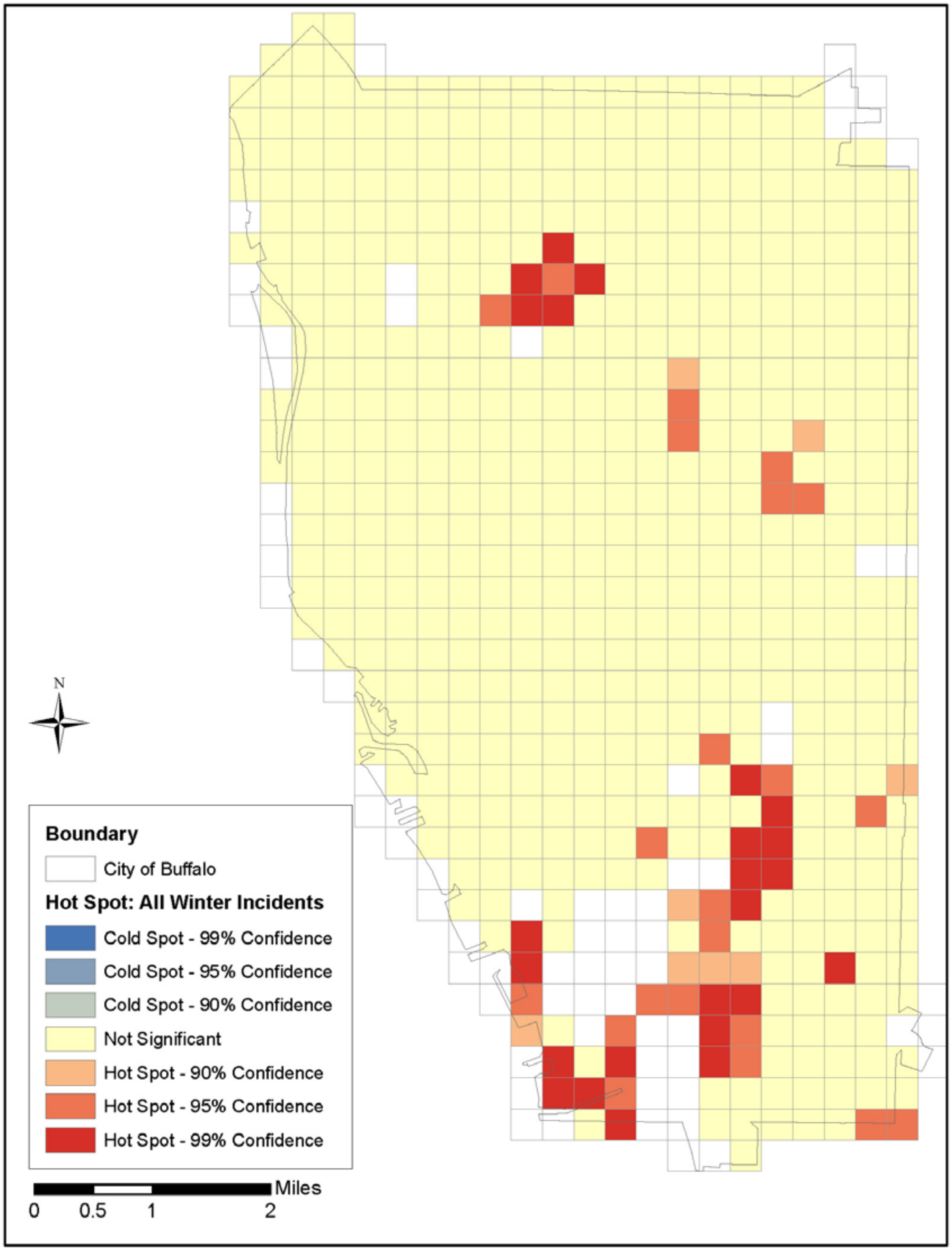

Figure 5. Hot spot map of hydrant damages in winter months from July 1, 2011 to June 20, 2015 (winter months). N = 494.

Additional hot spot analyses were performed on annual subsets of data for winter months. In winter 2012 to 2013, there were scattered hot spots throughout the city, primarily scattered through north Buffalo and south Buffalo. Again, there were no cold spots present, and no hot spots located in the downtown area (Figure 6). Hot spot analysis was also performed for winter 2014 to 2015. This winter, there was a very large hot spot in south Buffalo, covering nearly the entire area. There were no hot spots in the downtown area, and no cold spots present throughout Buffalo (Figure 7).

Weather patterns during winter 2014 to 2015 demonstrated significantly higher snow accumulation during November 2014 (results presented in section 4.3). The number of damages associated with that storm is high. As a result, additional hot spot analysis was run on a subset of the dataset, for the winter months of November 2011 to March 2014 only. Again, the resulting hot spot map shows no cold spots and no hot spots in down town; however, there are only small hot spots scattered through south Buffalo, and a slightly larger hot spot in north Buffalo (Figure 8).

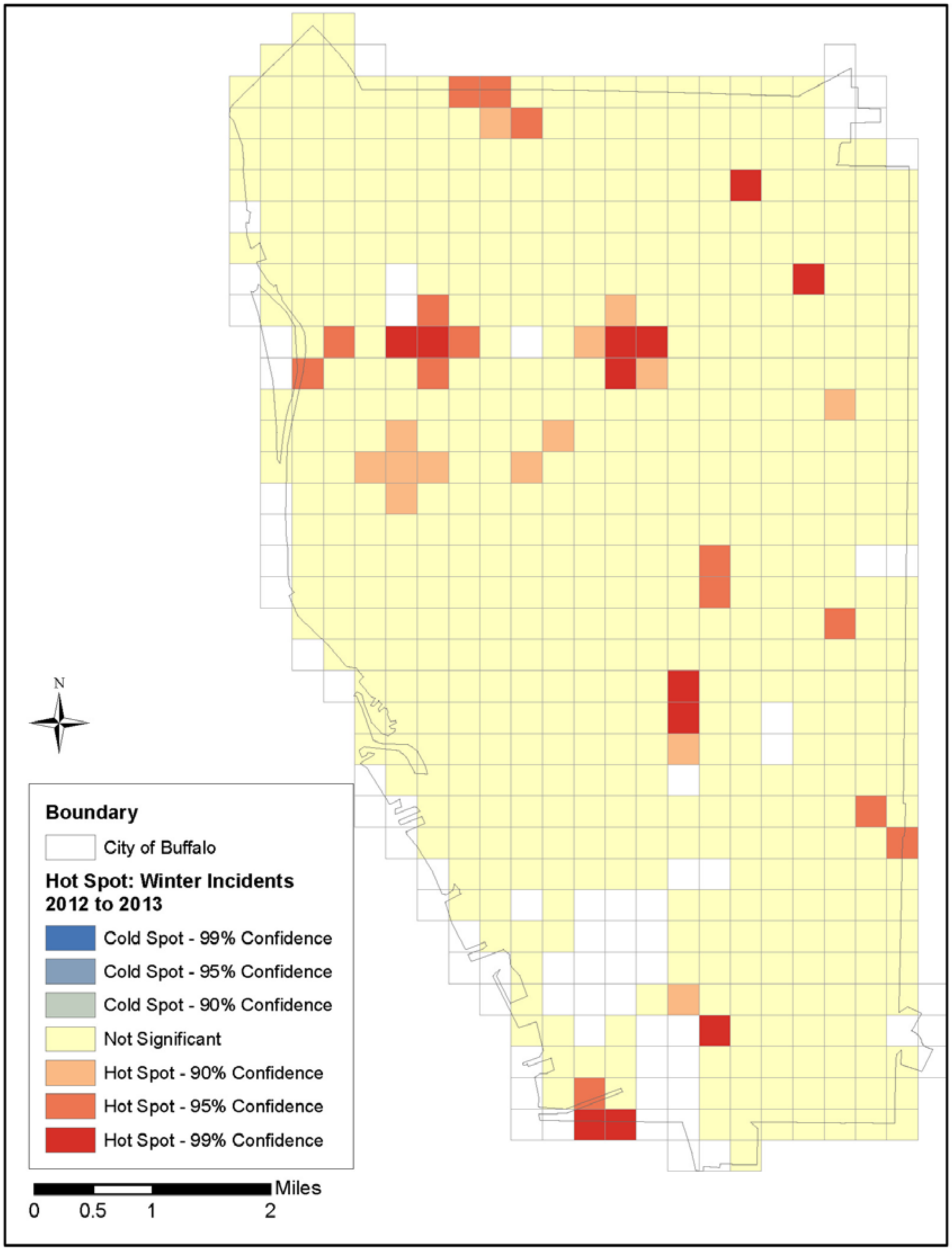

Figure 6. Hot spot map of hydarnt damages during winter 2012 to 2013. N = 68.

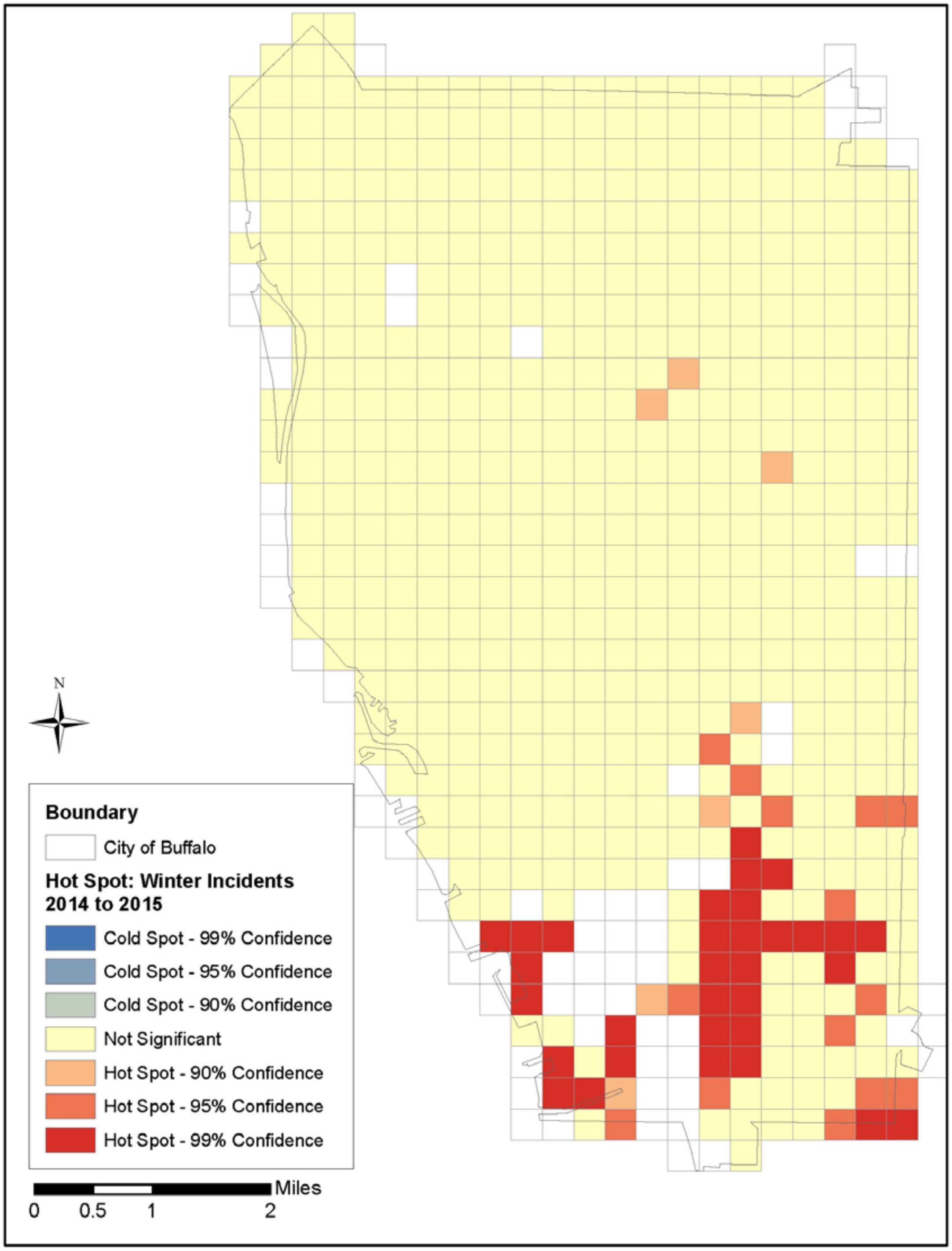

Figure 7. Hot spot map of hydrant damages during winter 2014 to 2015. N = 245.

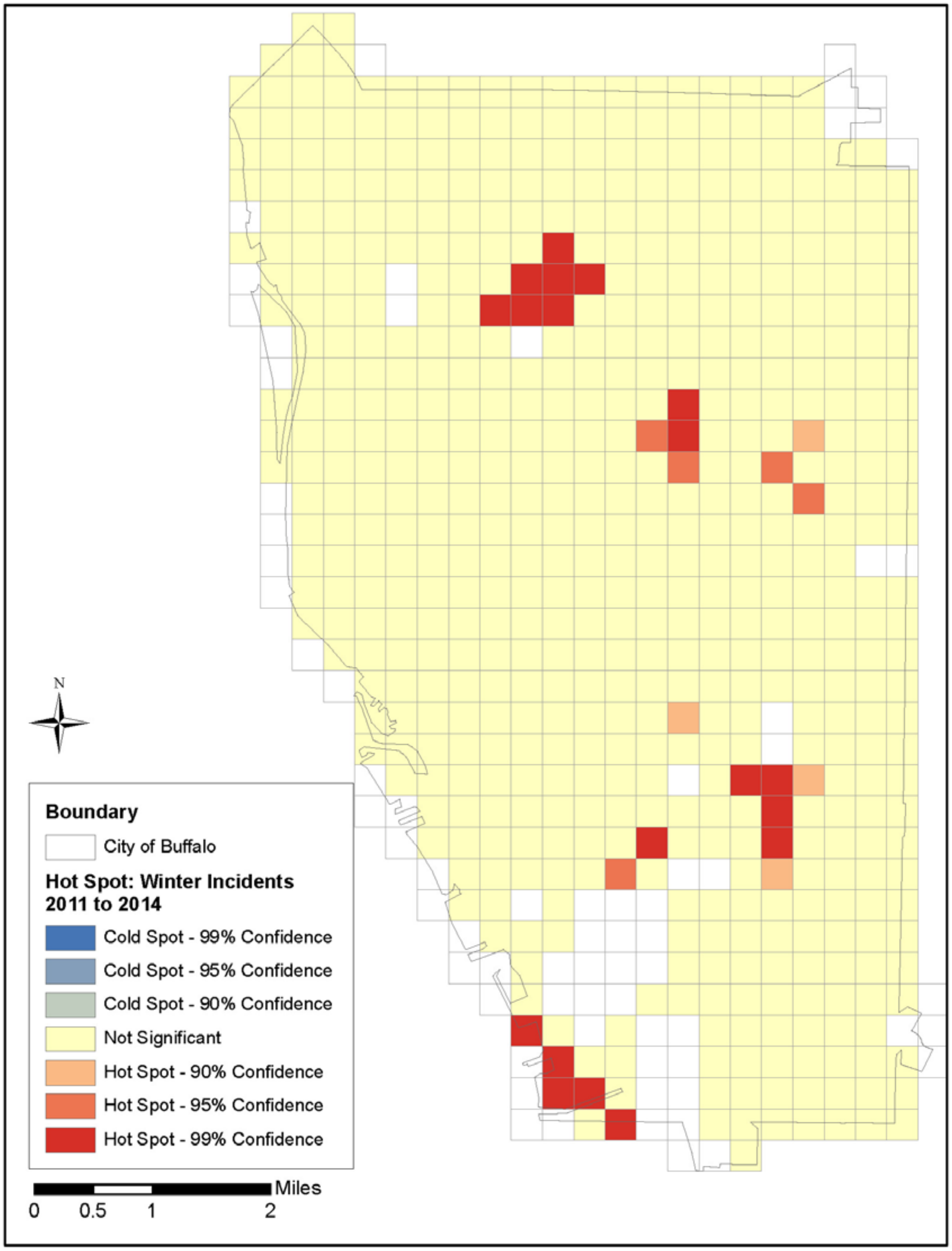

Figure 8. Hot spot map of hydrant damages during winter months November 2011 to March 2014. N = 249.

4.3 High Frequency Occurrences

Hydrant damages incurred by motor vehicles were assessed to determine what days showed an increased occurrence of hydrant damages. On individual days where an increased number of incidents occur, it is possible that a correlation can be determined based on weather conditions.

Out of 600 possible days in the winter months (November through March) in the four-year study, hydrant damage by a vehicle occurred on 274 days. On 256 of the 274 days, there were one, two, or three incidents that occurred; however, there were sixteen individual days where four or more incidents occurred (Figure 9). Two years are zoomed in and displayed more closely to see differences. Winter 2012 to 2013 was comparable to a more standard year in Buffalo, with a few larger winter storms and only a few days with three or more incidents reported (Figure 10). Winter 2014 to 2015 had atypical snowfall in November that accumulated nearly overnight, and a cold February that allowed snow to remain on the ground for longer than usual (Figure 11). The initial snowfall in November was followed by a peak in reporting of vehicular damages to hydrants (N = 24 on November 23 and N = 20 on November 25).

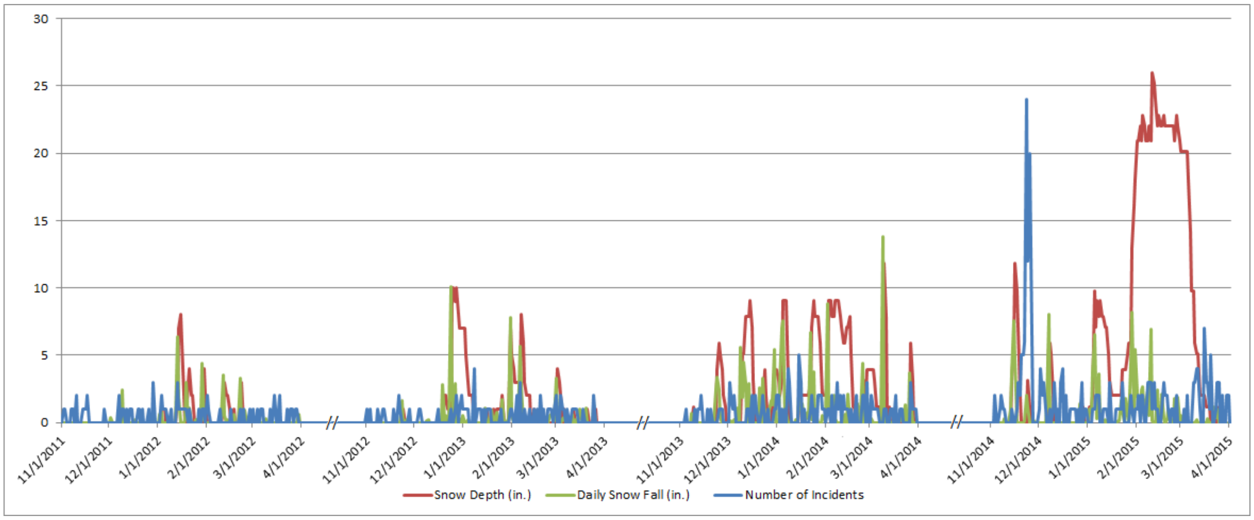

Figure 9. Hydrant damage incidents with cumulative precipitation and daily snow fall, 2011 to 2015 for winter months only. Days reporting one incident = 176; days reporting four or more incidents = 16.

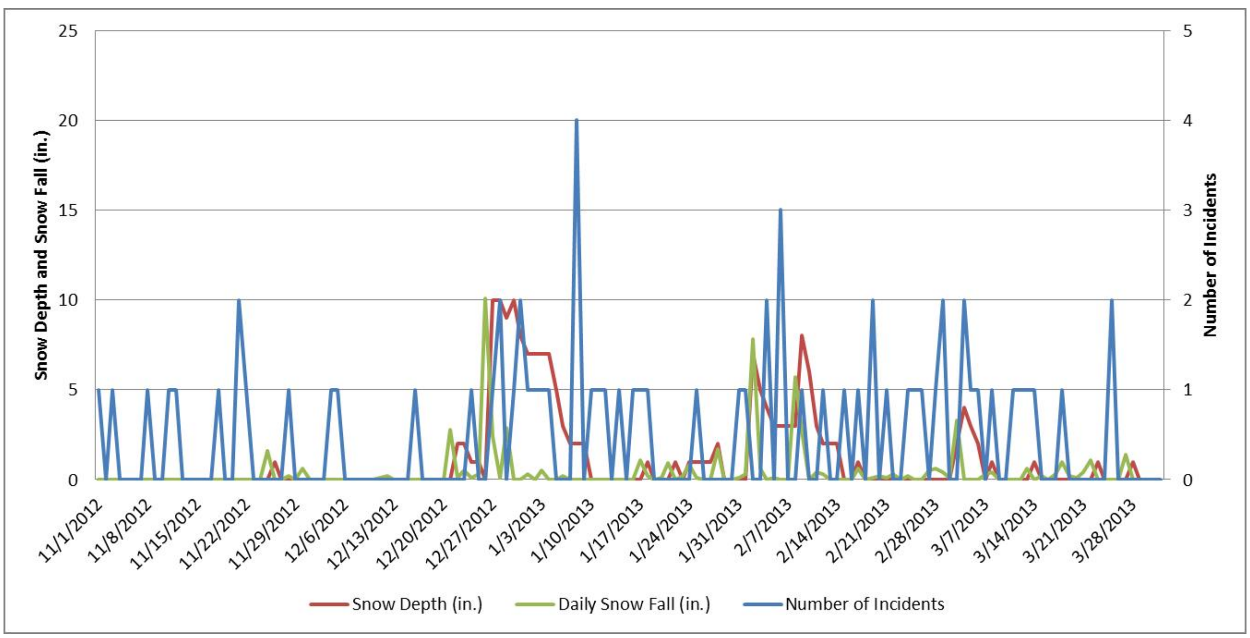

Figure 10. Hydrant damage incidents with cumulative precipitation and daily snow fall, by date, for winter of 2012 to 2013, days reporting more than two incidents = 2.

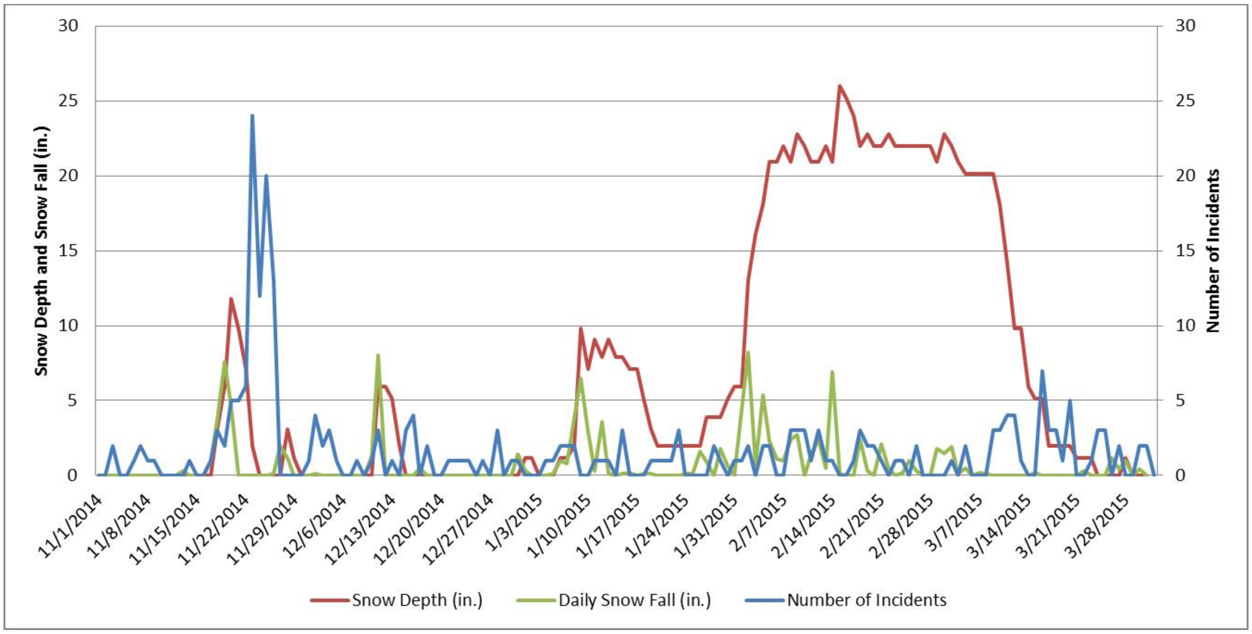

Figure 11. Hydrant damage incidents with cumulative precipitation and daily snow fall, by date, for winter of 2014 to 2015, Buffalo experienced higher than normal snowfall that accumulated quickly in November. In seven days, N = 85.

4.3.1. Events

Severe storm data from NOAA was parsed for storms where at least four incidents occurred. The result was sixteen severe storm events between July 1, 2011 and June 30, 2015. These sixteen storms were combined into nine events, for analysis. An event consists of a series of days where the frequency of incidents was greater than four within three days of each other. For example, during a harsh winter storm in November 2014, 85 hydrants were damaged by a vehicle over seven days (Table 3). Since each day with a high frequency occurred within three days of the next, they make up one event for the purpose of this study. All events are listed in Table 4.

Table 3. Dates and frequency per day for event from November 20 to 26, 2014

Frequency	Date
5	11/20/2014
5	11/21/2014
6	11/22/2014
24	11/23/2014
12	11/24/2014
20	11/25/2014
13	11/26/2014
85	Total

Table 4. All events analyzed with a frequency of four repairs or greater

Frequency	Date Range of Event
4	1/8/2013
4	1/8/2014
5	1/15/2014
85	11/20/2014 to 11/26/2014
4	12/2/2014
4	12/16/2014
8	3/11/2015 to 3/12/2015
5	3/16/2015
7	3/20/2015

4.3.2. Events and Weather

When considering the weather that occurred during high frequency events, I looked at the weather on the days of increased frequency of reported damages as well as the three days before, with the assumption that there would be a delay in time from the first snowfall until the snow accumulated. Additionally, after accumulation, snow clearing would have to occur.

Using the PRISM data, precipitation of the three days preceding the initial high frequency event, along with the precipitation for the date of the high frequency was extracted. The summarized results of each event are shown along with the location where damages occurred in that time period (Figures 12 through 15).

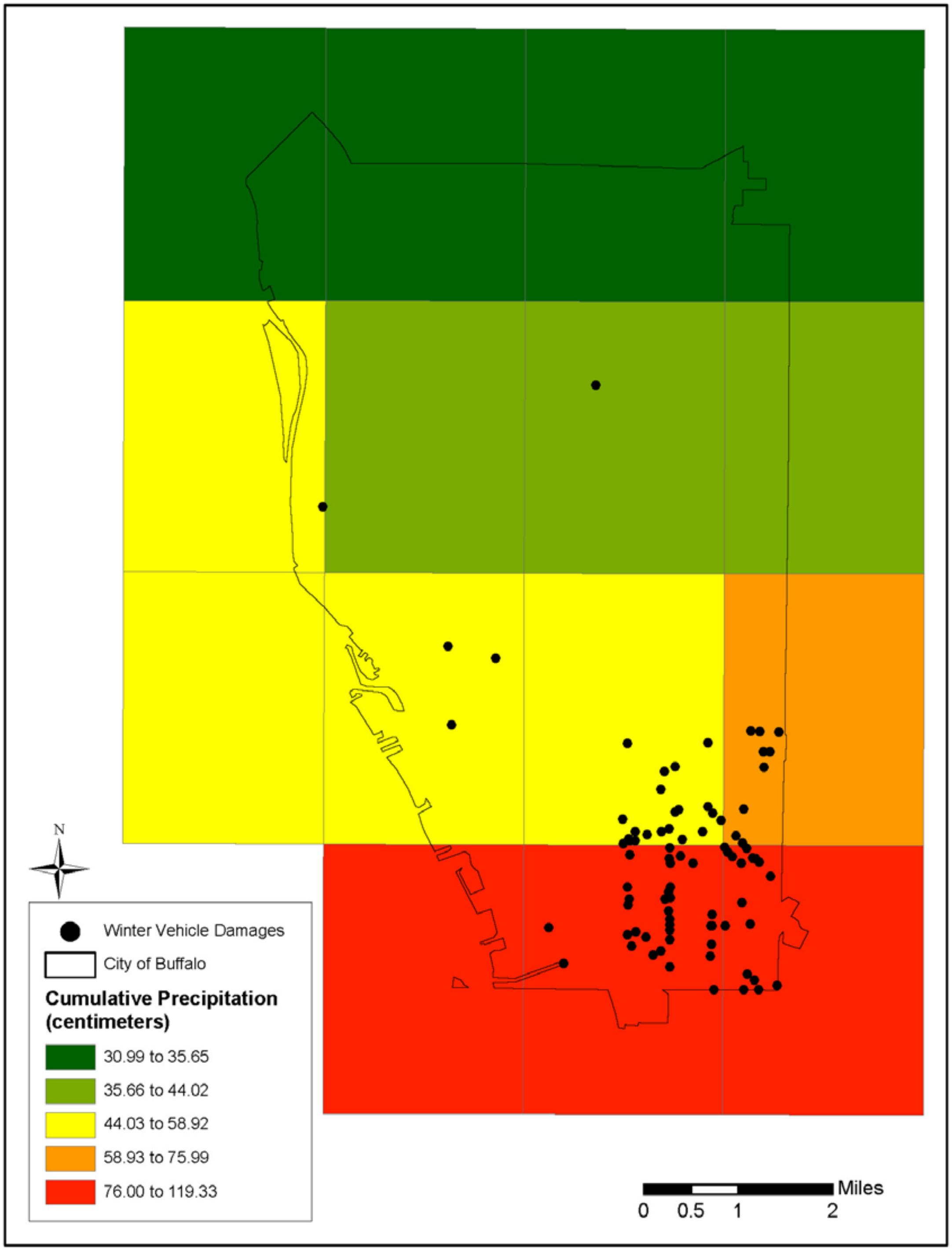

Figure 12. Hydrant damage incurred by vehicles that occurred between November 20 and November 26, 2014 (N = 85) and corresponding cumulative precipitation data from November 17 through November 26, 2014.

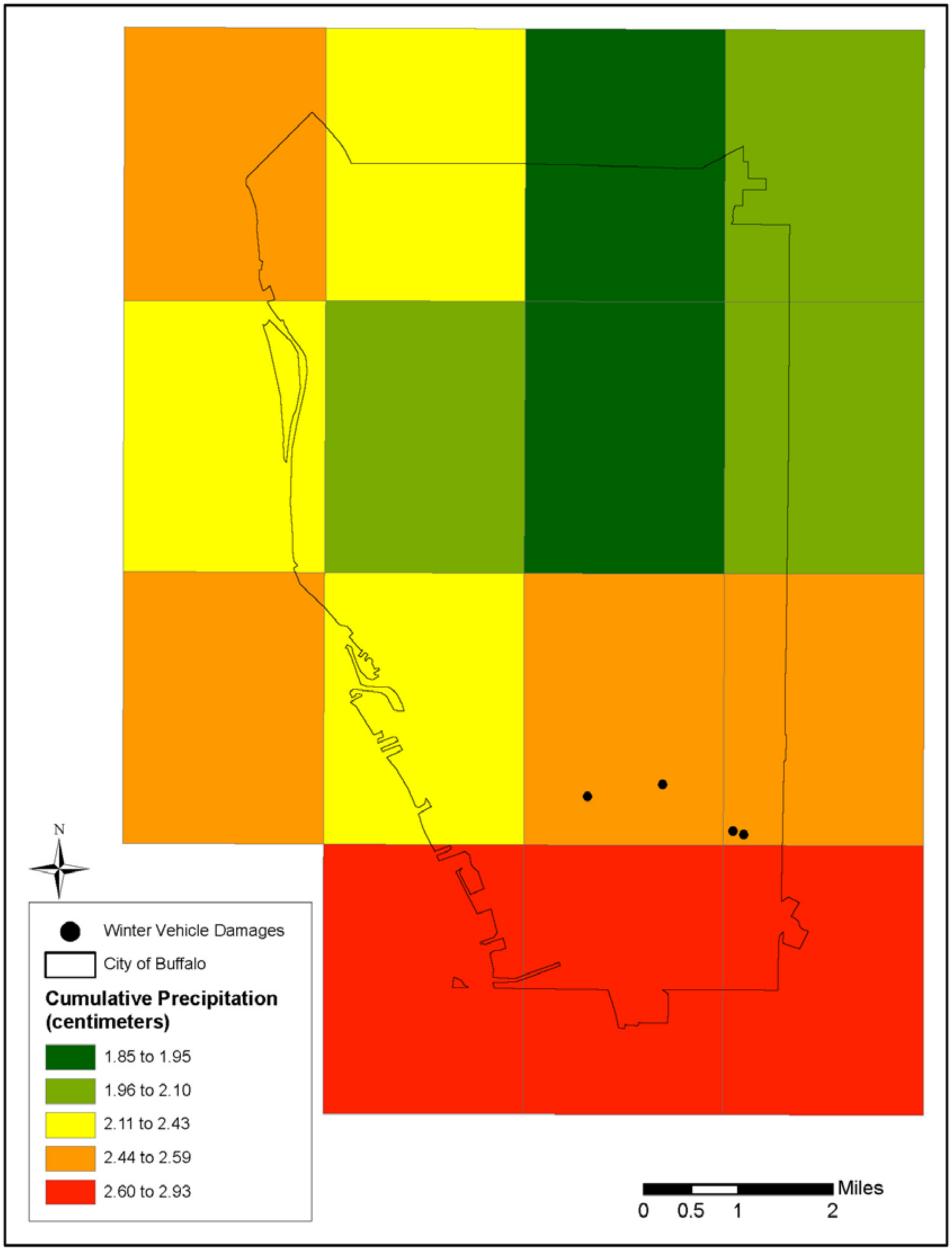

Figure 13. Hydrant damages incurred by vehicles that occurred on December 2, 2014 (N = 4) and corresponding cumulative precipitation data from November 29 through December 2, 2014.

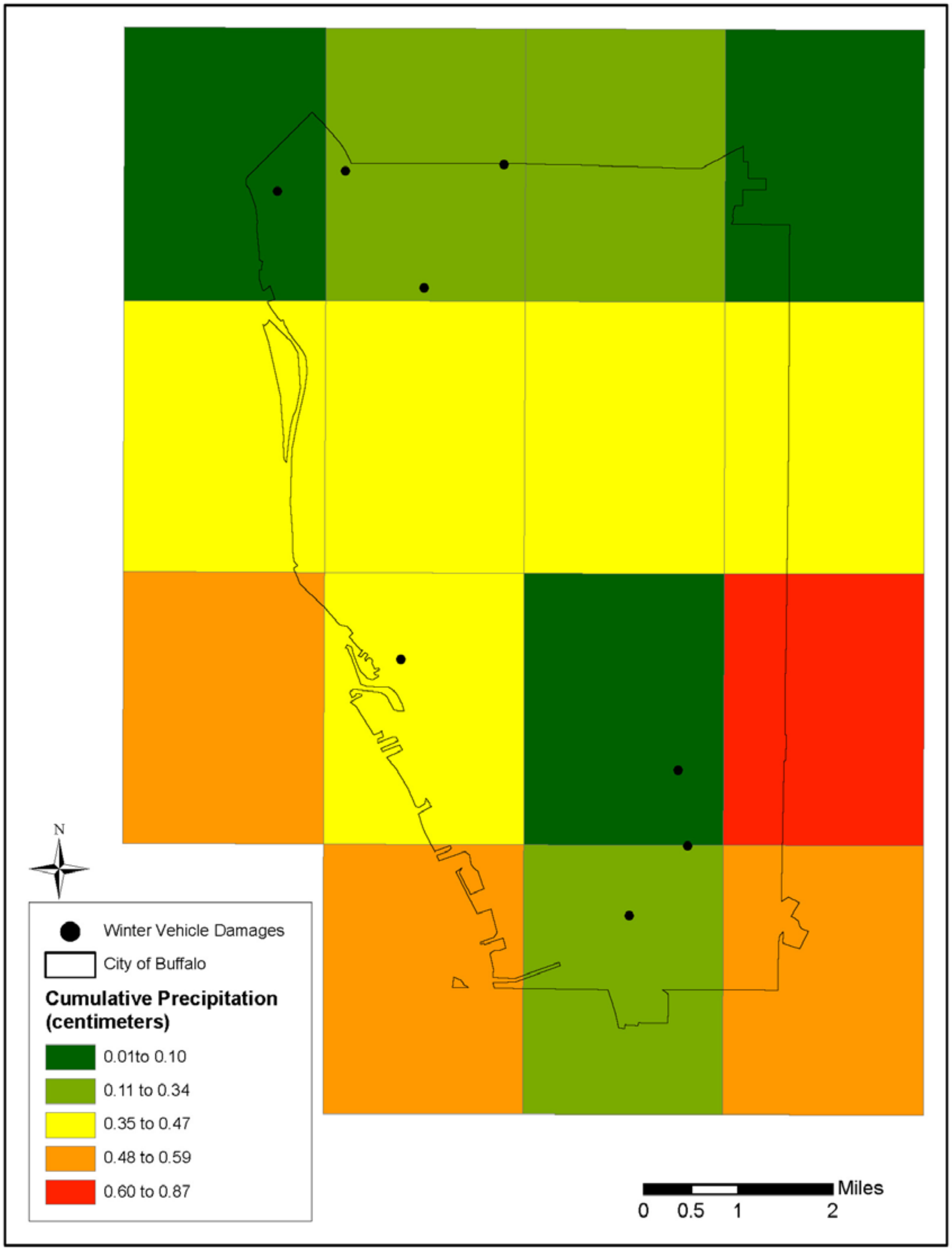

Figure 14. Hydrant damages incurred by vehicles that occurred on March 11 and 12, 2015 (N = 8) and corresponding cumulative precipitation data from March 8 through March 12, 2015.

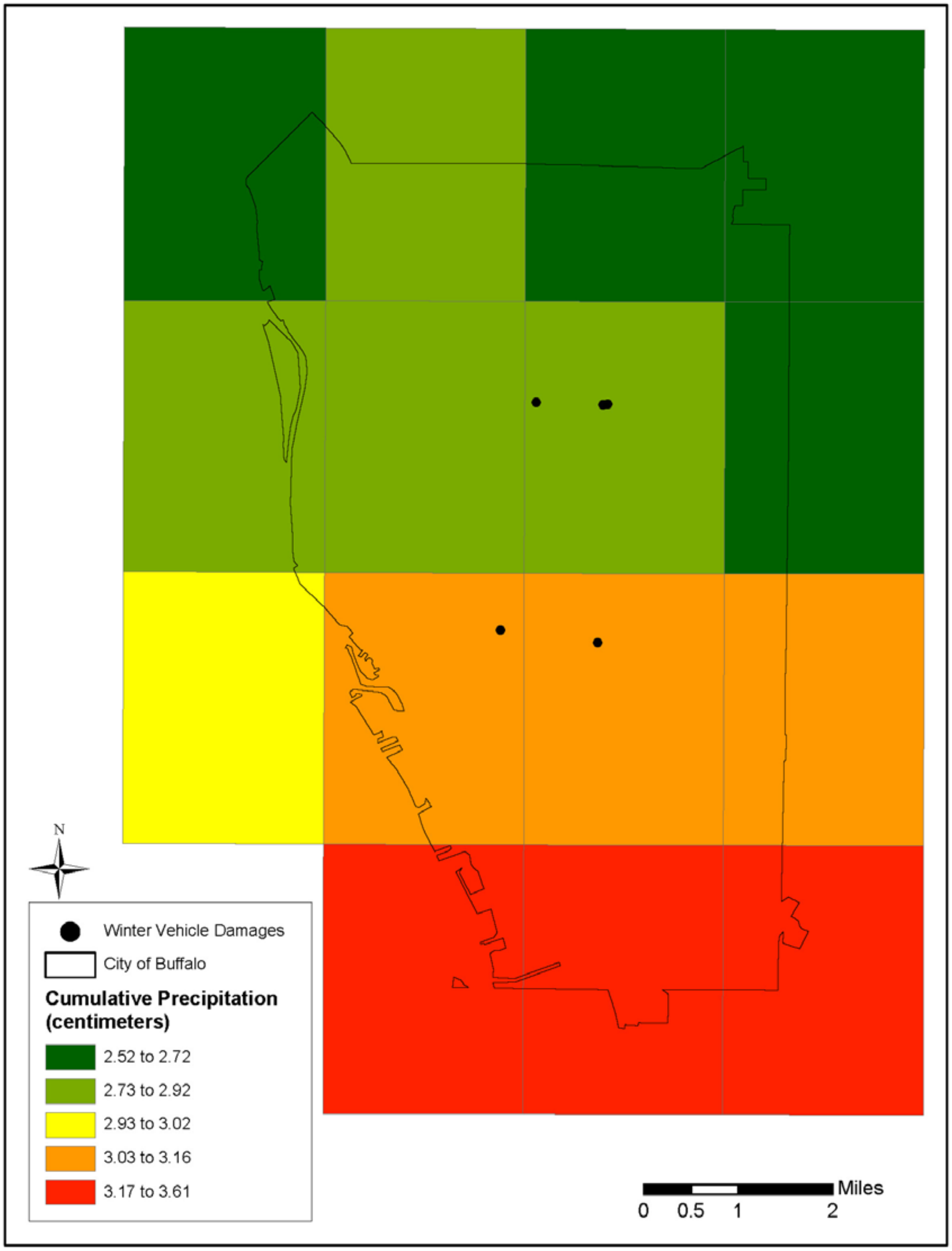

Figure 15. Hydrant damages incurred by vehicles that occurred on March 20, 2015 (N = 5) and corresponding cumulative precipitation data from March 17 through March 20, 2015.

4.4 Winter Storm Effects

Throughout the study period, there were several incidents indicated as severed storms in NOAA's Severe Weather Data Inventory. Storm events were selected based on winter severity in the Erie County region.

4.4.1. Severe Weather

Events for the severe winter storm data set consisted of days in NOAA's Severe Weather Data Inventory. If a second severe storm occurred within three days of the preceding severe storm, the storms were considered to be part of the same event for the purpose of this study. Seven severe storm events were documented in Buffalo during the study period. During these seven events, sixty-eight hydrant repairs were required. See Table 5 for the hydrant repair summary.

Table 5. Hydrant Damage Summary for Severe Storm Events

Total Damages	Date Range of Event
10	12/10/2013 to 12/21/2013
6	12/31/2013 to 01/02/2014
8	01/06/2014
6	03/29/2014
22	11/17/2014 to 11/19/2014
5	12/10/2014
11	12/31/2014 to 01/09/2015

4.4.2. Events and Weather

Once events were determined, weather data from PRISM were analyzed for total precipitation, based on the date range of the event. This was done because the NOAA weather stations in the area surrounding Buffalo were not sufficient at the scale of this analysis (Figure 16). Hydrant damages were evaluated based on damages that occurred on the first day of the event, and three days after the final day of each event. The results of the analysis are shown in

Figures 17 through 20. Overall there does not appear to by any significant correlations between severe weather events (NOAA) and higher incidents of damage. The next several figures demonstrate that there is very little correlation unless a severe storm, uncommon for the area, occurs. This is apparent in Figure 18, where the storm event and corresponding damages are localized to the southern part of Buffalo; however, northern Buffalo still received higher than average snowfall and also saw an elevated number of damages as compared to other events where there was less snow accumulation overall.

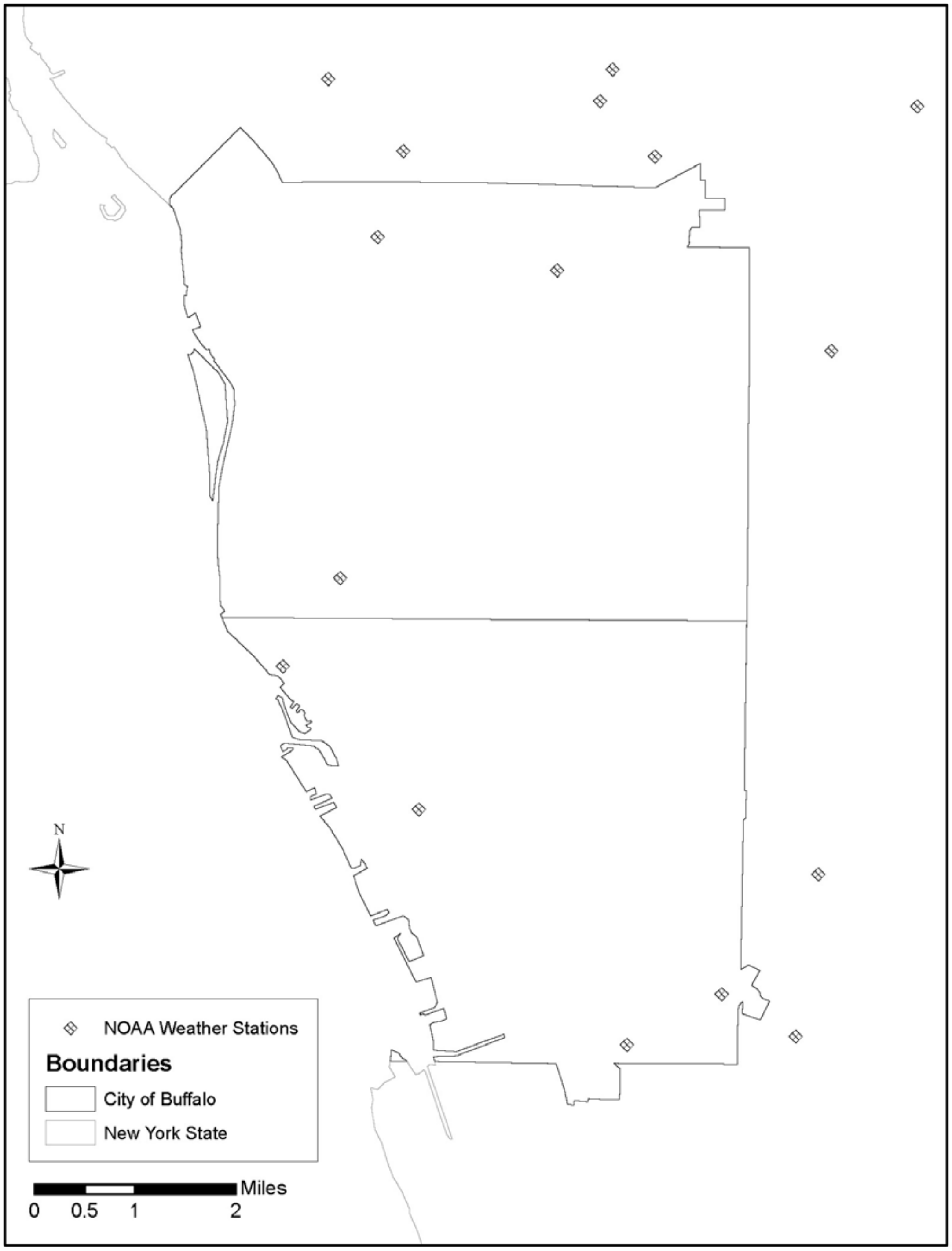

Figure 16. Location of NOAA weather stations used for detererrmining severe storm data. N = 16.

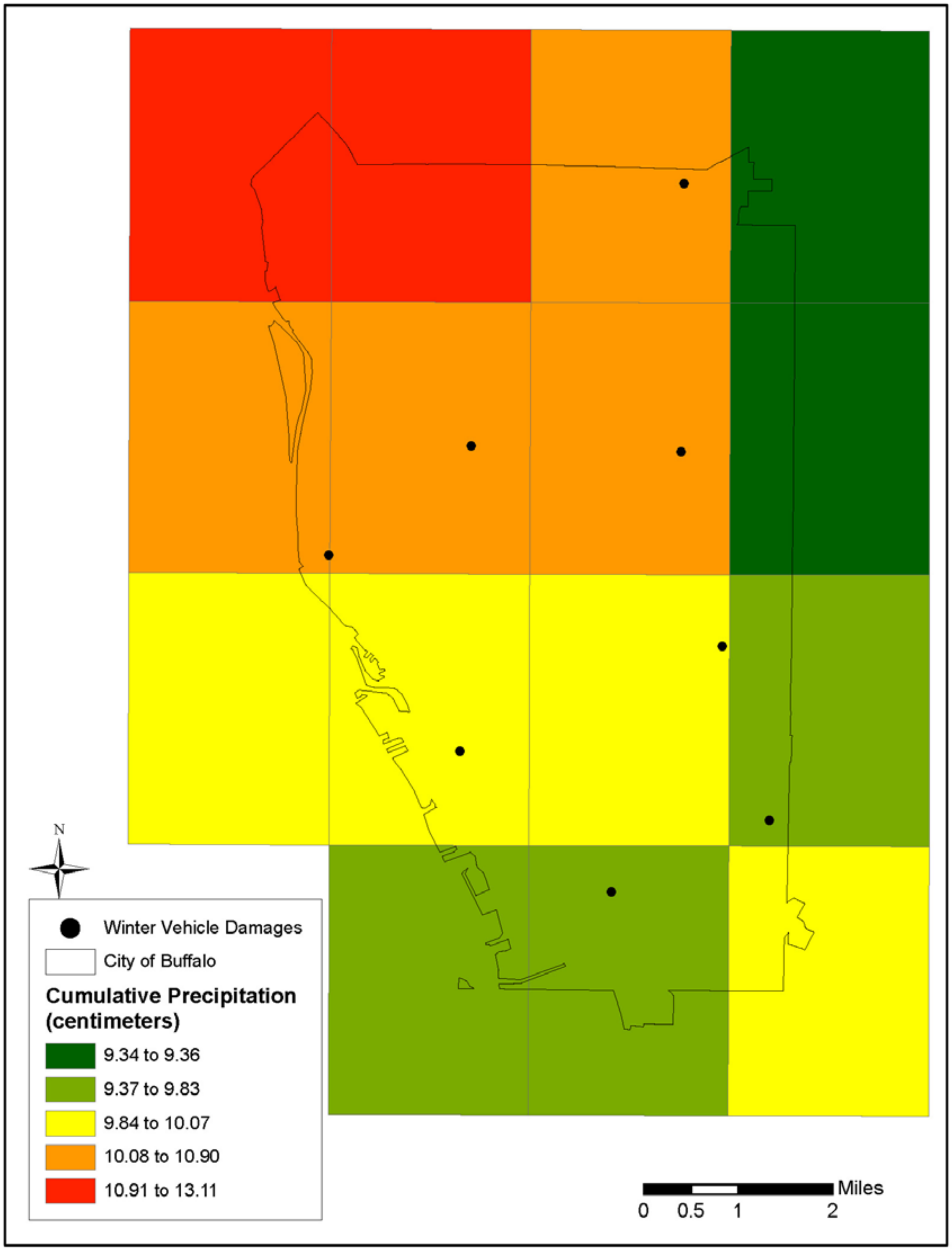

Figure 17. Cumulative precipitation data from a severe storm event on January 6, 2014 with corresponding hydrant damages (N = 8) incurred by vehicles on that day and three days following.

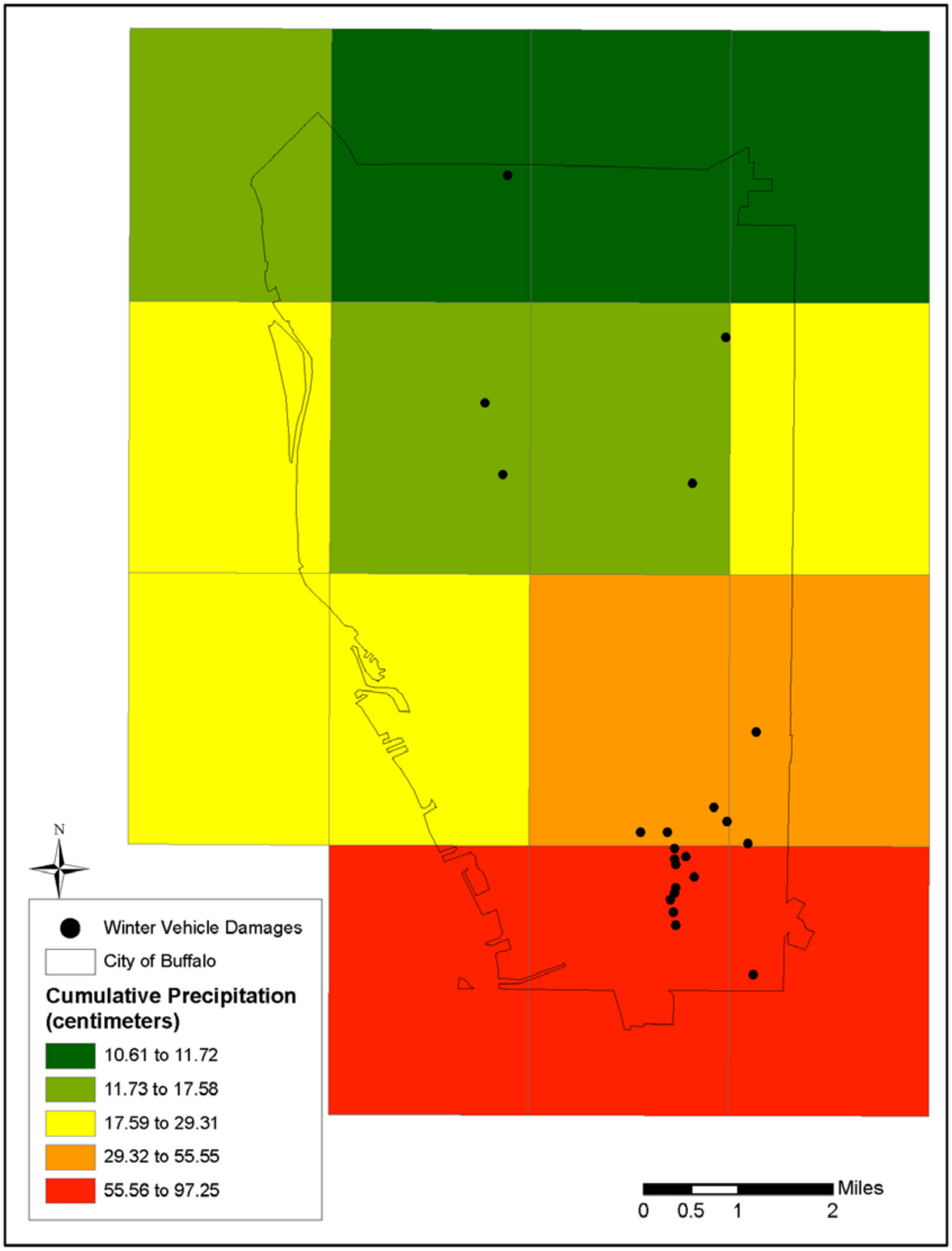

Figure 18. Cumulative precipitation data from a severe storm event that lasted from November 17 to November 19, 2014 with corresponding hydrant damages (N = 22) incurred by vehicles during that time and three days after the last day.

following.

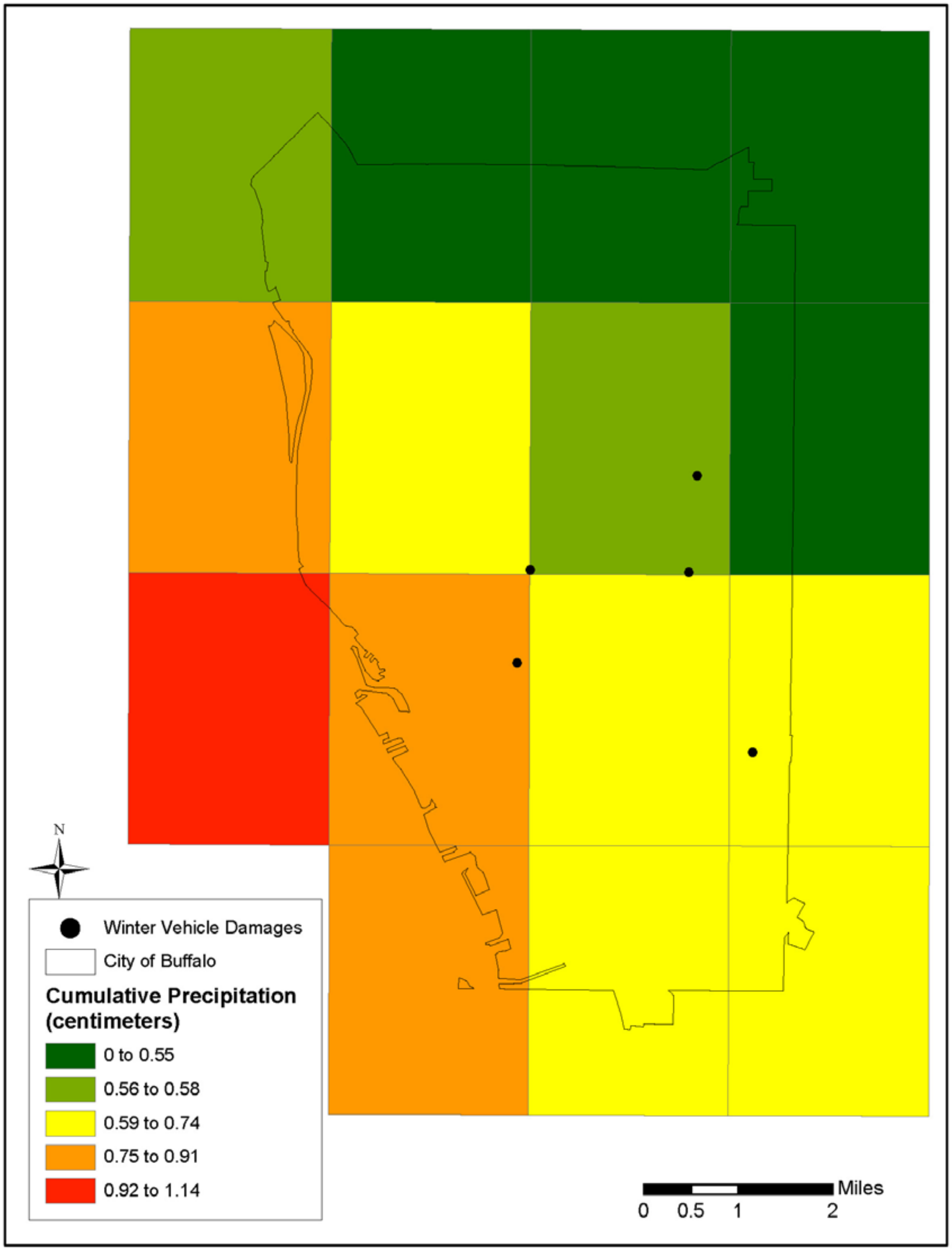

Figure 19. Cumulative precipitation data from a severe storm event on December 10, 2014 with corresponding hydrant damages (N = 5) incurred by vehicles on that day and three days following.

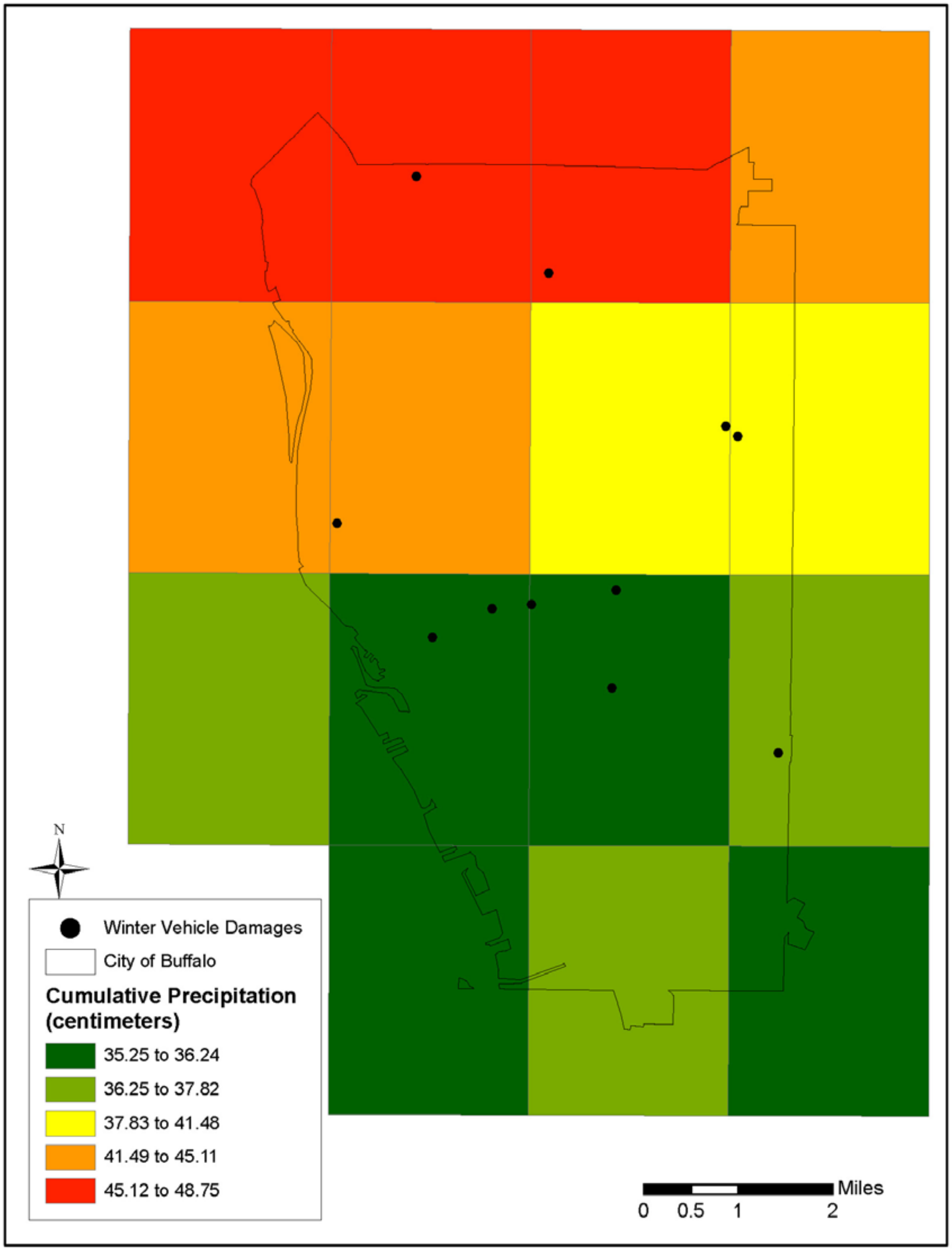

Figure 20.Cumulative precipitation data from a severe storm event that lasted from December 31, 2014 to January 9, 2015 with corresponding hydrant damages (N = 11) incurred by vehicles during that time and three days after the last day.

4.5 Spearman's Rank Correlation Results

During high frequency weather events, Spearman's Rank Correlation indicated that the only event with significant results was in November 2014 when comparing high frequency events to weather during the event and three days prior (Table 6).

Table 6. Spearman's Rank Correlation for high frequency events

Spearman's Rank Correlation			
High Frequency Events			
α = 0.05, n = 15, df = 13			
Date of Event	**rho**	**t-stat**	**p-value**
3/20/2015	0.13555	0.493286	0.630038
3/16/2015	-0.08846	-0.32011	0.753972
03/11/2015 to 03/12/12015	0.448784	1.810697	0.09335
12/16/2014	-0.07883	-0.28512	0.780046
12/2/2014	0.318029	1.209462	0.248021
11/20/2014 to 11/26/2014	0.694132	3.476749	0.004093*
11/15/2014	-0.25377	-0.94596	0.361422
1/8/2014	0	0	1
1/8/2013	0.227008	0.840431	0.415857

Spearman's Rank Correlation indicated that no events during severe storms had significant results when comparing incidents during the event and three days after to cumulative snow fall during the event (Table 7).

Table 7. Spearman's Rank Corrlation for severe storm events

Spearman's Rank Correlation			
Severe Storm Events			
α = 0.05, n = 15, df = 13			
Date of Event	**rho**	**t-stat**	**p-value**
12/31/2014 to 01/09/2015	-0.17366	-0.63582	0.53593
12/10/2014	0.016669	0.060109	0.952983
11/17/2014 to 11/19/2014	0.327118	1.248108	0.234004
3/29/2014	0.236747	0.878581	0.395577
1/6/2014	0.123718	0.449525	0.660457
12/31/2013 to 01/02/2014	-0.01839	-0.06631	0.94814
12/10/2013 to 12/13/2013	-0.24378	-0.90632	0.381257

Chapter 5 Discussion and Conclusions

The results of this study included some expected results, while also demonstrating unexpected findings. The hypothesis for this thesis is: Weather patterns in Buffalo will influence the pattern of hydrant damages, resulting in the most damages in south Buffalo and in areas where higher precipitation was recorded. This final chapter examines the major findings from the analyses, and considers the hypothesis by answering the following questions: is there a difference in the number of hydrants damaged in north Buffalo versus south Buffalo; is the weather in Buffalo a factor that may result in additional hydrant maintenance as a result of vehicle damage? This chapter discusses limitations of the data and future analysis that can be performed. Additionally, this chapter considers how asset management and detailed data collection will assist in future analysis.

5.1 Findings

This section considers the results of analysis performed in this research project and what they imply for hydrant damages and maintenance. It explains what is implied by the overall data summary and hot spot analyses, while illustrating the relationship of the hydrant work orders to weather data.

5.1.1. Summary of Data and Hot Spot Analysis

The initial data summary demonstrated the expected initial findings. The total number of hydrant maintenance incidents required is greater in the summer than the winter; however, the number of hydrant maintenance incidents that are caused by vehicles is greater in the winter than in the summer. The observation that the number of hydrants damaged differs drastically between seasons indicates that weather may play a role in these damages.

First, more hydrant maintenance incidents were reported in the summer due to routine summer maintenance. In summer, hydrants are inspected by district in Buffalo, and preventative maintenance is reported and executed. While the preventative maintenance is performed, a hydrant that fails to operate properly is reported. Additionally, in the summer, hydrants are typically used more often. Summertime activities that involve hydrant operation include, but are not limited to, flushing programs for water main maintenance, leak detection, flow testing, dust control for building demolitions, street cleaning, and community gardens. In general, after a hydrant is used, routine maintenance should be performed, therefore explaining why the overall number of maintenance incidences increases in the summer.

Hydrant maintenance in winter is reduced from summer regarding total hydrant repairs or replacement, but it is increased when you consider the cause of the damage. Again, this number is in line with expectations that although preventative maintenance work decreases, winter driving conditions and snow plowing potentially create above ground hazards that may increase hydrant damages. Analysis described in this study focused on this subset of data: winter hydrant maintenance incidents required as a result of vehicular damage.

Hot spot analysis was carried out on all hydrants in the study area (Figure 4). The hot spot located in downtown Buffalo is expected as there are many small blocks that intersect in that area, and a greater number of hydrants are present. Hydrants are installed to be easily accessible, and thus have a high concentration in the downtown area. As discussed earlier, north Buffalo has a lower concentration of hydrants than south Buffalo; therefore the cold spots in north Buffalo and the hot spots in south Buffalo coincide with general hydrant numbers. There are also a few cold spots on the southwestern most part of Buffalo, along Lake Erie. These hydrants exist along the harbor and are surrounded by Lake Erie to the west and manufacturing areas to the east. Hydrants exist scattered around one water main that goes along the coast.

Several hot spot analyses were also performed on the data set of work orders used for this study. For the hot spot analysis on that considered all winter hydrant maintenance incidents caused by vehicles, the large hot spot in south Buffalo covers a large portion of south Buffalo, all the way to the western most part (Figure 5). In regards to hydrant distribution, this southwestern most part of Buffalo has a large cold spot, and there are few hydrants located there. It is important to consider north Buffalo and south Buffalo as they have different characteristics, especially regarding weather patterns. The smaller hot spot in the northern part of Buffalo occurred in an area where there was not a hot spot for hydrant distribution, while there is a small hot spot for hydrant distribution in south Buffalo.

In all of the hot spot analyses that considered hydrant maintenance incident locations, there are variations; however, no years indicate a hot spot in the downtown area, where the largest hot spot of hydrants are present.

In winter 2012 to 2013, hot spots for hydrant maintenance incidents are scattered throughout Buffalo, in no apparent pattern (Figure 6). There are small hot spots scattered through both north Buffalo and south Buffalo. In winter 2014 to 2015, there is a drastic difference where nearly the entire hot spot area is located in south Buffalo (Figure 7). When the hot spot analysis is performed only on the winter months between November 2011 and March 2014, there is a hot spot in the southwestern most part of Buffalo, as well as a few small hot spots scattered north into north Buffalo (Figure 8). Since 2014 to 2015 was an outlier winter, with heavy snowfall and a severe winter storm, it is reasonable to conclude that only an extremely severe storm, resulting in many hydrant maintenance incidents, has an impact on work order location.

5.1.2. North Buffalo versus south Buffalo Hydrant Damages

In the predefined boundaries of north and south Buffalo, there are 4,945 hydrants in north Buffalo and 2,995 hydrants in south Buffalo. Using the same boundaries, an analysis was performed to determine how many hydrants were damaged by vehicles in winter months. In north Buffalo, 239 hydrants were damaged, while there were 255 damaged in south Buffalo. With the greater number indicated as damaged in south Buffalo, and fewer hydrants total, hydrant damages occurred in south Buffalo at nearly twice the rate that they did in north Buffalo.

These findings support the first part of the hypothesis, which states that more hydrant damages will occur in south Buffalo instead of north Buffalo. The increased rate of hydrant damages as a result of a vehicle in south Buffalo may be due to overall harsher weather patterns. These patterns were explored in the second phase of this study; however, it is also possible that the increased density of hydrants may increase the chances of being hit due to the hydrant's locations. This was not explored in this study and will be discussed in section 5.3.

5.1.3. Discussion of High Frequency Occurrences

On the majority of days in the winter that were analyzed in this study, most days saw zero or one hydrants damaged by a motor vehicle; however, there were several days where more damages occurred. In this part of the study, analysis focused on sixteen individual days where four or more incidents occurred. Ultimately, these sixteen days made up nine events.

In only three of nine events did the visual analysis indicate that more than half of the incidents occurred in the areas of Buffalo where there was greater snow accumulation (January 8, 2013; November 20 to 26, 2014; December 2, 2014). On the remaining days, at least half of the incidents occurred in areas where snowfall was in the lower half of total accumulation for the days of the event. During most of these events, the accumulation was greater in south Buffalo than in north Buffalo, with the exception of January 8, 2013, where snow accumulated on the western side of Buffalo and indicated heavy snow in both north Buffalo and south Buffalo.

Visually, it is possible to see that the majority of hydrant damages for this part of the study occurred in the southern part of Buffalo; however, the inconclusive clustering and varying weather results indicates that more factors may be involved than weather; however, due to data limitations (Sections 5.2) additional analysis could not be done. Additionally, due to the scale of the study area, PRISM data were not sufficient or reliable for all events. As a result, the modeled weather may have some variance from what truly occurred on the ground.

5.1.4. Discussion of Severe Storm Data

Throughout the time of this study, eight severe storm events were documented as occurring in the Buffalo area. While performing a visual analysis, data are inclusive regarding the direct impacts of weather. During several of the events (December 31, 2013 to January 2, 2014; January 6, 2014; March 29, 2014; November 17 to 19, 2014; and December 10, 2014), hydrant damage locations tended to fall in areas where there was greater snow accumulation during each specific event; however, the remaining three events do not show this pattern. Of the remaining three events, one storm did not indicate any snowfall in Buffalo for that day, but an increased number of hydrants were still reported as damaged throughout Buffalo that day.

It is again possible to determine that the majority of the hydrant damages did occur in the southern part of Buffalo. On several days when severe storms occurred in the Buffalo area, south Buffalo experienced greater snow accumulation than north Buffalo, but there are a few days where this pattern is not observed. Reliable NOAA data exists, but could not be used for the study area due to the scale; the weather stations were not sufficient in quantity or location for the region of this study. As a result, NOAA data were used to determine dates that experienced severe storms, and then analysis was performed backwards to use the PRISM data. Using the PRISM data again posed an issue of scale and reliable information.

After performing Spearman's Rank Correlation, it is possible to conclude that weather and winter precipitation accumulation does not have a great impact on the number of winter hydrant maintenance incidents that occur in specific areas of Buffalo.

5.2 Limitations

Due to several limitations in data completeness, the results of this study have been overall inconclusive to answer the question of what impact the weather has on fire hydrant damages.

5.2.1. Fire Hydrant Data

At the beginning of this study, several other factors were going to be considered in overall analysis.

First, hydrant age was to be considered to determine whether or not an older hydrant was more susceptible to damage. Only about one-tenth of the hydrants in the system had a value in the attribute field for year installed. Once making this finding, age was to be determined based on manufacturer; however, manufacturer models have not consistently been recorded therefore making it impossible to determine age from the manufacturer alone. Through word of mouth, and in discussion with senior employees, there are many known hydrants in the system to be over ninety years old. Although aging infrastructure may pose issues with failure, there is not enough past data to determine whether or not age is an attributing factor to hydrant failure.

Long-term weather patterns of freezing and thawing were going to be analyzed to determine how these cycles and whether or not the number of cycles impact hydrant failure. This analysis was not possible due to limitations of hydrant data (discussed above) and limitations of weather data discussed in 5.2.3.

5.2.2. Work Order Information

The most significant work order limitation for this study was in the reporting of hydrants that were used and how frozen hydrants are reported in the winter. Between the months of October and March, Buffalo Water considers that all assets may be exposed to consistent temperatures below freezing. As a result, Buffalo requests that the local streets department and fire departments notify Buffalo that a hydrant was used. Once a hydrant is indicated as used, a representative from Buffalo Water will inspect the hydrant to ensure water is drained from the barrel and will not freeze if exposed to consistent freezing temperatures. Many hydrants are reported and are indicated properly in the InfoNet system; however, hydrants that are not reported will not be noted in the system. These hydrants are often discovered when Buffalo Water personnel go hydrant-to-hydrant throughout winter months to check for signs of usage. In an average winter, each hydrant is checked six to eight times throughout the winter. During these rounds, only the total number of hydrants found frozen in each district is documented. This information is not linked to individual assets, but rather hydrant inspection districts. As a result, there is no way to track which hydrants were used or which hydrants were found frozen based on the current routine maintenance documentation.

5.2.3. Weather Information

There are several limitations with the weather data that are discussed in this section.

The PRISM data, although it appeared to be a robust dataset, was potentially unreliable for this study. The data were provided in a way that was not easy to isolate or manipulate for large scale analysis. As a result, I observed only specific events rather than a larger time period. The scale of the PRISM data may have also created some uncertainty as there were few data cells that covered Buffalo. Kim et al. (2016) discuss specifically the limitations of PRISM data in relation to weather stations used in the model. As a result, Kim et al. utilized the PRISM model at a 30km scale to reduce the effect of locality in the model. Using PRISM data at a 30km scale would not be feasible in Buffalo. Additionally, another limitation of PRISM data was the lack of cumulative precipitation data. As a result, precipitation data from days of an event were added together, which indicated the total amount of winter precipitation that fell during the event, and may not be representative of the actual amount of winter precipitation, typically snow, on the ground.

The storm data from NOAA contained a lot of information, but lacked some location-specific information. Many of the storms are indicated based on county, not specific municipalities. Buffalo's location is on the western edge of Erie County, but it is centrally located between the north and south aspect of the county. Any storms that were indicated as part of Erie County, northern Erie County, or southern Erie County had to be further analyzed to determine whether or not the storm event came in close proximity to Buffalo. Tracking storm events on a larger scale may be beneficial to municipalities performing weather analysis.

Perhaps the most beneficial weather information that was not available for this study is not the amount of cumulative snow during an event, but rather the amount of snow on the ground on any given day as well as data on the occurrence of freeze/thaw cycles for each winter period. In Buffalo, winter typically lasts several months, and snow accumulates, packs down, and melts several times throughout the season. As a result, a series of minor storm events with only one inch of snow would not have stood out in either analysis; however, the overall accumulation may be more important than the amount of fresh snow that accumulated in an event. Cumulative snow data that was used in Figures 9 through 11 were obtained from NOAA, at the Buffalo Niagara

International Airport location. The airport is approximately 10 miles northeast from downtown Buffalo, and lies outside of the Buffalo city limit; however, it was the best fit for use here.

5.3 Future Work and Recommendations

Although weather data came back inconclusive for causing an increase in hydrant damages, it is possible that season-long effects of winter may have a greater impact than individual storm events. As a result, Buffalo Water should consider including climate data in work orders. If incorporated into work order information, data specific to each hydrant incident will be documented. Alternatively, Buffalo could consider installing weather stations on all city-owned buildings, though it is cost prohibitive. This data could be compiled and shared across various agencies for additional research.

Another immediate next step that Buffalo Water could take is to document specific hydrants that are pumped or found frozen in the winter to determine whether or not there is a pattern. This information will help with management of future winter maintenance. In conjunction with more specific information on frozen hydrants, all hydrant usage and maintenance should be documented on each individual asset for proper condition monitoring. At the time of use, a condition assessment should be performed to document whether or not the hydrant requires maintenance.

An analysis could be performed in conjunction with data on hydrant usage and freeze thaw cycles. The analysis could consider the water main size to determine whether or not the size of the water main impacts the likelihood that a hydrant would require corrective maintenance. This specific analysis was not part of the focus of this project because it was pertinent to hydrant failures and not hydrant damages by a motor vehicle. Additionally, the size of the main that the hydrant is off of would have to be verified for many hydrants as this data are only accurate for ranges of pipe sizes and not the specific pipe size. Additionally, once pipe sizes are verified and addition flow data are collected, a network flow analysis could be performed to determine if network flow has an impact on hydrant failures. Buffalo Water also has additional data sets on water main breaks that could be integrated into research to determine the impacts network flow has on the entire distribution system.

As indicated in Section 5.1, hydrant damages occurred at nearly double the rate in south Buffalo than they did in north Buffalo. Although weather may be a factor, the results from this study were inconclusive, and it is important to consider other reasons. Overall, south Buffalo covers a smaller area as much of the south east section of Buffalo is industry. An increased concentration of hydrants may be one part; however, the hydrant placement may also be important. It is possible that there are more hydrants on street corners or closer to the street than in the northern parts of Buffalo.

A thorough street inventory should be taken for both north and south Buffalo. In general, south Buffalo has fewer main roads than north Buffalo, causing various side streets to be more travelled in south Buffalo. Traffic volume on various streets in south Buffalo could also be a potential factor, as more traffic may increase the chances of hydrant damage. Additionally, since different parts of Buffalo developed at different times, it may be imperative to research the width of streets, whether or not streets are one way, and parcel use information.

When a hydrant is damaged by a vehicle, Buffalo rarely obtains a copy of a police report because the damages are often reported after the event has occurred and the person responsible is unknown. As a result, Buffalo Water Authority is unable to note whether or not the damage was a result of a citizen, hazardous driving, poor conditions, snow plow, or any other vehicles. Documenting this information in the asset management could be useful for further analysis to determine if there is a correlation to damages caused by being hit before, during, or after snow is plowed.

Starting in 2015, Buffalo began installing snow flags on hydrants in south Buffalo. In future years, these efforts will expand to the remainder of Buffalo. This may help mitigate damages, especially due to snow plows hitting hydrants. With additional information collected in the future, work can be performed on the area in south Buffalo where the hot spot of hydrant damages occurred. With the harsh winter storms that hit that area, Buffalo Water should monitor the occurrences to see if that area continues to have an increased number of hydrants damaged, particularly during years when snow accumulation is greatest. Installing flags, bollards, or even moving hydrants away from curbs, street corners, and driveways may lessen the damaging impacts that vehicles have on hydrants. Taking these preventative measures will help Buffalo save on funds and labor needed to replace damaged hydrants.

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