A Flash Flood Risk Assessment of the Colorado Front Range using GIS

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Abstract

Although significant research has been performed on impacts and mitigation of flash flood events, the methodology for assessing social vulnerability and regions at risk has not been fully developed. This project explored the environmental-social links of flood hazards and developed a GIS-based methodology for flood risk assessment. The assessment was based on a model that risk was a product of exposure to a hazard and societal vulnerability. Vulnerability was represented by population characteristics and distribution of critical facilities. Exposure was estimated by combining the Areal Mean Basin Average Rainfall (AMBER) method combined with GIS techniques. This method involved relating precipitation accumulation, averaged over a stream basin, to National Weather Service flash flood guidance values to identify basins with flooding potential. The vulnerability and the exposure were integrated in a GIS to estimate the total risk. The 1997 extreme precipitation event in Fort Collins, Colorado was used as a model to assess potential flood risk in two metropolitan areas: Fort Collins and Denver. Results yielded a GIS-based model that combines hydrometeorological information with social data, and allowed for radar-derived precipitation data to be integrated into the GIS to map key areas at risk in Fort Collins and Denver. Early identification of risk areas can assist emergency and flood-plain managers in developing response and mitigation measures. These results can provide a framework to expand this study of flood risk by introducing near-real time precipitation data, hydrological models and, detailed socio-economic geographic data.

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1. Introduction

Flash floods are a recurring natural disaster affecting life, health, and the economy. The financial and social costs of flash floods continue to rise as the population in at-risk areas increases along with the amount of property at risk (White et al. 2001). In a summary of impacts of major natural hazards in the U.S. from 1996-2000, the National Weather Service (NWS) concluded that the total monetary loss for floods was $15,900,000, with 7408 total morbidity accounts and 490 mortalities (NWS 2001). A *flash flood event* results from intense precipitation when water rises within a few minutes or up to six hours after the rainfall event.[1] Warnings must be issued by local NWS forecast offices rather than regional NWS River Forecast Centers (RFC) (NOAA 1981a). Just 6 inches of flash flood waters is all it takes to knock an individual down and 24 inches can sweep away a car (FEMA 2004).

Flash flood mitigation is difficult because of the complexity of meteorological, hydrological, and social processes. Flood risk for a given area can vary widely due to changes in local climate, topography, soil characteristics, and land use that call into question the accuracy of floodplain maps, flood forecasts, engineering calculations, and forecasts of socioeconomic conditions (Downton et al. 2005). Other problematic areas include "limited hydrometeorological observation records; spatiotemporal variability in precipitation and flood potential; approximations in statistical techniques and hydrologic modeling; contributors to flooding such as debris, structural failures, and stormwater drainage; and changing risk levels due to societal factors such as land development near floodplains, land surface alteration, and the dynamic nature of social systems" (Morss et al. 2005).

Technological advances such as Geographic Information Systems (GIS) have made it possible to improve floodplain management and develop more accurate risk assessments of key areas such as housing districts, government buildings, future building sites, and financial districts. Although GIS has been used since the 1970s, extensive application of GIS to floodplain mapping and management did not begin until the early 1990s (Vieux 2001). Application was delayed because GIS use was limited to larger organizations due to the cost of software and hardware and the difficulty in obtaining detailed hydrological and socioeconomic data (Bedient 2002).

An accurate assessment of the flood risk associated with each of these concerns can help city planners and emergency managers develop appropriate flood control policies and mitigation measures for areas and populations at risk (Boyle et al. 1998). The meteorological forecast community lags behind in the use of GIS that would integrate forecast and warning data with socioeconomic information that communities already have available (U.S. Department of Commerce 1997). This gap has become increasingly recognized, and this work will provide a framework for this new direction.

[1] In contrast, a *flood* occurs when the water level increase continues for more than six hours after the rainfall event (Doswell III 1997).

Integrating data from disciplines such as meteorology, geography, and sociology enhances understanding of flood risk and vulnerability. This project expanded upon this integration, explored the potential applications specifically for meteorological forecasters, and overlaid this information with predetermined demographic networks. GIS enables linking location to relevant information to help visualize phenomena, improve decision-making, and plan implementation of mitigation measures. A GIS helps to identify where something is located or where an event occurred and displays this information in layers composed of point, line, or polygon features (referred to as vector features, Fig. 1). Each theme exhibits the special characteristics of a geographic feature (ESRI 2005).

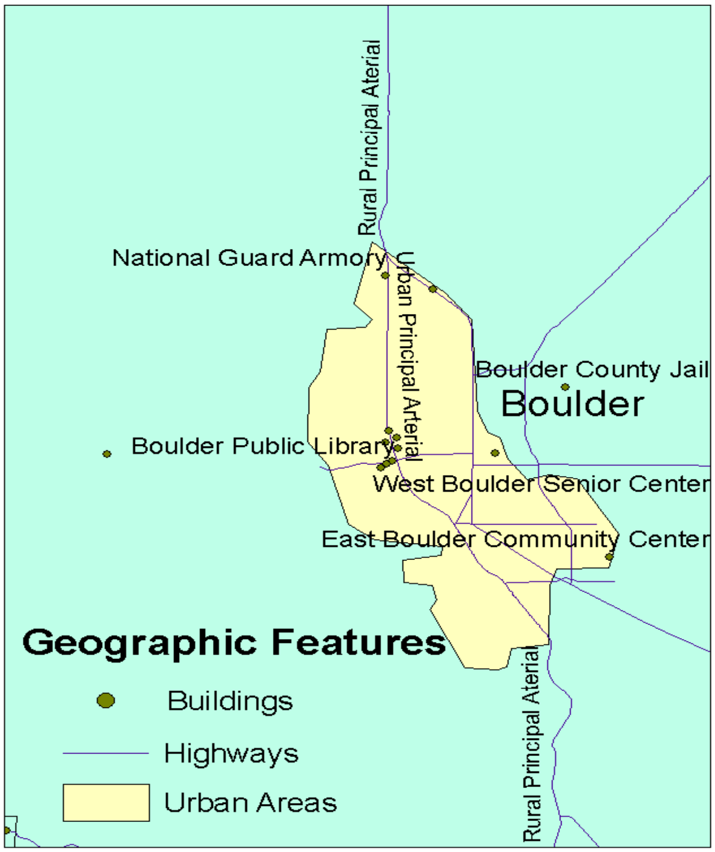

Fig. 1. Representation of vector data in GIS.

GIS also allows showing gridded data in a raster format. Thus data can be represented in cells oriented in rows and columns; each cell contains a single point value (Fig. 2). These points can be extended to represent continuous values such as rainfall (ESRI 2005).

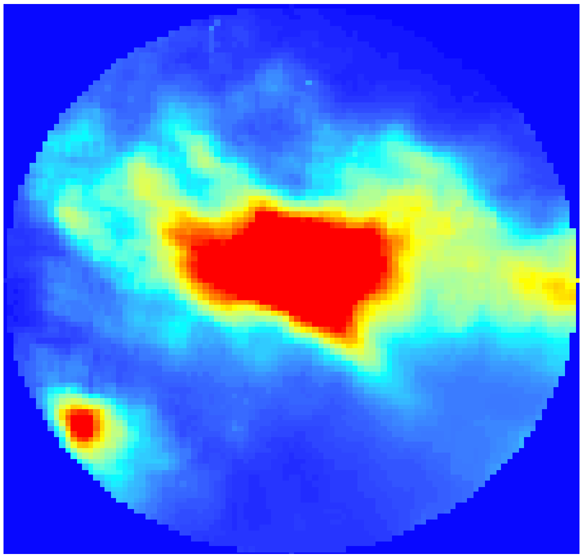

Fig. 2. Representation of raster data in GIS

The magnitude of the loss due to flooding and its distribution in the floodplain is dependent on hydrological, land use, and human factors (James and Lee 1971; Flood 1976). Thus, when developing a regional risk assessment, planners must take into account exposure to a hazard and vulnerability:

(1) Risk = Exposure * Vulnerability

In flash floods, *exposure* represents the flood hazard in a specific area and its probable severity and frequency; exposure also accounts for the proximity of population and structures to floodplains and the intensity, duration, probability, and frequency of flooding events. *Vulnerability* is the characteristic of the capacity of a person or a group to anticipate, cope with, resist, and recover from the impact of a natural hazard (Blaikie 1994) and is represented by the three factors defined below:

- **Preparedness** relates to issues such as drainage systems, building codes, and warning systems.
- **Coping** relates to the warning process, evacuation procedures, insurance programs, and timing of the event itself.
- **Recovery** considers the economic status, age, health, support networks, and language proficiency of those affected, as well as the types of insurance and government assistance available (Mitchell et al. 1997).

The study area for this research project is the Colorado Front Range area of the Rocky Mountains (Fig. 3).

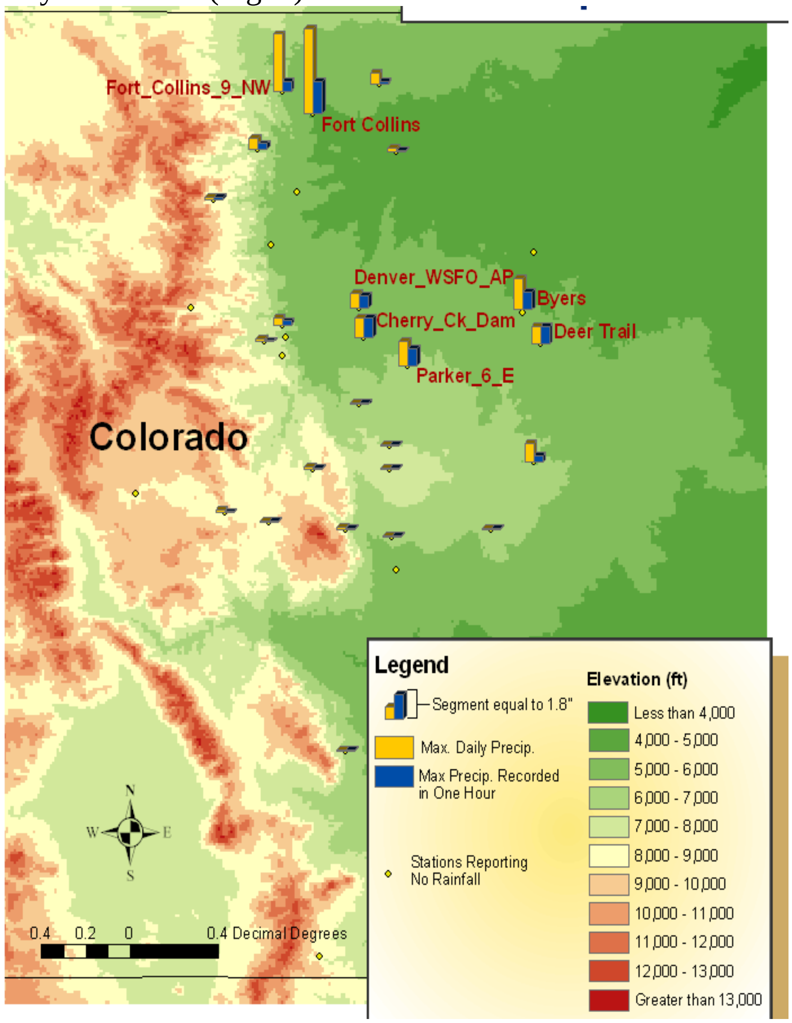

Fig. 3. Colorado Front Range study area

Flash flood forecasting is difficult in this area due to the mountainous terrain. Mountains can block radar echoes, and mountainous slopes accelerate the speed of water, particularly as the water flows into the hard-surface urban terrain where less water infiltrates. In urban areas, pavement and rooftops allow less water to be absorbed; instead, more of the water travels through gutters and storm sewers which increase the volume of water flow. For example, the design of many cities such as Boulder, Colorado interrupts natural drainage paths, further concentrating the flow of water into smaller channels. This causes the water not only to speed up, but clogs drainage paths if too much water is flowing through them.

The combination of all these factors can lead to three different types of flooding: over bank, irrigation ditch/canal, and street flooding (Mendez et al. 2002). The mountainous terrain accelerates the rate of condensation and efficiency of convective systems which further increases a storm's potential energy in terms of convective precipitation (USGS-NOAA 1979; NOAA 1981b). Over the past 15 years the Front

Range has experienced a dramatic increase in population. Many new residents may be unaware of the risks associated with flood hazards.

One of the tools used by the NWS for flash flood alerts is the Areal Mean Basin Effective Rainfall (AMBER) method. This method takes spatially distributed rainfall input (e.g., radar-derived rainfall), averages the rainfall over a watershed and a specified time period, and compares the averaged rainfall with a threshold to determine whether excess runoff will occur. Once the runoff threshold is reached in a watershed, areas in the watershed and downstream at risk for flooding can be alerted. We implemented this method in a GIS to assess risk, which can help forecasters and emergency management warn those in harm's way.

a. Key technical issues

One key technical issue is obtaining accurate precipitation estimates in real time and after an event has occurred. Pinpointing the exact location of intense precipitation and flood risk in mountainous regions is particularly challenging because of the difficulty radars have penetrating canyons (Romero et al. 1998). By the time a warning is issued, it may be too late for those in the path of the storm or flood water.

Another key technical issue is that 100-year floodplain boundaries are constantly changing because of land-use change due to new development. In addition, population changes affect the vulnerability of each section of a county. Data format differences and current limitations of GIS also present a technical challenge for data integration and analysis. Although researchers use GIS to manage, display, and analyze geographic knowledge, representing dynamic phenomena such as meteorological data in a GIS can be challenging.

The AMBER method's simplicity makes it useful for alerting areas at risk in real time but does not treat important flood factors such as infiltration, overland flow, and acre-lot size in sufficient detail to provide estimates of flood risk. Nor does it account for detention-pond locations, time of travel, and other important factors in flooding and flood risk. The current method involves using flash flood guidance (FFG) thresholds provided by the NWS's River Forecast Centers; these values are generated by using river models to estimate soil moisture. However, they do not take into account urbanization or fire burn areas. Because of the short time scale on which flash floods occur, key information is dependent upon the knowledge of local forecasters and emergency managers. Nevertheless, getting this information into GIS helps them consider hydrometeorological and societal aspects of flood risk together, thus improving warnings.

b. Goals

The goal of this research was to use GIS (ArcGIS 9.1, ESRI, Inc) to evaluate the risk of flash floods in the Colorado Front Range region by combining meteorological, geographical, and hydrological information with socioeconomic factors. We identified the potential effects of atmospheric conditions on society based on analysis of meteorology and other flood-risk factors. Specific objectives included identifying the primary exposure and vulnerability factors contributing to the risk of flooding in the Front Range, analyzing and integrating data representing these factors in a GIS, and mapping flash flood risk caused by an extreme rainfall event.

2. Methods

We identified the primary exposure and vulnerability factors contributing to the risk of flash flooding in the Front Range and analyzed data representing these factors using GIS techniques. The risk equation (1) discussed earlier was used to estimate the overall risk to flash flooding in two cases: Fort Collins and Denver metropolitan areas.

In the first phase of the research we determined which data sets were available for spatial analysis of flash flood risk. Spatial data for the study area, the Colorado Front Range, were obtained from a variety of sources (Table 1).

Data	In GIS format	Original source
Front Range demographic characteristics	ESRI, Inc.	U.S. Census 2000
Front Range watersheds boundaries	National Weather Service, Forecast Office, Boulder, CO (courtesy of Treste Huse)	National Weather Service
Fort Collins precipitation data	Courtesy of D. Yates (NCAR/RAL)	F.L. Ogden (Univ. Of Connecticut)
Flash Flood Guidance values	Created	NWS River Forecast Centers
Infrastructure, and critical facilities	ESRI, Inc.	ESRI, Inc.

Table 1. Spatial data sources

a. Representing and mapping vulnerability

Factors that contribute to societal vulnerability and to flood hazard are numerous. Analysis of hazards literature (Mitchell et al. 1997; White 2001), suggestions from flood hazard researchers, and available social data for the study area helped to determine factors contributing to flood hazard vulnerability. Previous research (Cutter 1996, Wilhelmi et al. 2004) showed that age, ethnicity, gender, home ownership and household characteristics influence societal vulnerability to natural hazards and a flood hazard in particular. Eight factors, based on Census 2000 block groups were identified as key vulnerability factors for this project. These factors included population density, renters, females, female households with at least one child, Hispanic households (due to lack of English skills), children between 5 and 17 years old, children younger than 5 years old, and population over 65 years old. Each of these categories had an equal weighting in terms of its contribution to overall vulnerability except for the *renters* class, which was weighted less heavily. This weighting scheme was selected based on previous research on each group's vulnerability to a flash flood event. In addition to demographic data, data concerning critical facilities (e.g., schools, hospitals, churches) were included in estimating total vulnerability for each of the census block groups.

Once these vulnerability factors were identified, graphics of established relationships were created. Key areas of social vulnerability were mapped in a GIS and different classes showing density of vulnerable groups and facilities were color-coded. The process of constructing the vulnerability index is shown in Fig. 4.

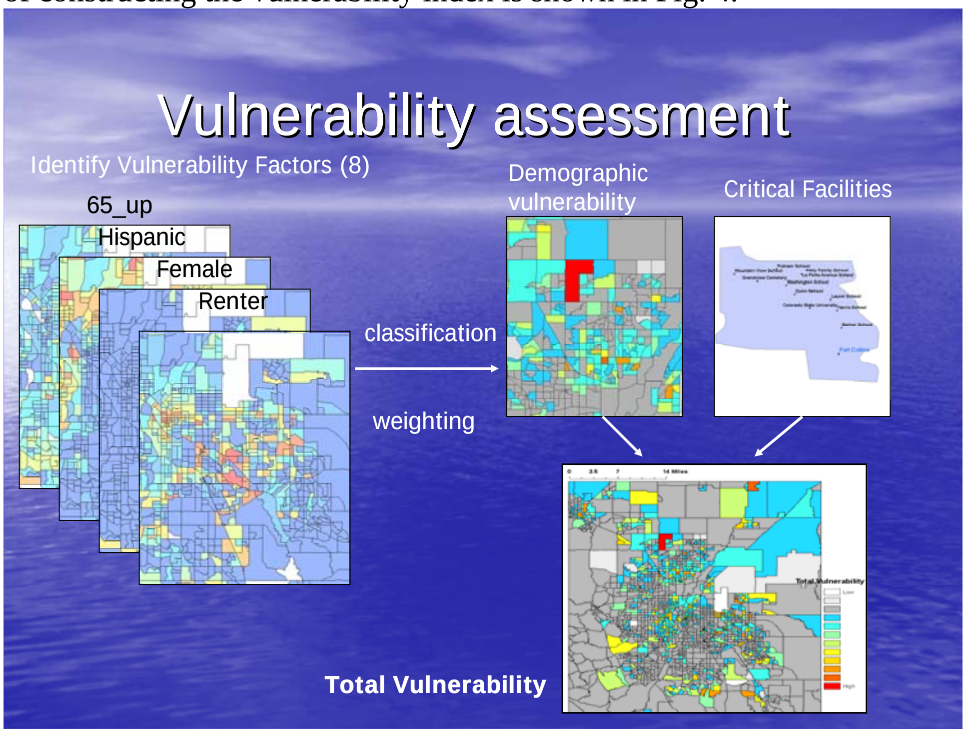

Fig. 4. Vulnerability assessment process

b. Representing and mapping exposure

The next step in the risk assessment was to analyze the exposure element of the risk equation (1). Estimating exposure to a flood hazard was based on the AMBER method. When performing calculations in GIS it was important to have all the data in the same projection. For this project we selected the UTM Zone 13N WGS 1984 projection as a spatial reference for all the data. Several datasets had to be re-projected using re-projecting tools in ArcGIS. To implement the AMBER method, we used archived radar data from the Fort Collins 1997 flood event, calculated the basin average rainfall using GIS and compared those averages to the county wide flash flood threshold values issued by the National Weather Service. The process is shown in Fig. 5 and the main steps of this GIS-based process are outlined below.

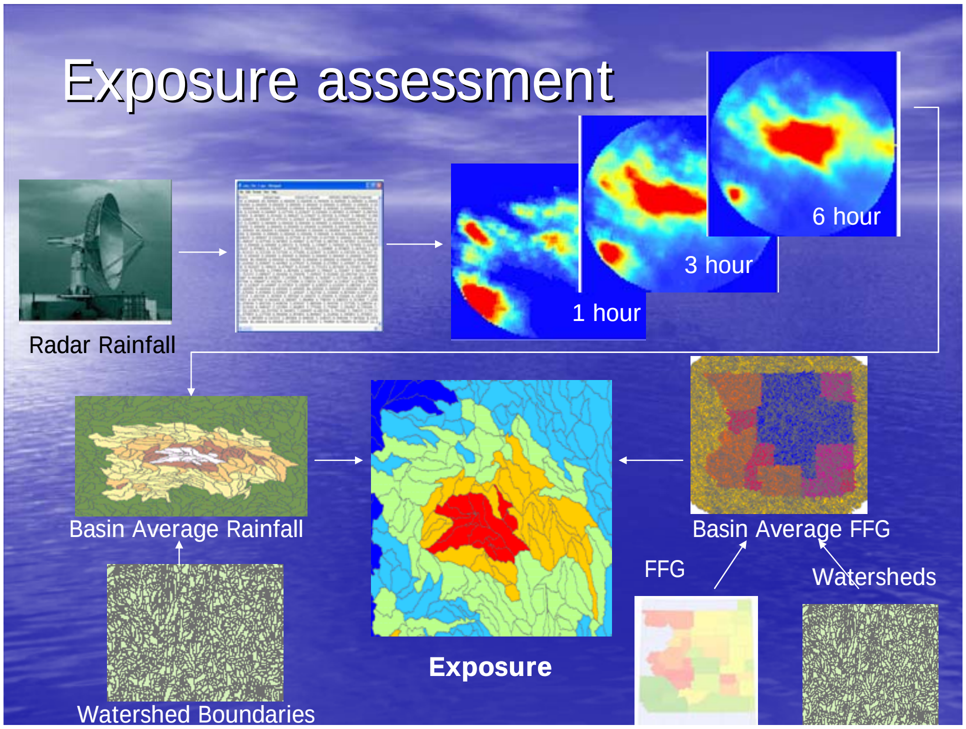

Fig. 5. Exposure assessment process

To use rainfall data in ArcGIS, the data needed to be converted from their original format to an ESRI GRID raster format. We used a conversion tool (courtesy of D. Yates, NCAR) to convert radar precipitation values integrated over different time intervals into a file format that could be imported into ArcGIS. As a next step, the watershed averages for 1, 3, and 6 hour precipitation event time intervals were calculated using the Ft. Collins rainfall data. This was performed in ArcGIS using *Zonal Statistics* tool. This tool allows one to calculate statistics on values of a raster within the zones of another dataset, which in this case is the watershed dataset (courtesy of T. Huse, NWS). A color scheme was applied to the output watersheds to represent the amount of precipitation that occurred over it. The process was repeated for all rainfall event time slices, eight in total, consisting of five 1-hour, two 3-hour, and one 6-hour intervals.

The next step was to determine the Flash Flood Guidance (FFG) values for the Colorado Front Range counties and create a spatially referenced FFG dataset. The fact that the rain events were broken into 1, 3, and 6 hour intervals made for effective comparison to the FFG values determined by the NWS for all the Front-Range counties for the same time intervals. This data was obtained from the NWS Missouri Basin River Forecast Center and the Arkansas-Red Basin River Forecast Center, and converted into a database format using Microsoft Excel. The output database file was joined in ArcGIS with the spatially referenced file representing Front Range counties. Because of this spatial join we were able to represent the FFG values by county and color code the counties based upon the FFG values in the same manner we did for the watersheds. The output dataset was converted from a shape file format to a raster format. This was done in order to use the *Zonal Statistics* tool in ArcGIS for estimating average FFG values for all the watersheds.

The final step of the AMBER method was to compare basin average rainfall amount with basin average FFG values. The calculated difference between the watershed precipitation and the FFG thresholds indicated run-off and flooding potential. The watersheds that exceeded the threshold FFG value were selected and identified as "flooding alert" or primary exposure factors contributing to the flash flood risk.

c. Estimating and mapping risk

Once the exposure assessment was completed we were able to combine our final flood alert assessment with the urban areas information. Urban areas are of interest because they have a lower FFG values due to the inability of these areas to absorb water, and the AMBER model treats surface features equally. So to account for this, the urban areas dataset was then combined with the exposure and the total vulnerability to create a total risk of the area (Fig. 6).

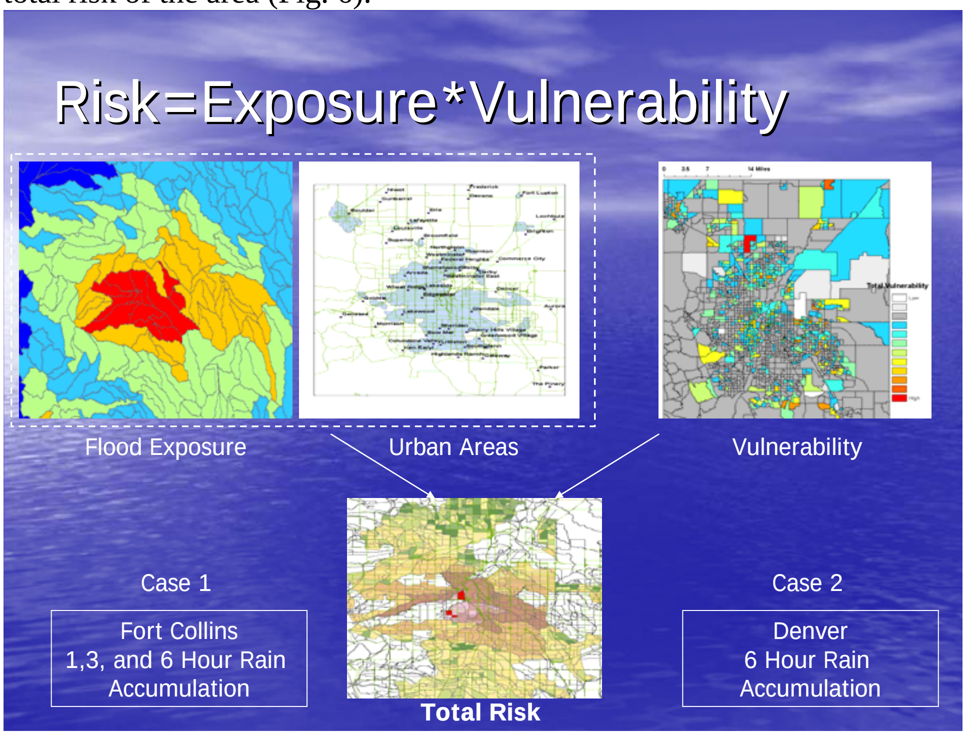

Fig. 6. Risk Assessment process

This methodology can be applied to different regions of the geographic area of interest by using the *Georeferencing* tools in ArcGIS. This tool allows one to take a raster file and its corresponding data set, and transpose it over another location in the geographic area. Thus, after performing the above procedure for the Fort Collins 1997 storm in its original location, we transposed the storm over the Denver area and performed a risk assessment with Denver watersheds and population characteristics if the Fort Collins storm occurred over that area.

3. Results and Discussion:

Vulnerability assessment was performed for the entire Front Range domain (Fig. 7) and then combined with exposure and analyzed in terms of total risk detail for two cases: Fort Collins and Denver metropolitan areas.

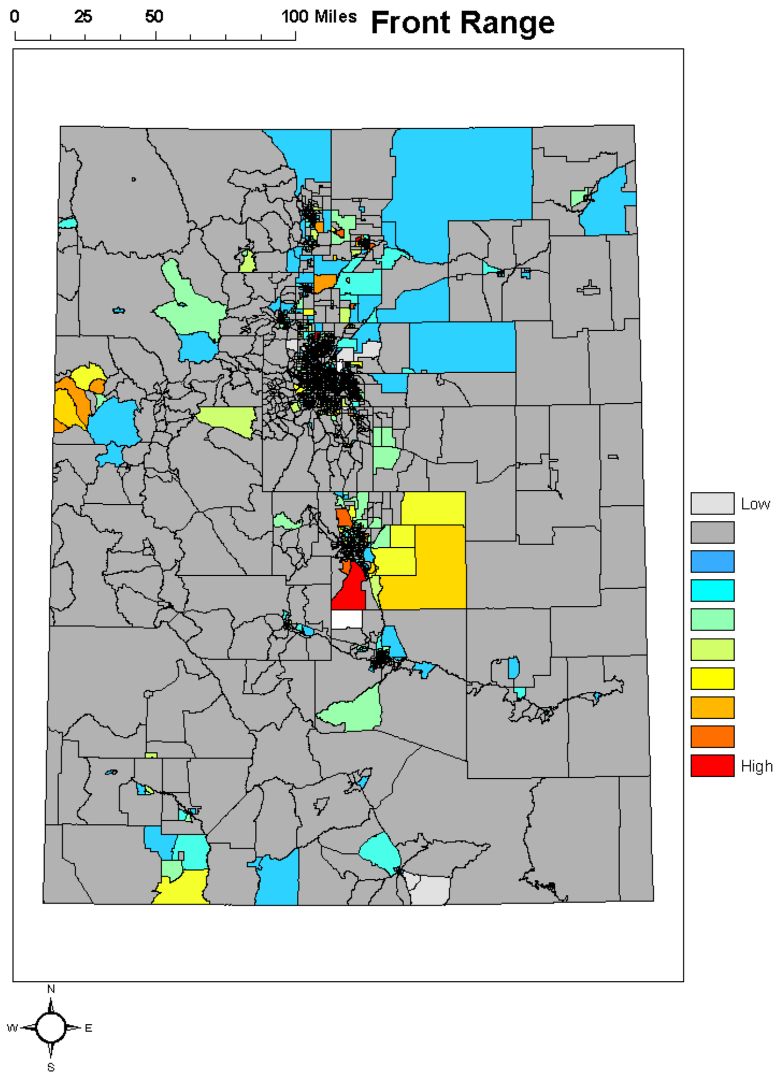

Fig. 7. Front Range Vulnerability

Figures 7, 8 and 11 show relative vulnerability ranking, from *low* to *high*. Higher rankings indicate higher density of vulnerable social groups in a given census block group and presence of vulnerable critical facilities (Fig. 9, 12). Please refer to the Appendix A for detailed graphics on the particular groups which compose the total vulnerability zones in Fort Collins and Denver.

a. Fort Collins

In the Fort Collins area, as shown in Fig. 8, we see significant spatial variability in vulnerable locations with highest concentration of vulnerable populations located in the southwestern part of the city. Figures 15-22 in Appendix A show that this area contains high densities of children, females and Hispanic population. Given the fact that the total vulnerability was a composite of the entire Front Range, the local vulnerability factors in Fort Collins were diluted. Thus, when focusing on this particular area, the vulnerability levels will not necessarily be as high because they are being estimated for the entire Front Range. The distribution of critical facilities in Fort Collins in shown in Fig. 9.

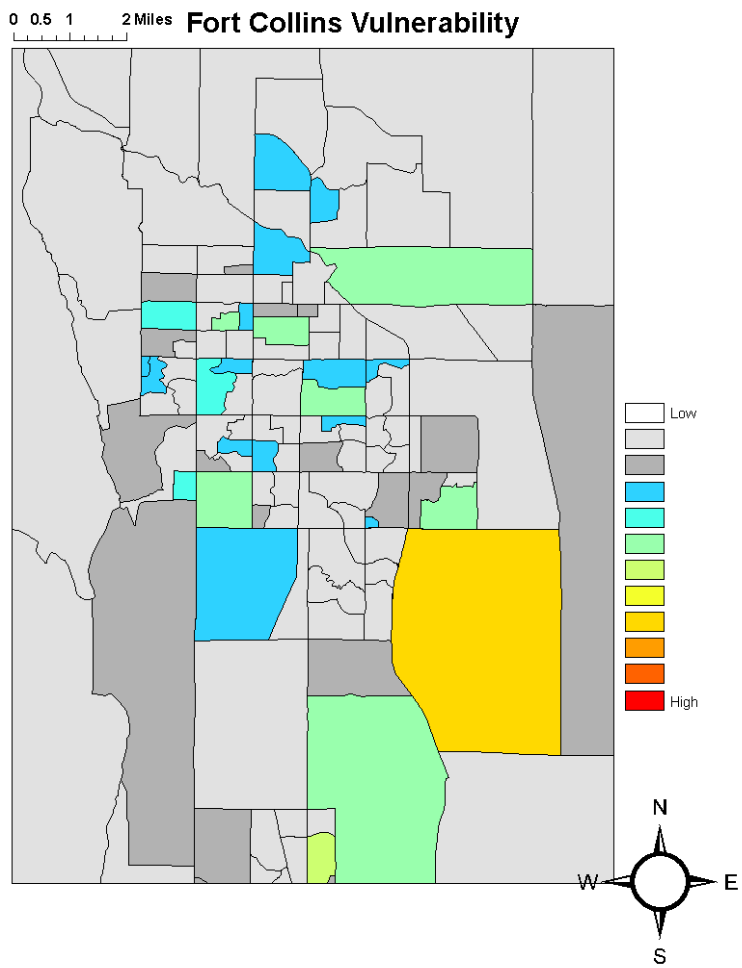

Fig. 8. Vulnerability distribution in Fort Collins metropolitan area

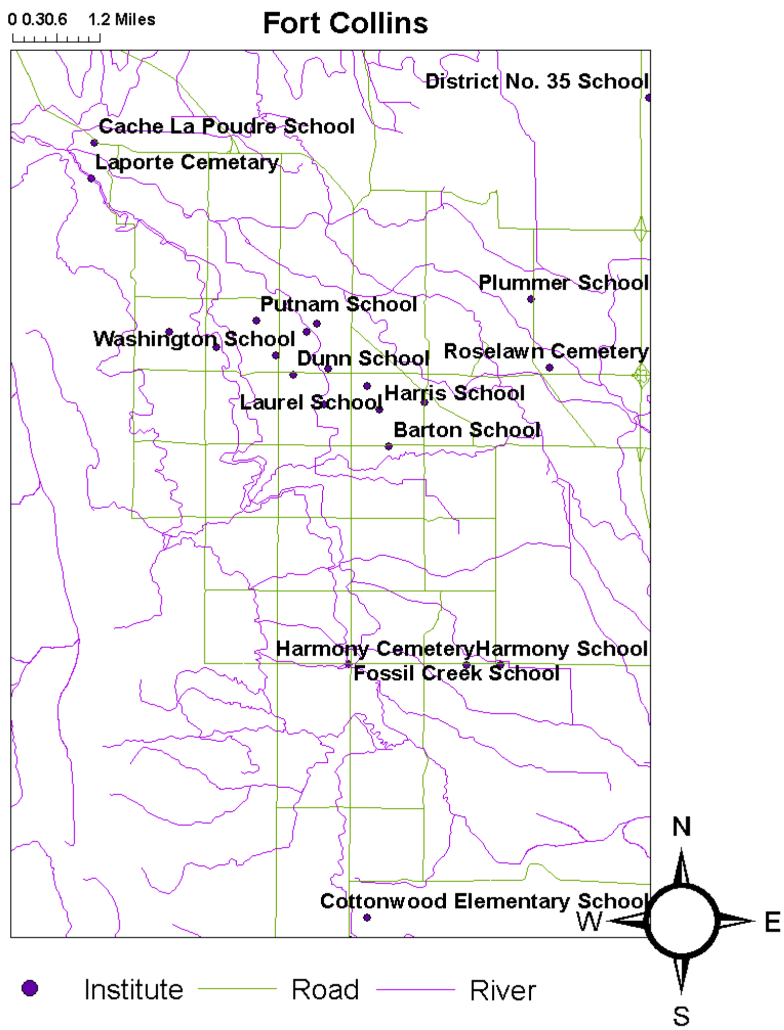

Fig. 9. Distribution of critical facilities in relation to roads and rivers in Fort Collins

When assessing flash flood hazard, i.e., the exposure element of the risk equation (1), in Fort Collins, we were able to see the propagation of the flood alerts as the storm moved over the area. Fig. 10 shows precipitation accumulation in three time intervals and its effect on flash flood exposure. In addition, it is important to remember that due to runoff, areas not directly affected by precipitation are not immune to the flooding that occurs upstream.

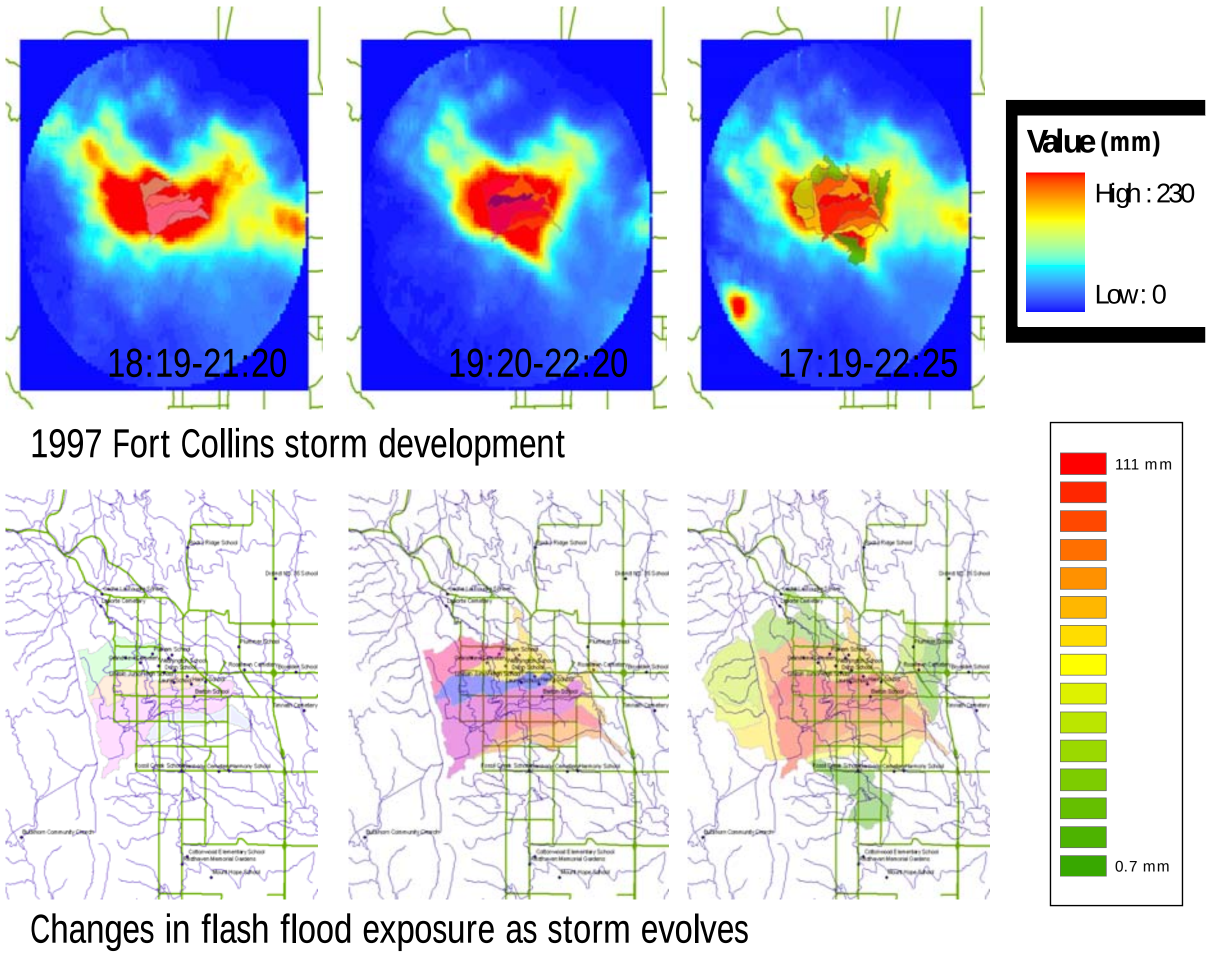

Fig. 10. Fort Collins flash flood alert evolution

b. Denver

When looking at Denver, we noticed significant spatial variability in terms of vulnerability (Fig. 11). The suburban areas of Denver featured the highest concentration of children, while the more urban areas featured more Hispanics and elderly population (Fig. 23-30 in Appendix A).

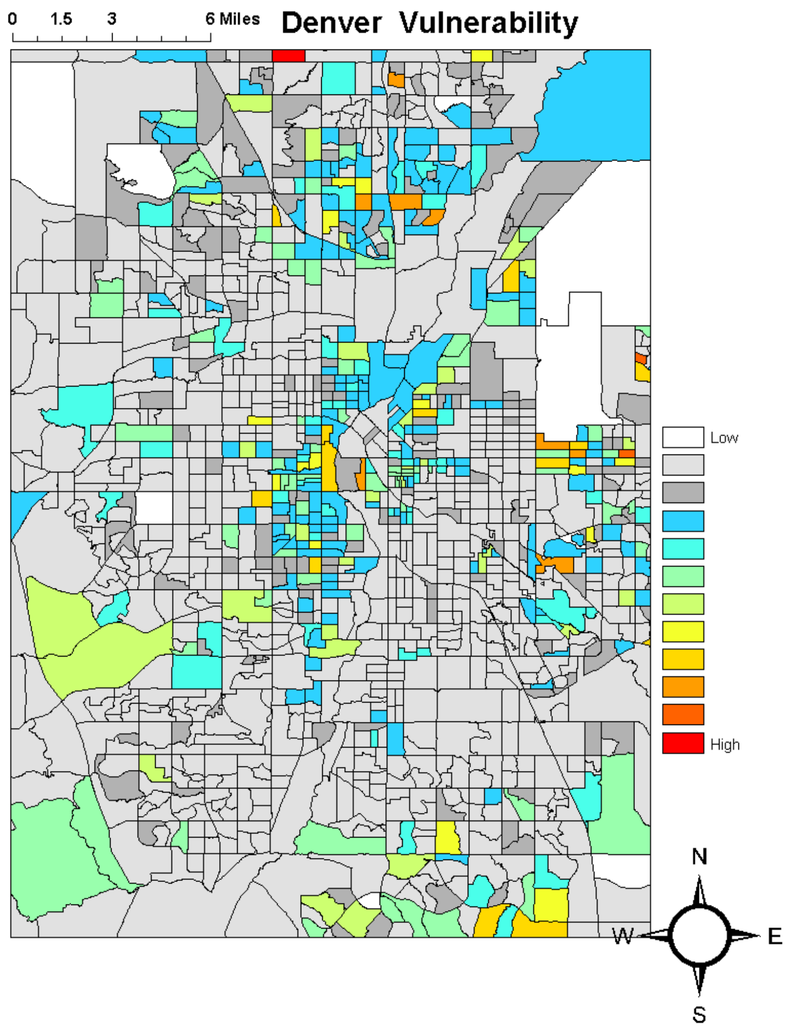

Fig. 11. Denver total vulnerability

There are also numerous institutions (Fig. 12) throughout the Denver metro area, which could make it difficult to move people in need in case of a flash flood event due to the spatial variability in the institution locations.

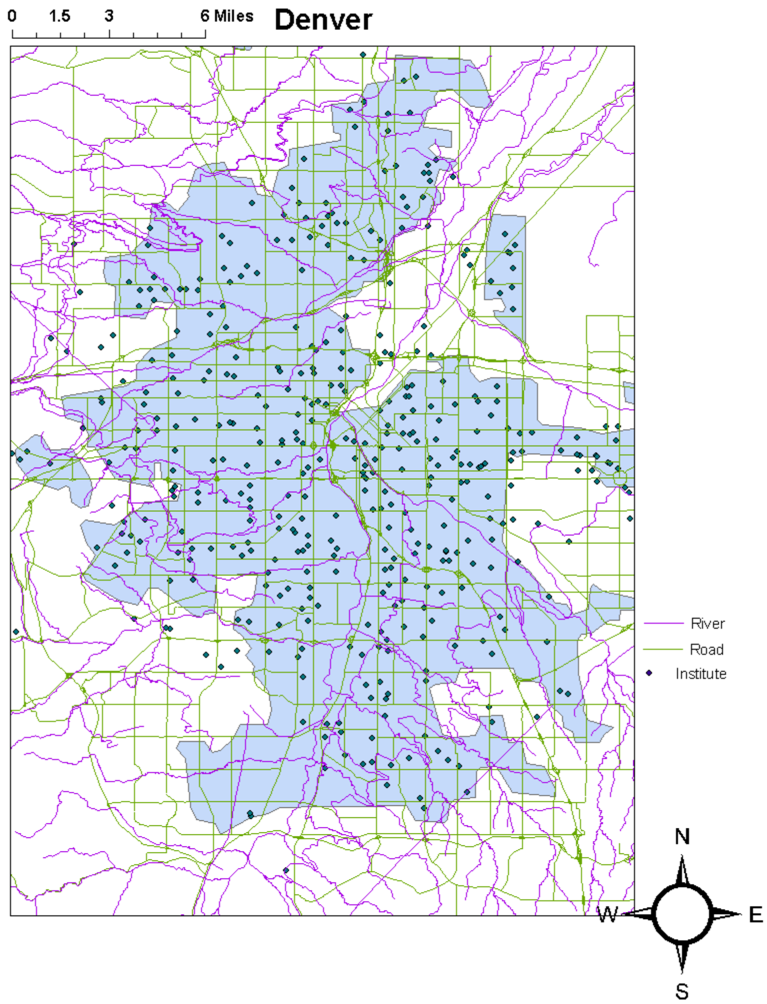

Fig. 12. Distribution of critical facilities in Denver metro area

c. Flash flood risk in Fort Collins and Denver

When comparing the risk estimates for Fort Collins and Denver (Fig. 13-14) it was important to note that Denver had a significantly higher population than Fort Collins. However this element did not affect the wide spatial variability in risk for each location. This spatial variability also provides an added difficulty for emergency management, in terms of distributing resources to all the locations at risk. If these locations were more centralized, then the difficulty to the emergency management would not be as great. On the other hand, due to the spatial variability of these risk zones, if a flash flood event were to occur, the probability of the entire risk zone being affected would not be as great. In Denver it is also important to take note of the road networks in terms of the traffic network in relation to the population density and risk of the area. If a key road network is next to a high risk zone, then an added risk factor would be incorporated depending upon if this road network was disrupted by the flash flood event.

Another important aspect is the type of institutions in a risk area. For example, hospitals are themselves vulnerable buildings, due to the importance of medical care during a flood and the people inside, many of whom are not in good health and cannot easily evacuate or be evacuated. When looking at the risk for the Fort Collins area we see that our methodology is sound because of the location of high risk over Colorado State University. This area suffered extensive damage during the Fort Collins 1997 flash flood event.

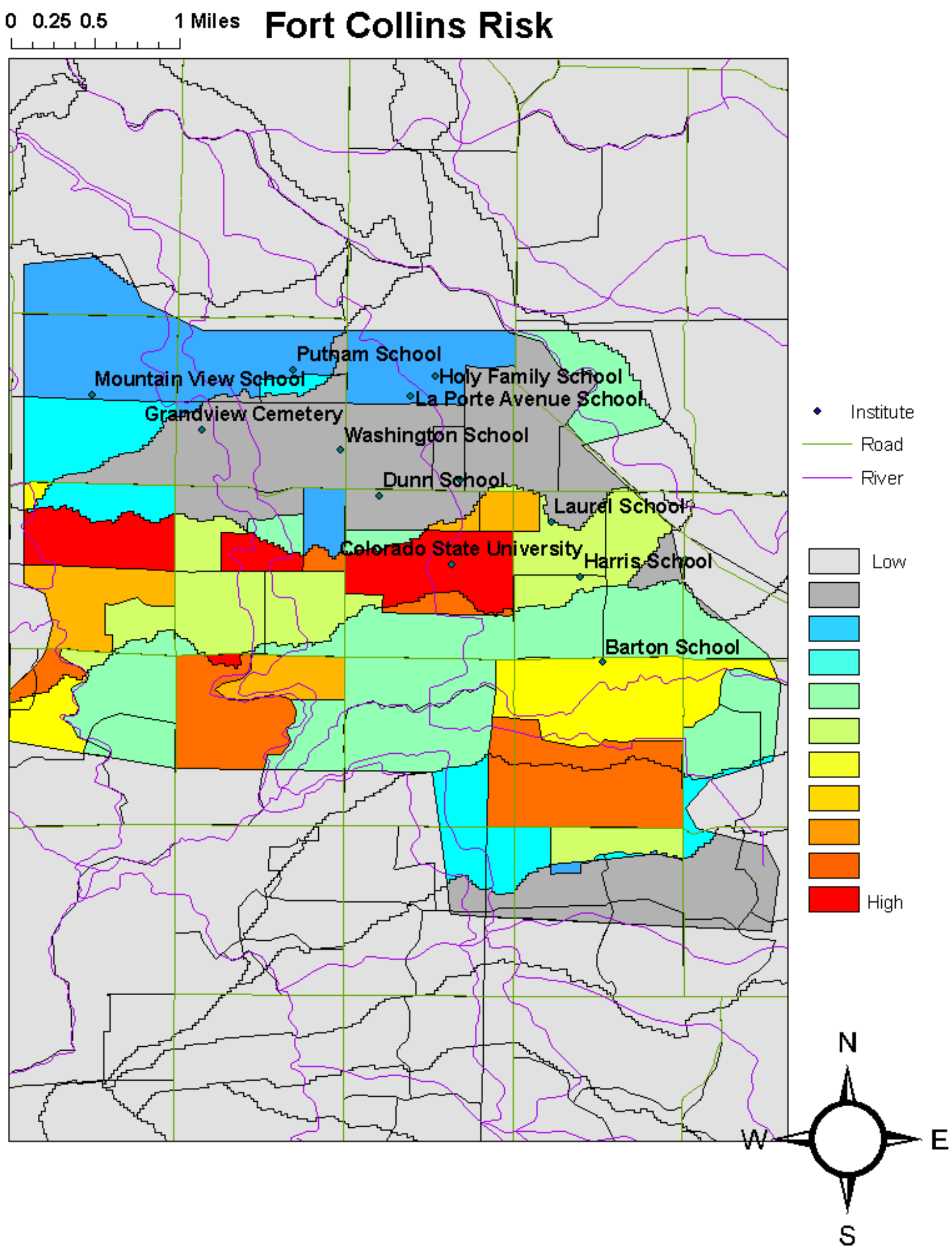

Fig. 13. Flash flood risk areas in Fort Collins

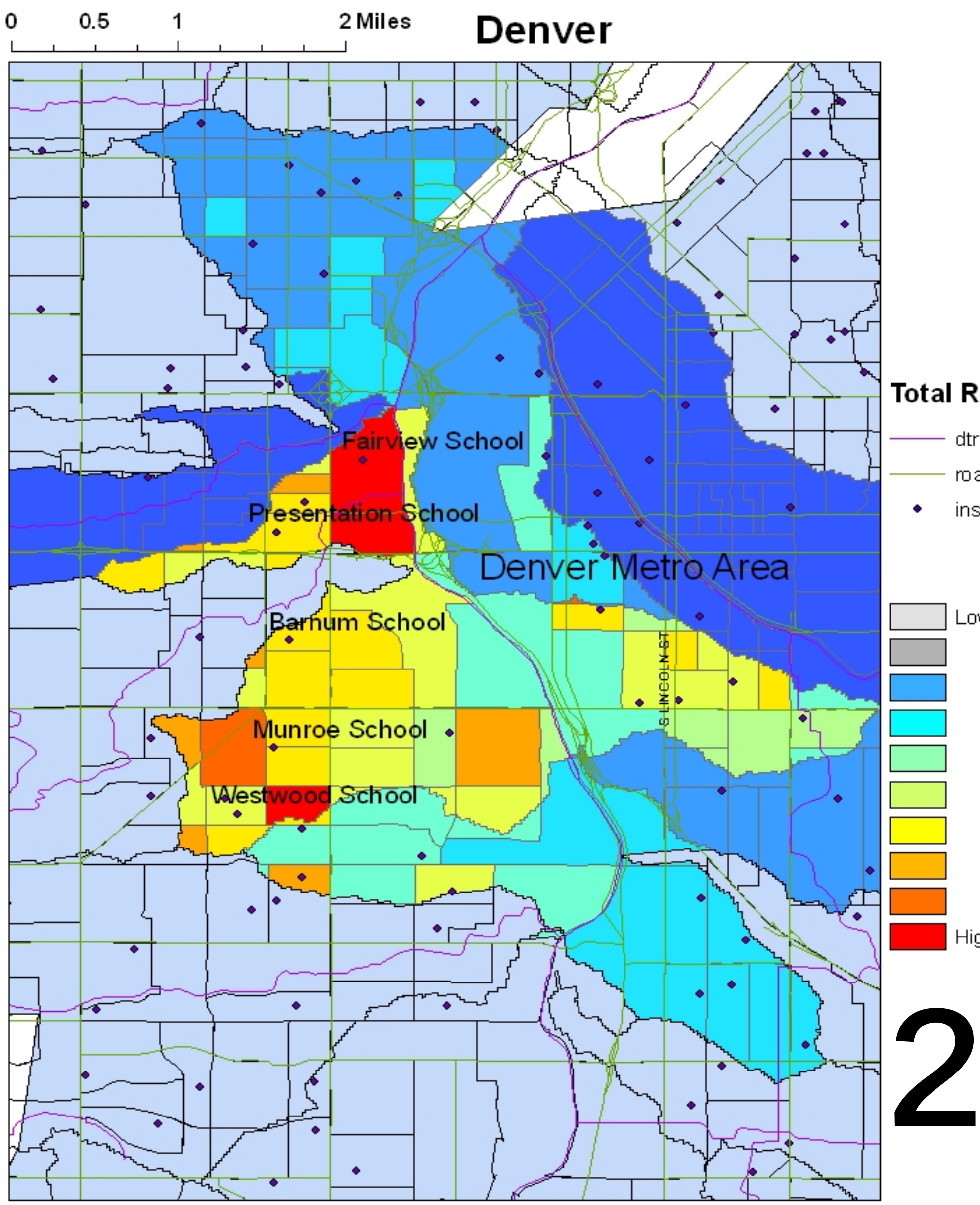

Fig. 14. Flash Flood risk areas in Denver

4. Conclusions

In this study, we used a GIS to evaluate the risk of flash floods in the Colorado Front Range region, specifically in the Fort Collins and Denver areas, by combining meteorological, geographical, and hydrological information with socioeconomic factors. The method developed in this research can be applied to any area on the globe where there is socioeconomic and precipitation data available, which makes it valuable for providing a focal point of information for meteorological forecasters and emergency management. This focal point of information is critical for providing quick and accurate risk assessments of a given area. By highlighting the key areas at risk due to meteorology, hydrological, and socioeconomic factors, emergency management can effectively devise mitigation strategies.

5. Acknowledgements

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Appendix A:

Fort Collins:

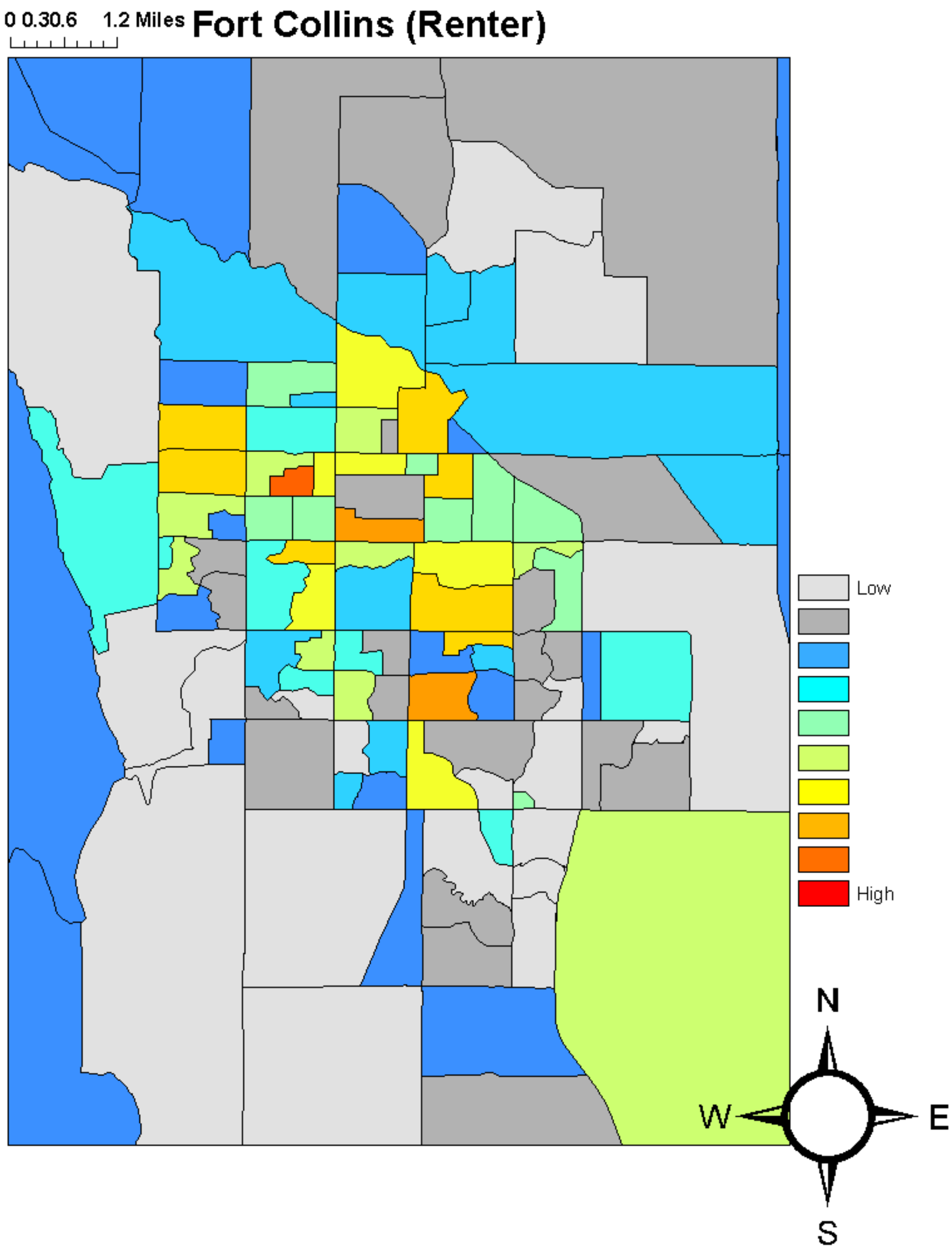

Fig. 15. Fort Collins Renters

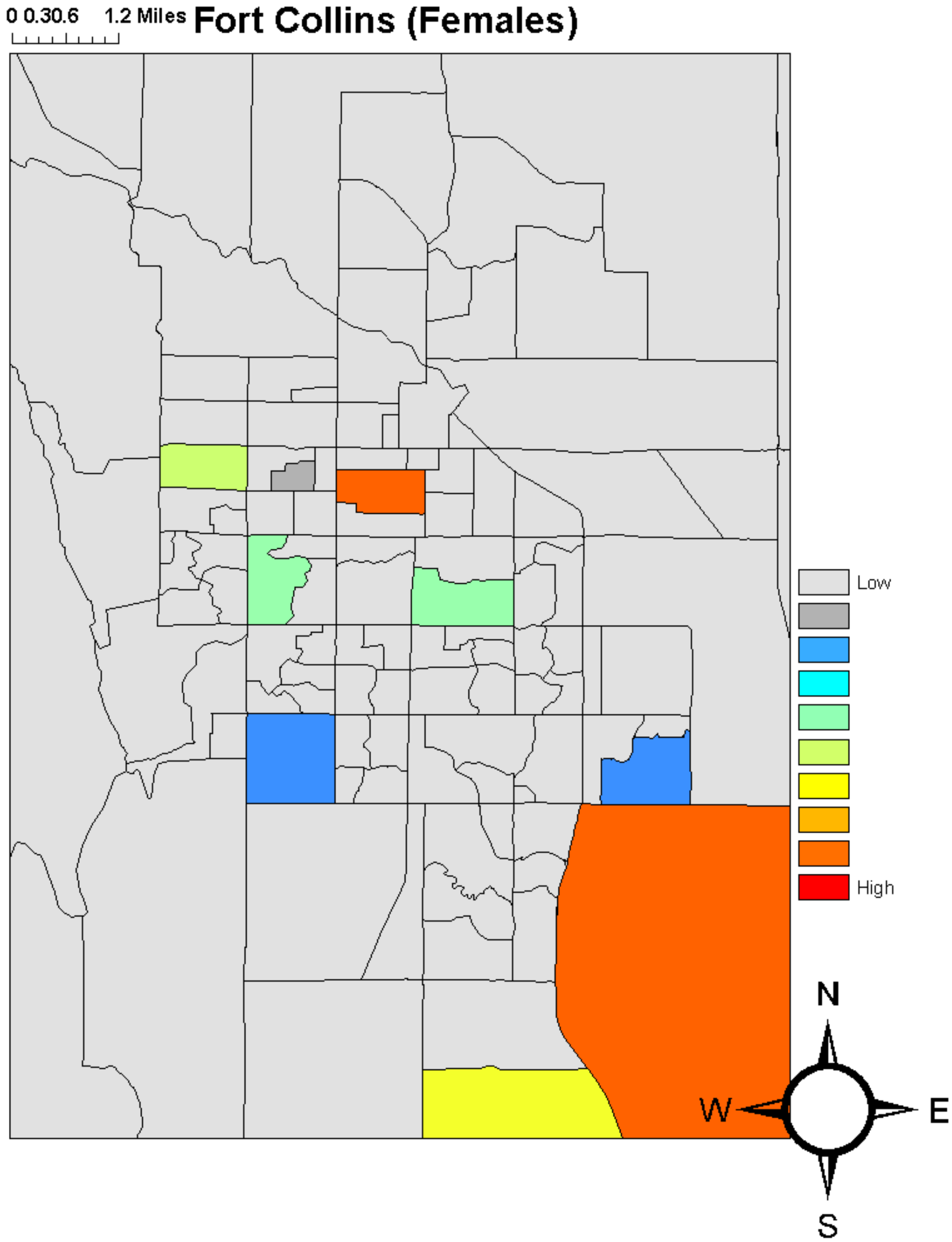

Fig. 16. Fort Collins Females

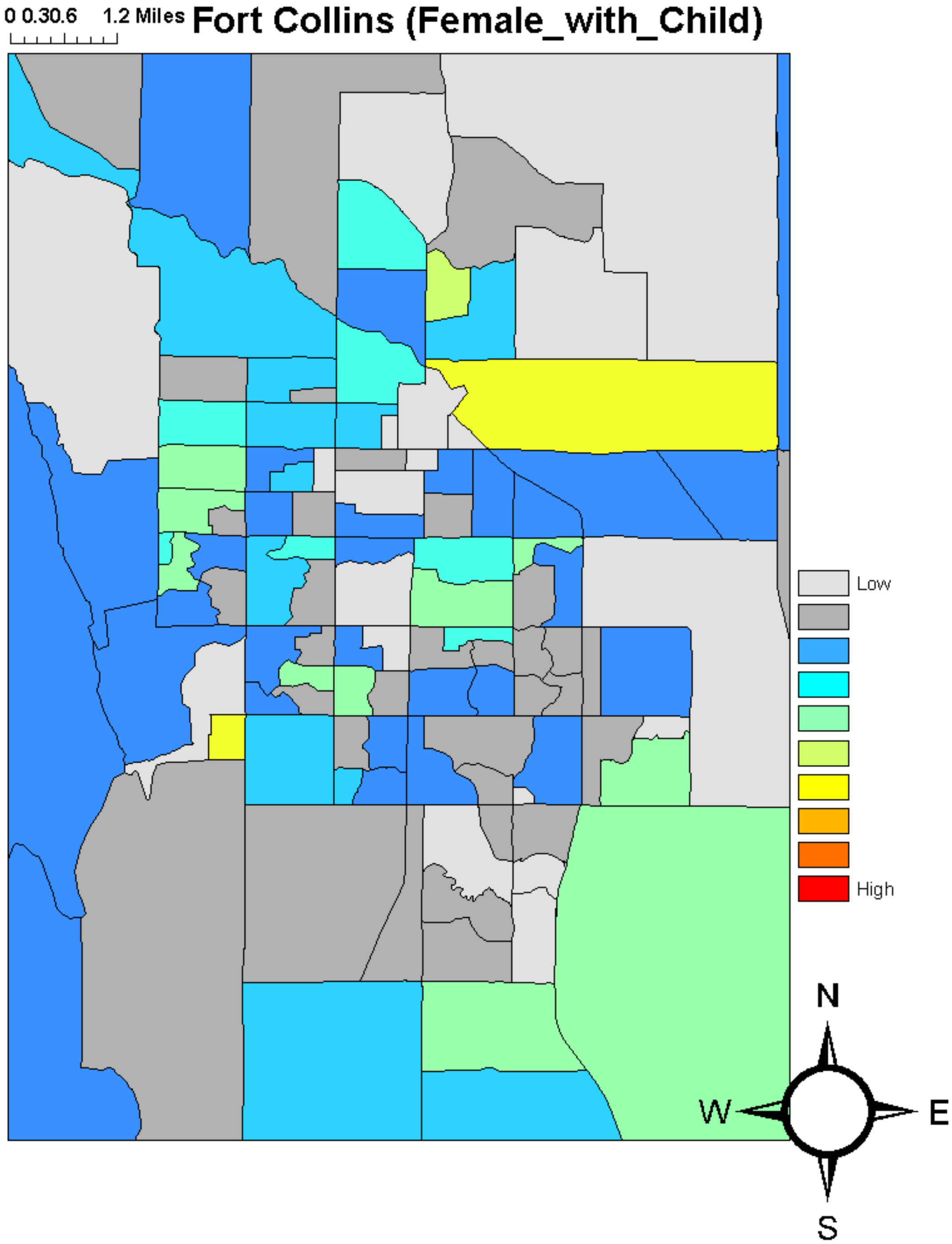

Fig. 17. Fort Collins Female Households with Child

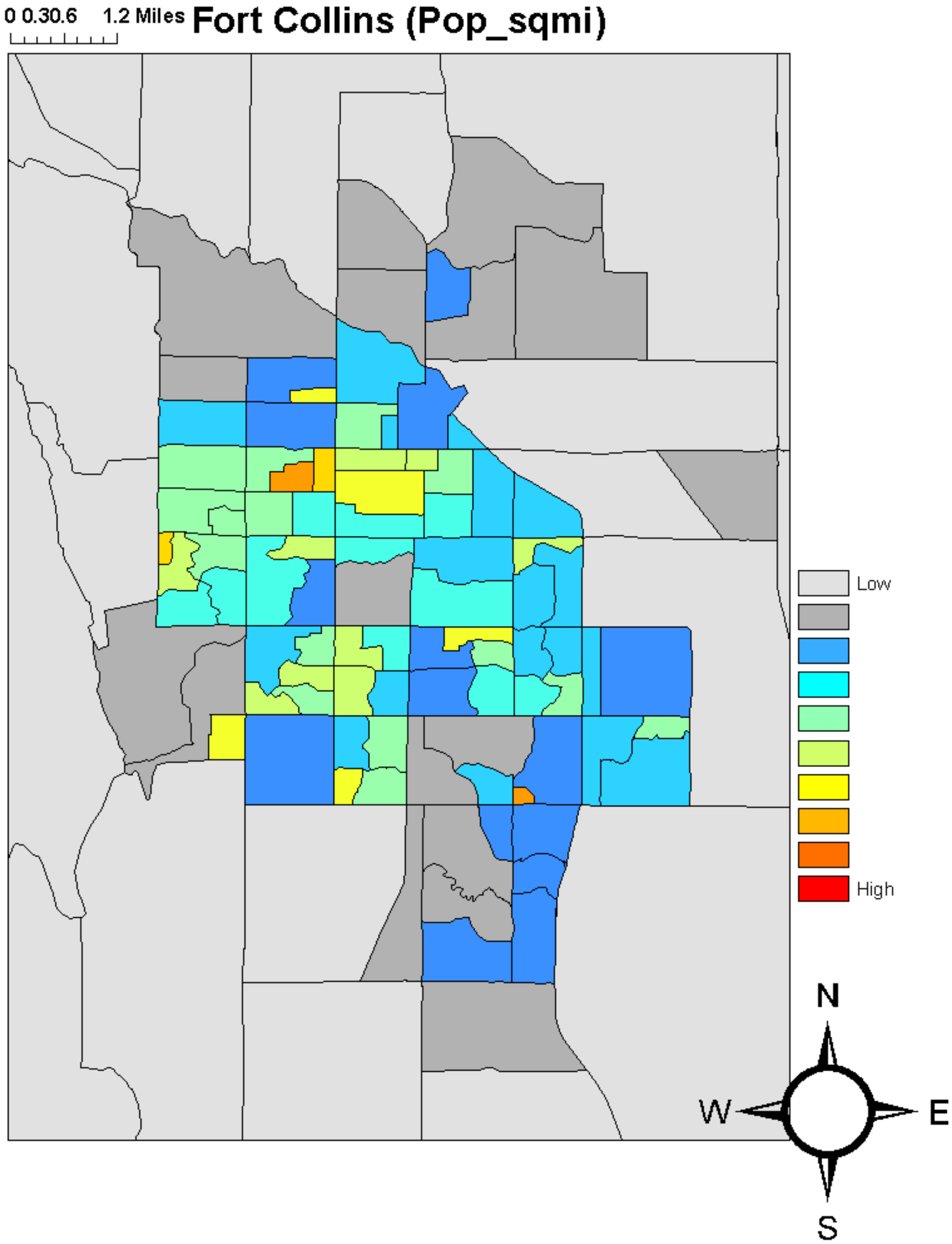

Fig. 18. Fort Collins population per square mile

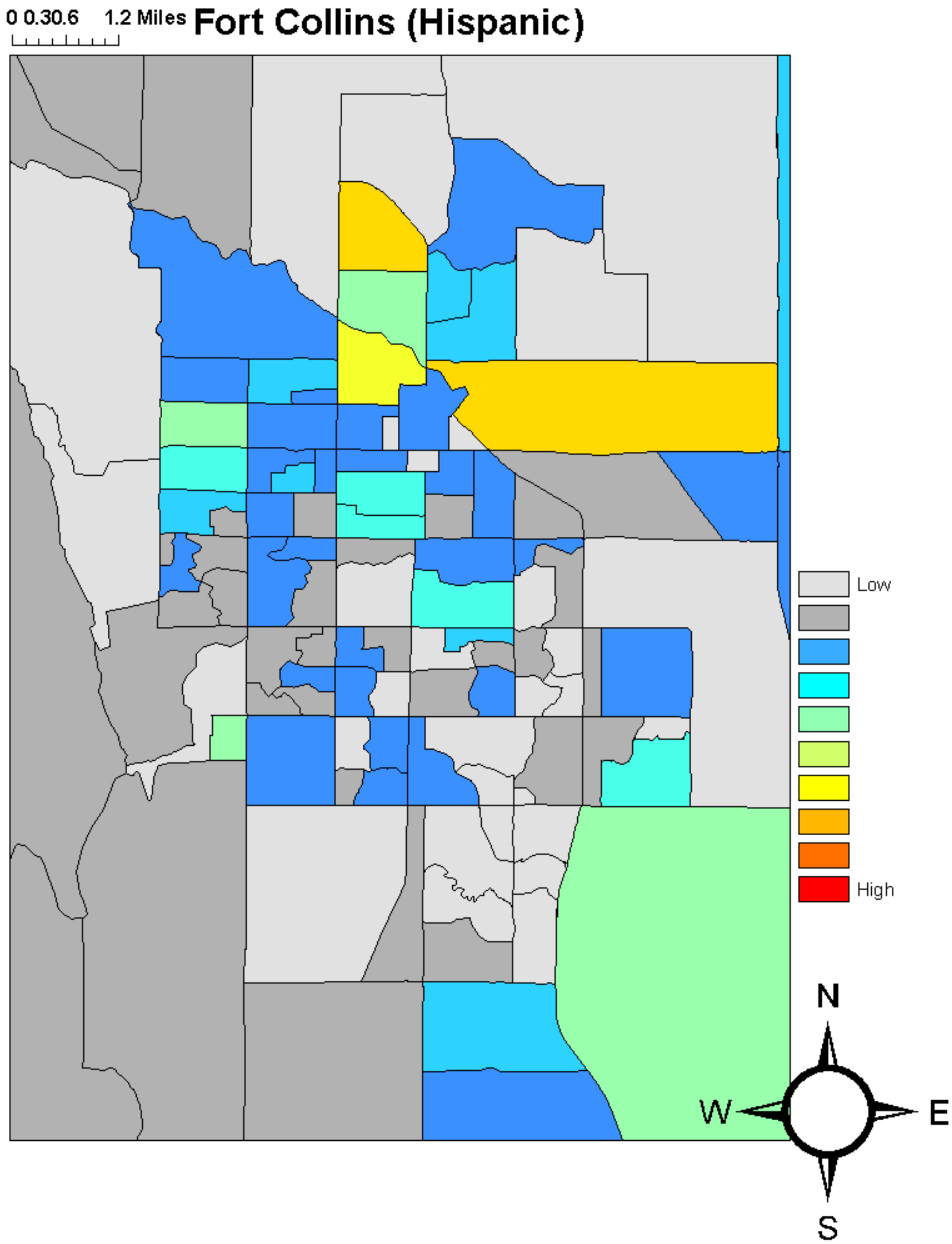

Fig. 19. Fort Collins Hispanic

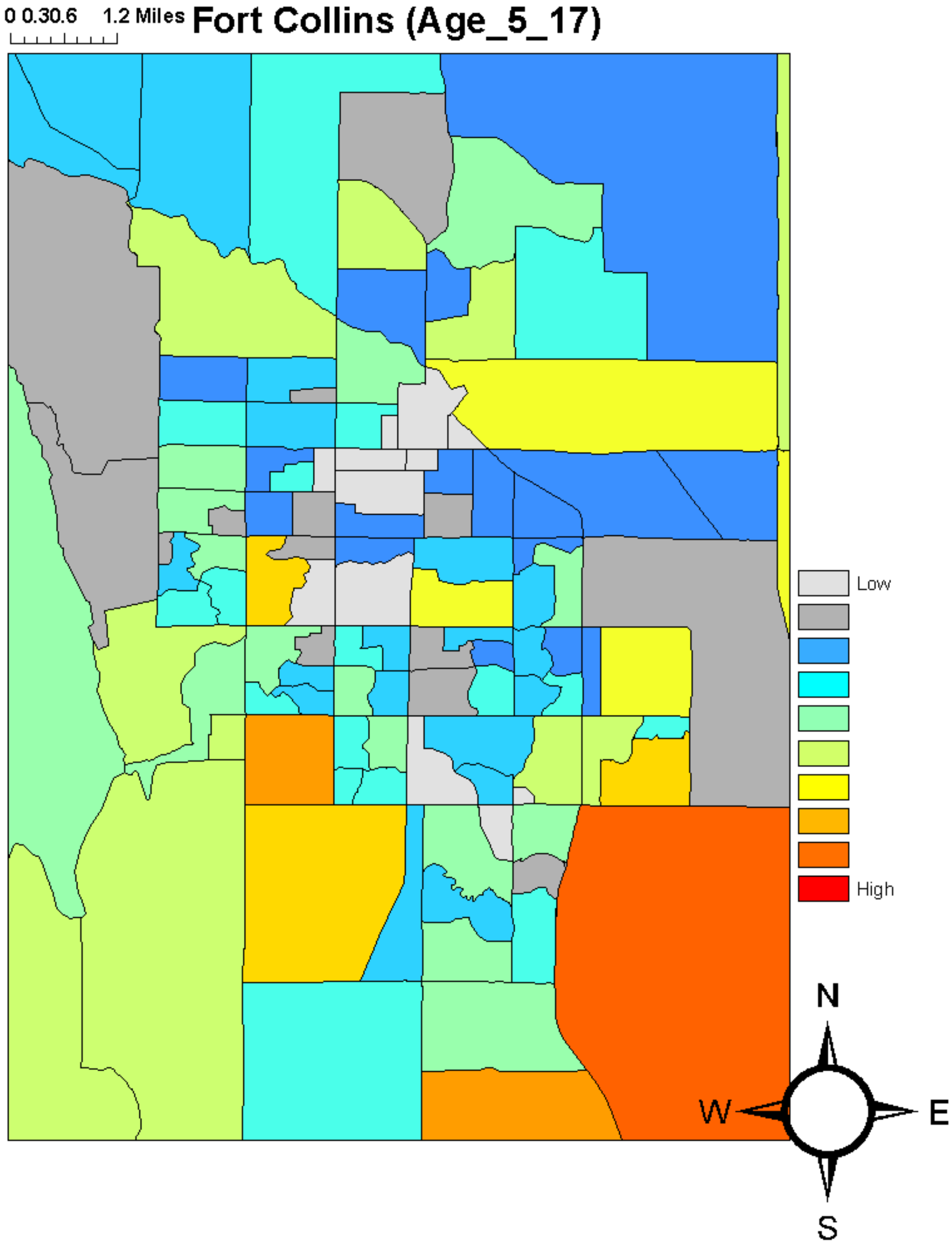

Fig. 20. Fort Collins Age 5-17

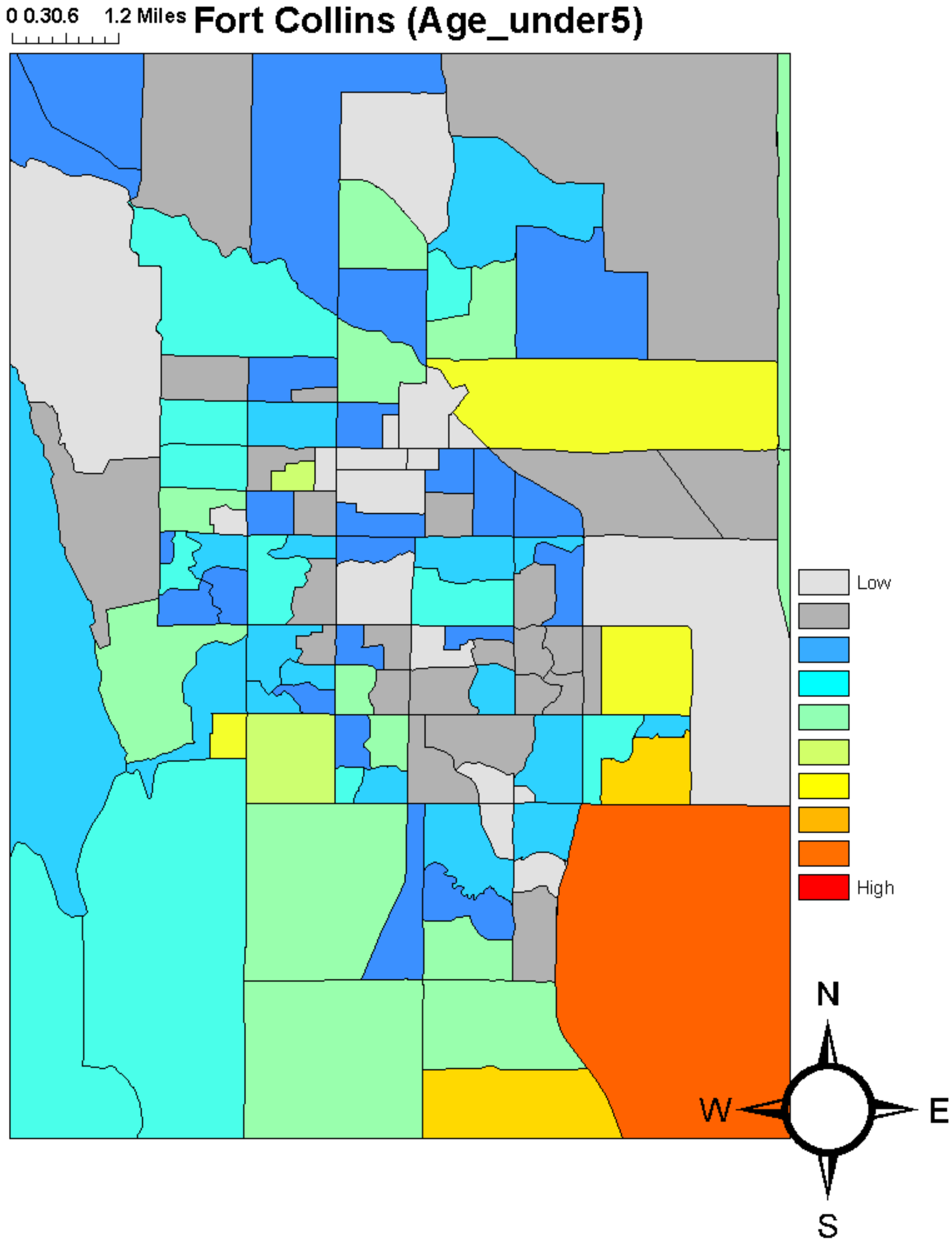

Fig. 21. Fort Collins Age 5 and under

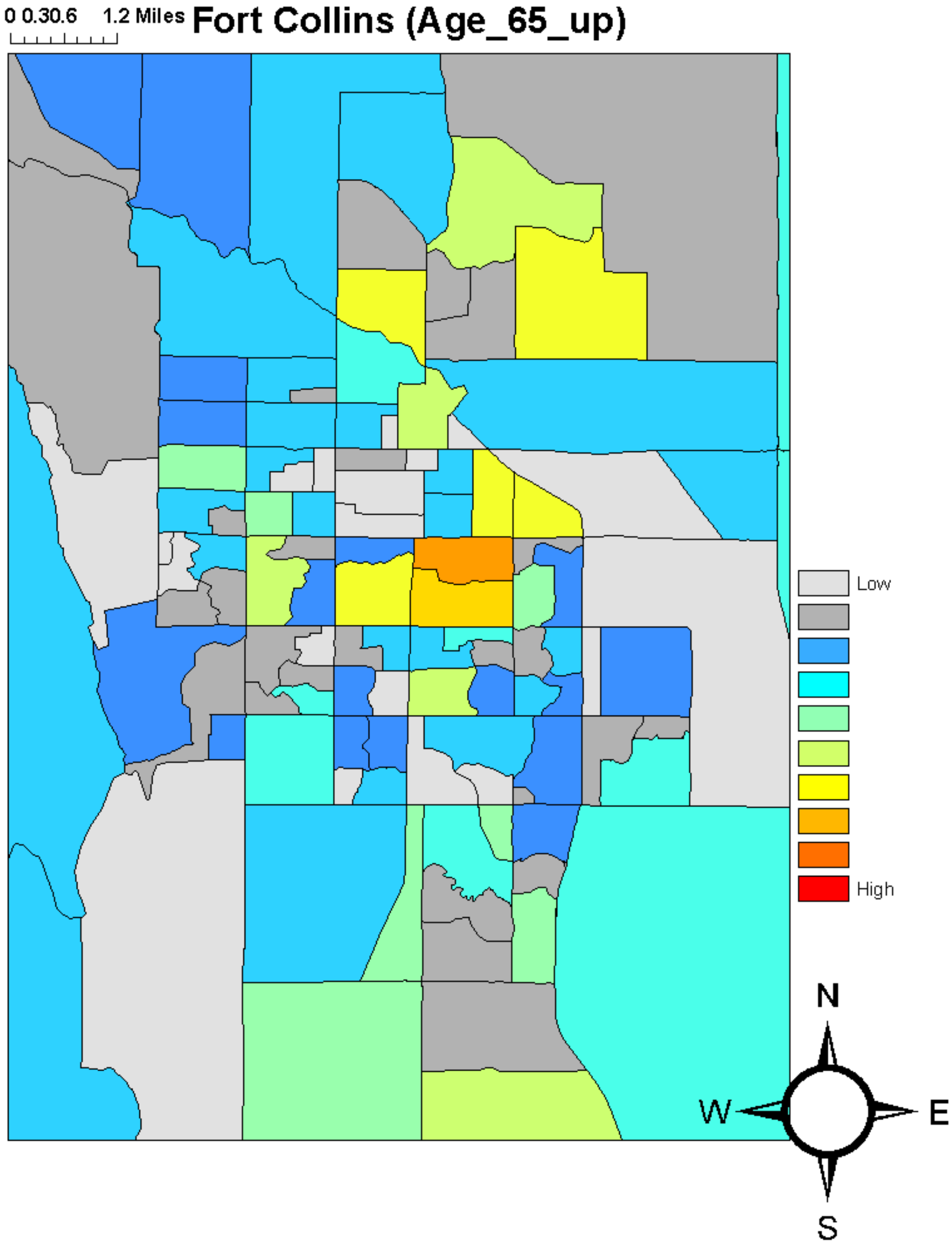

Fig. 22. Fort Collins Age 65 and over

Denver:

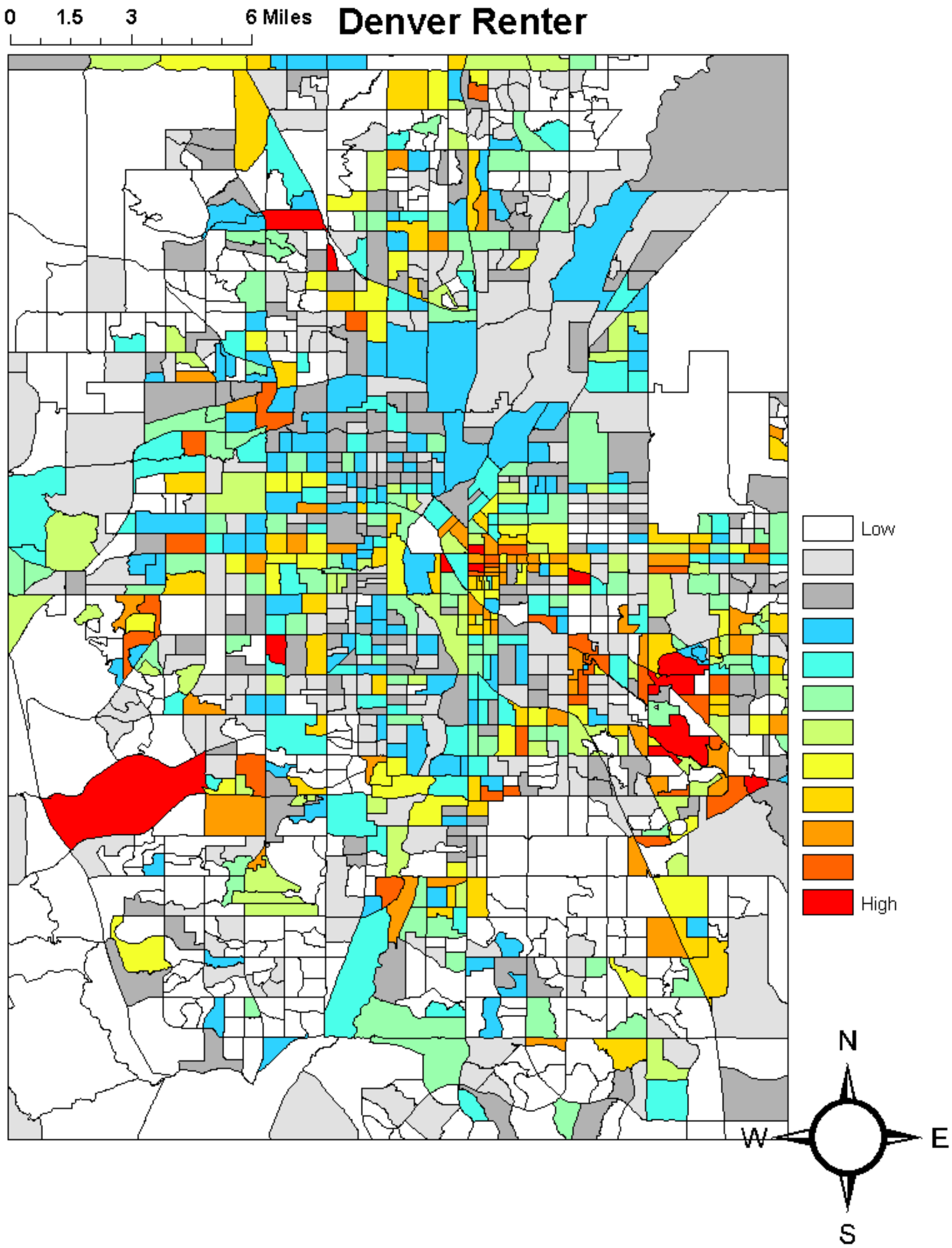

Fig. 23. Denver Renters

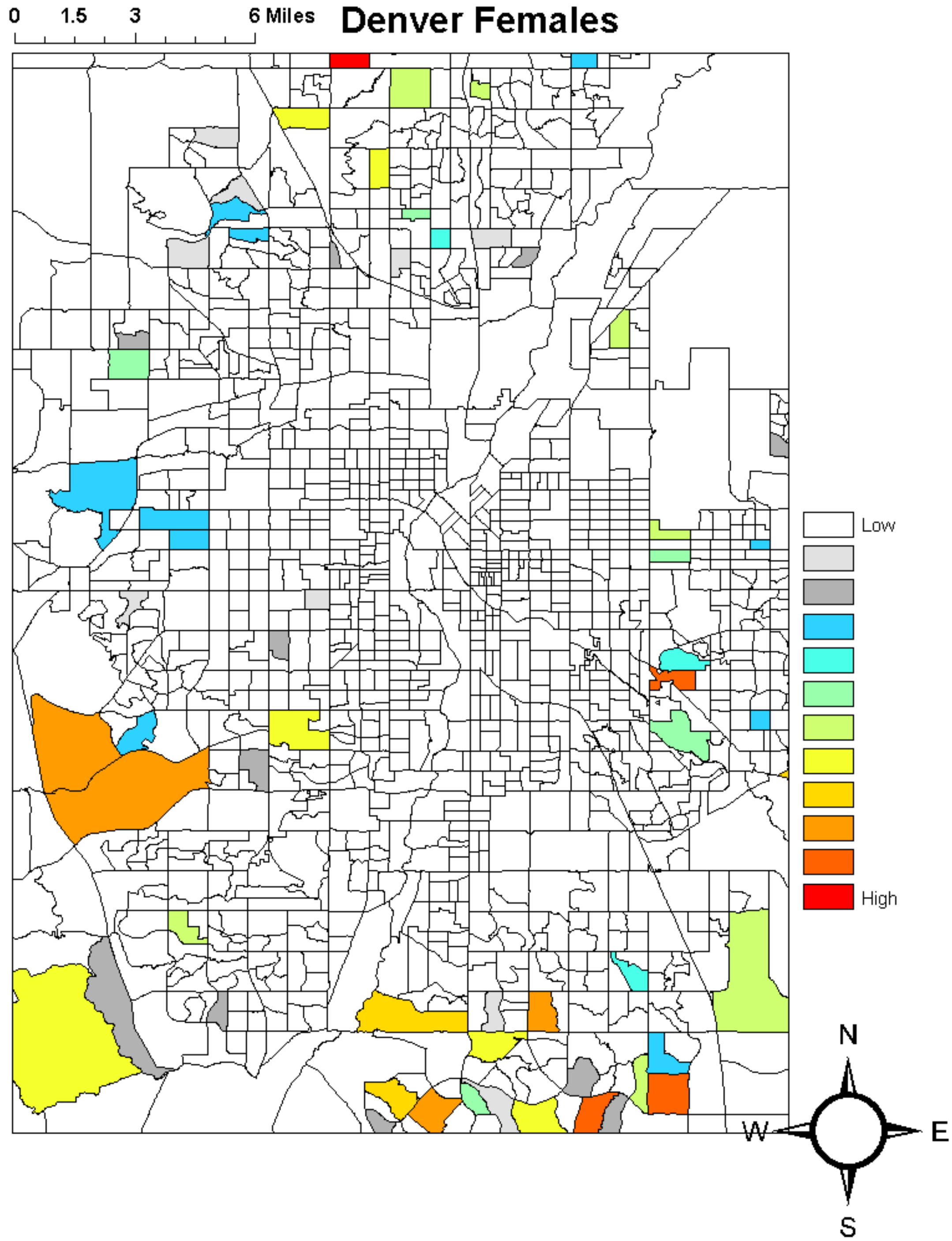

Fig. 27. Denver Females

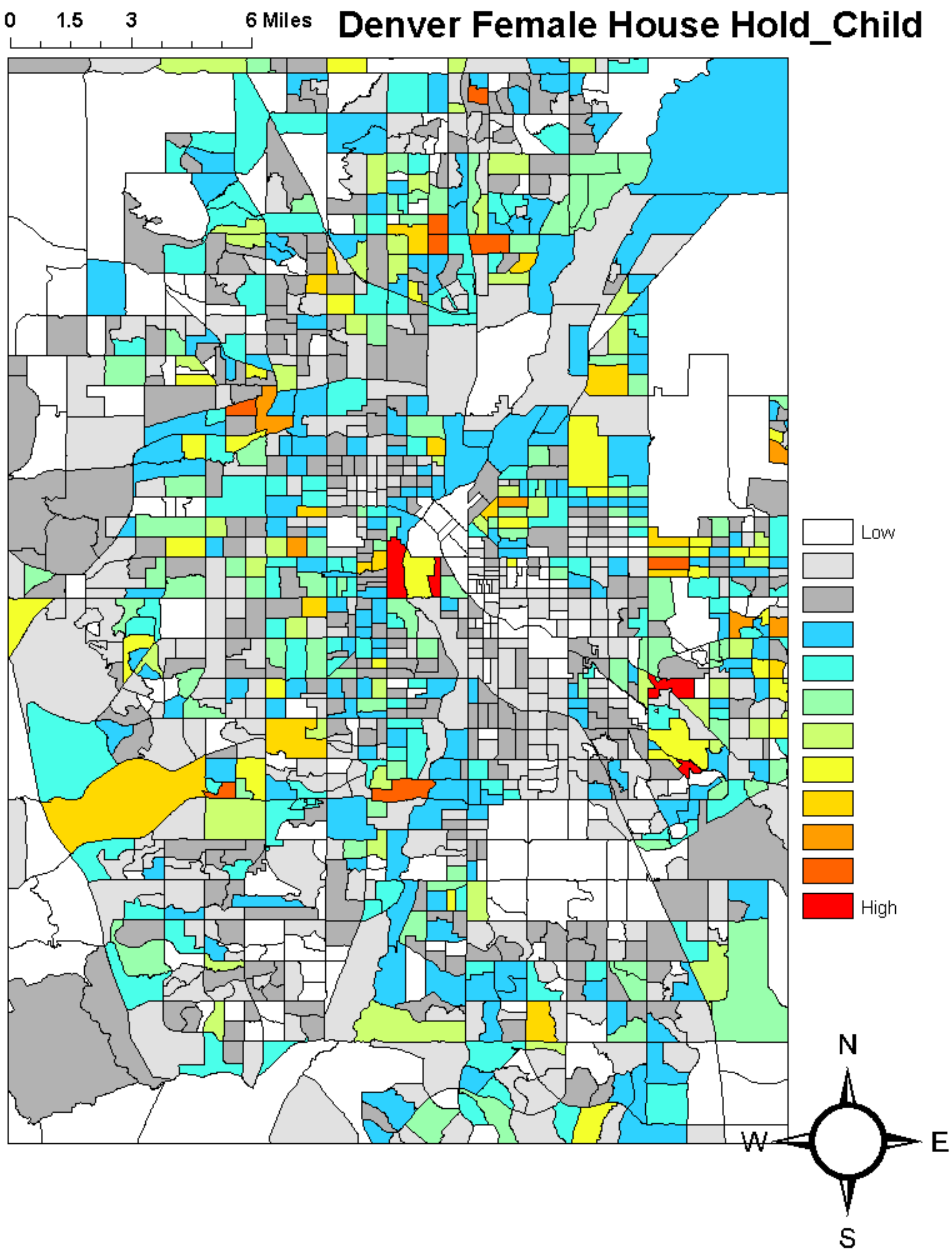

Fig. 28. Denver Female Household with Child

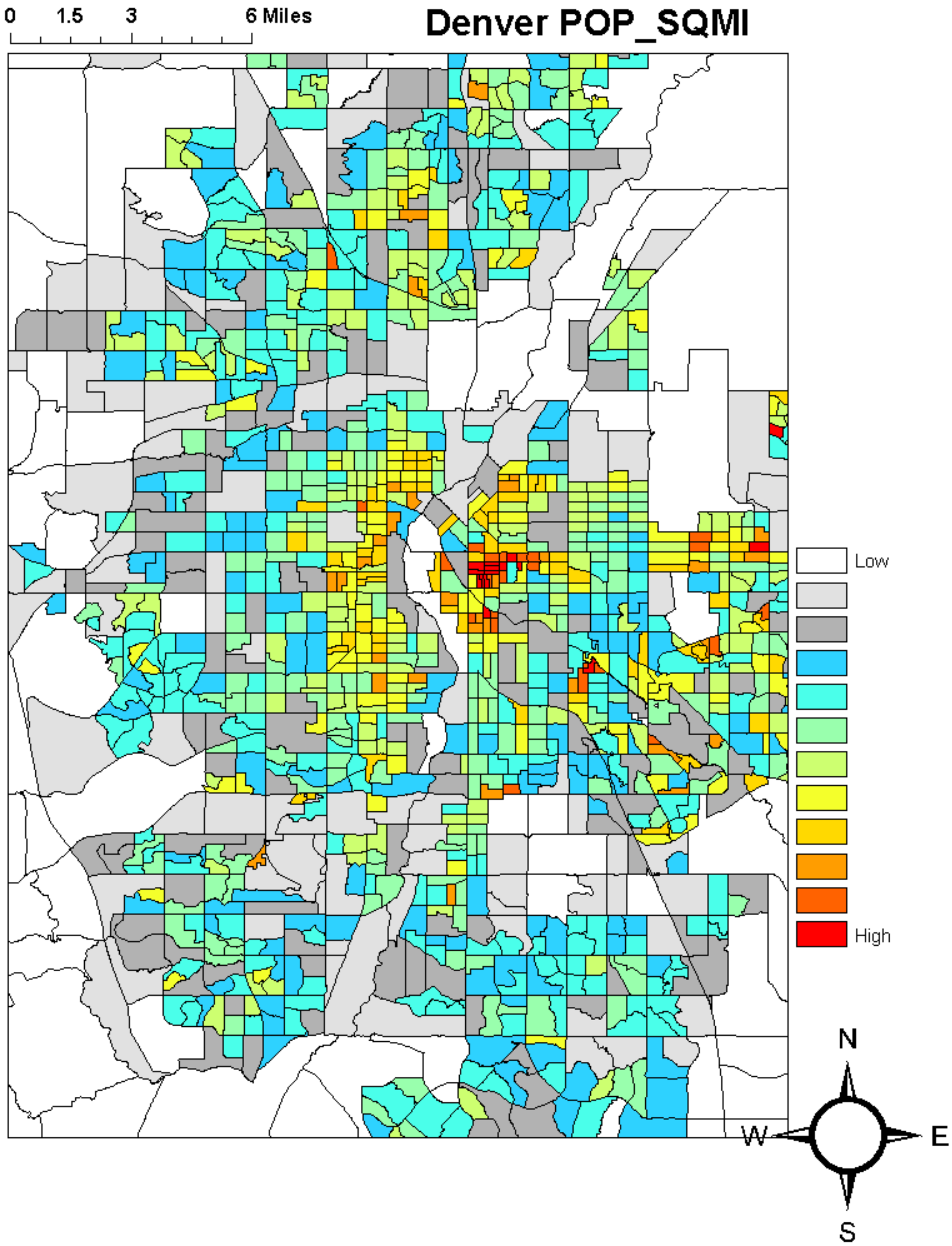

Fig. 30. Denver Population per square mile

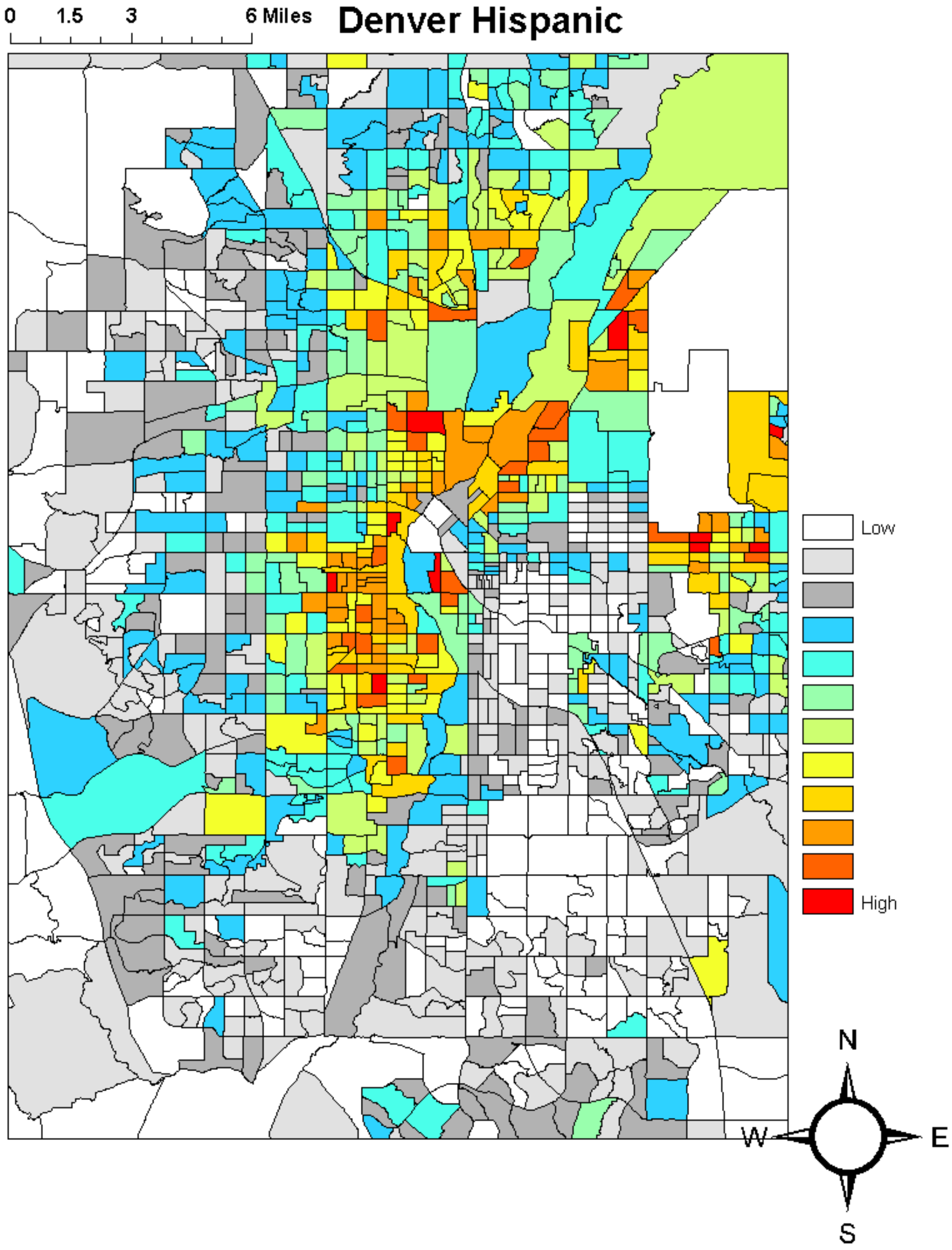

Fig. 29. Denver Hispanic

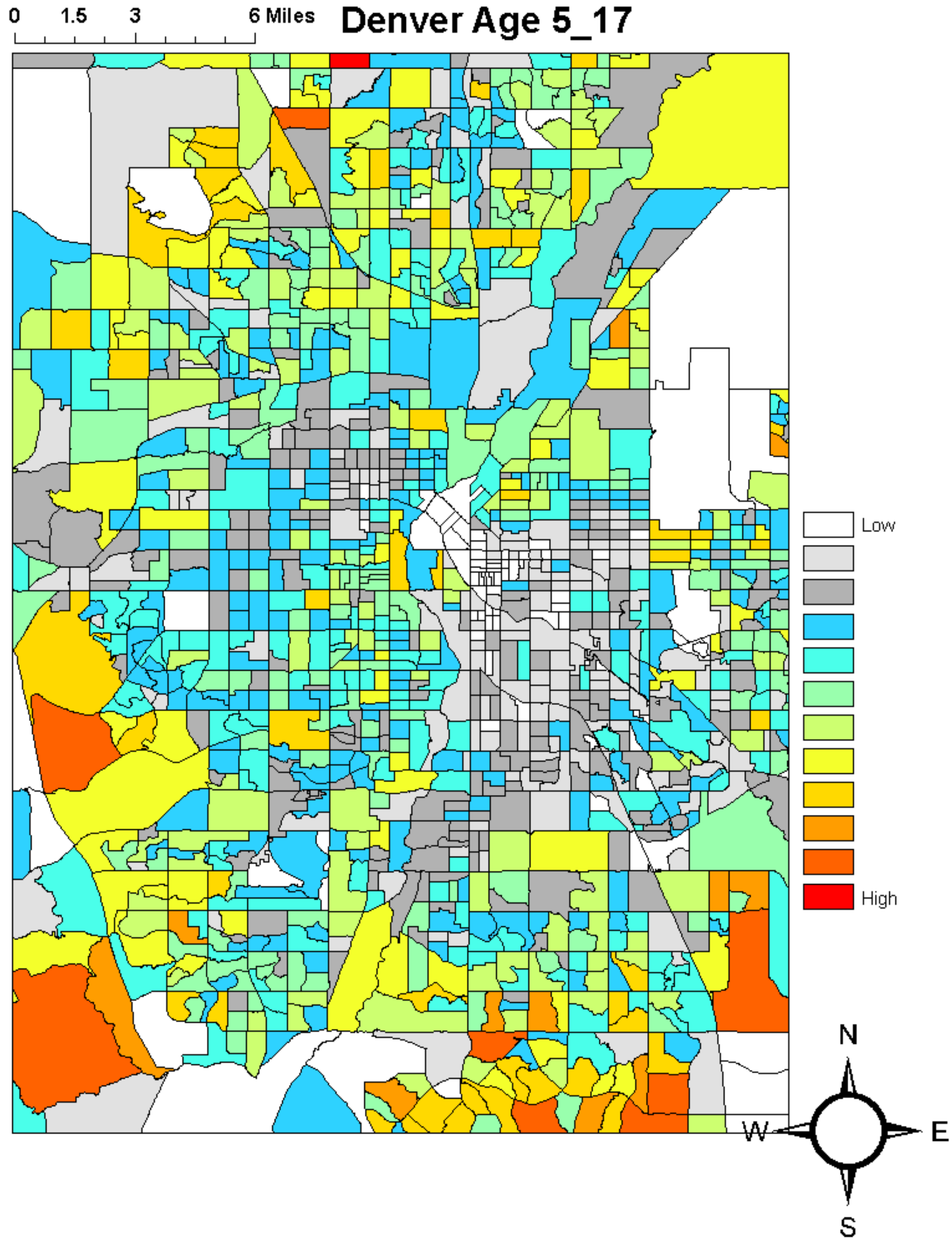

Fig. 25. Denver Age 5-17

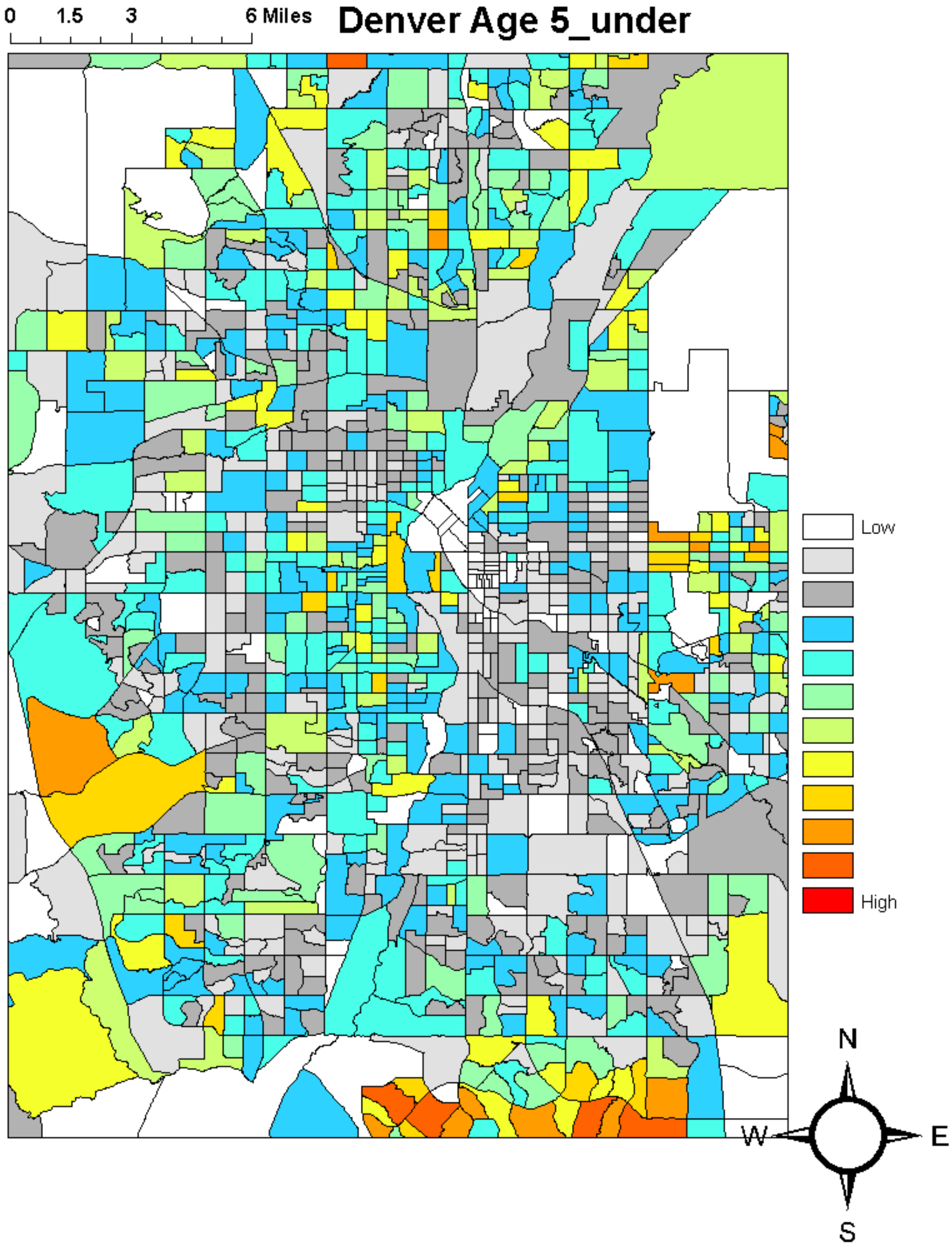

Fig. 26. Denver Age 5 and under

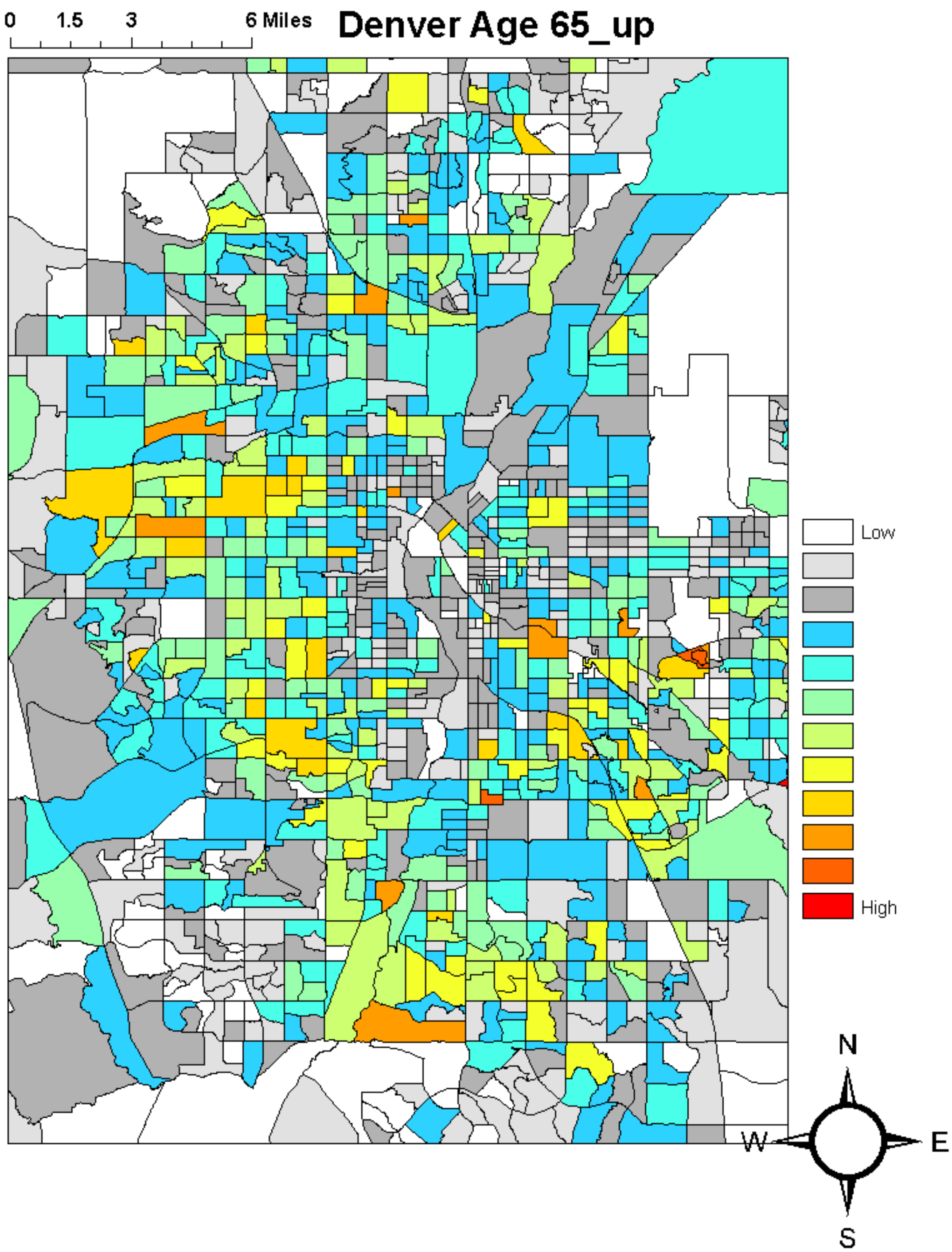

Fig. 24. Denver Age 65 and over