Dynamic Hazard Assessment: Using agent-based modeling of complex, dynamic hazards for hazard assessment

by

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Submitted to the Graduate Faculty of

Graduate School of Public and International Affairs in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

University of Pittsburgh

2005

UNIVERSITY OF PITTSBURGH

GRADUATE SCHOOL OF PUBLIC AND INTERNATIONAL AFFAIRS

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November 22, 2005

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This exploratory study examines the use of agent-based modeling for the dynamic assessment of the hazards associated with flooding responses. While flooding is the specific agent used the techniques are applicable to any type of hazard. The equation upon which the model is built considers three components of vulnerability: geophysical, built, and social environments and one component of resiliency, public safety response organizations. The three components of vulnerability combine to create an initial vulnerability level. The public safety response capability is subtracted from the initial vulnerability to provide an adjusted vulnerability. The adjusted vulnerability varies as response assets fluctuate between available and assigned. The development of the agent characteristics for both vulnerability and resiliency requires quantification of the interdependencies of the environment as well as the interaction among the response agencies in a complex adaptive system. The result of the study is a realistic method of conducting an assessment of hazards through the use of vulnerability and resiliency models and a computer simulation that allows the user to evaluate potential impacts.

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PREFACE

The completion of this dissertation was made possible through the support and cooperation of many individuals. First and foremost, I thank my wife and family who suffered innumerable hours of lost time together. Second, to Dr. Louise Comfort, who has provided thoughtful guidance and encouragement through, what seemed to be, a never-ending process. I would also like to specially thank Adam Zagorecki for helping to me bring the model to life by creating the simulation through his programming skills and many iterations. Thanks also to Robert Skertich and Dr. Joseph Petrone, who provided insight, feedback and support as well as the occasional reality orientation. It is on the shoulders of all of these people that I stand in achieving this goal.

Several groups provided technical assistance. The staff of the Allegheny County Department of Emergency Services assisted with data acquisition and feedback. Finally, thanks to those who graciously participated in this study from the various public safety agencies in the study area without whom, this would not have been possible.

1.0 INTRODUCTION

This study will explore the complex system that results in the vulnerability to emergencies and, on a larger scale, disasters. Herbert Simon described a complex system as a system that can be analyzed into many components having relatively many relations among them, so that the behavior of each component depends on the behavior of others" (Simon, 1996). The interdependencies and dynamic interactions among elements that create hazards must be analyzed in order to develop a method of modeling vulnerability. The inclusion of these interpretations will provide a more accurate hazard assessment. This model could be used in all phases of emergency management: preparedness, response, recovery and mitigation. Specifically this model investigated the interdependence among the geophysical, built and social environments that play a crucial role in the genesis of flooding hazards or exacerbate the impact of the event. The model includes the interdependencies among these systems with the intent of providing new insight into the ways in which these hazard agents pose risks to the jurisdiction. The model also takes into account the existing ability of the response organizations to address the hazards, the state of the infrastructure and environmental conditions surrounding them.

We live in a world that endangers us with numerous threats. Some of these threats are the result of natural processes, and some are created by human actions. A third variation is the result of interdependency between natural conditions and human actions that has a destructive effect on the populations in or around the impact zone. Comfort (2003) notes that in complex disaster environments, failure of one component of an interdependent system triggers failure of other components, decreasing performance throughout the system and threatening collapse. All three of these processes can be observed and assessed in terms of the hazards they present to human communities.

A primary challenge faced by emergency managers is the timely, accurate assessment of vulnerability of their communities to the interdependencies of these hazards. Often a threat begins from what seems like a self-evident single cause. Unfortunately, a single cause is rarely the only problem to be dealt with during the response and recovery to a disaster. Often emergency managers must commit more of their already scarce resources to address these unanticipated threats. These threats develop from a complex web of existing elements that act alone or in association with others. This interdependency can result in their changing states and in doing so create conditions that result in subsequent hazards that may disrupt our daily lives. On a small scale, these disruptions create inconveniences or nuisances. On a large scale, they are considered disasters that result in the loss of life, property and in some cases the existence of entire towns or even future generations.

To better understand the genesis of these large-scale incidents and their dynamic changes we need to examine the structure and content of the natural, human, and built systems that may go awry and how they interact. This study will examine elements of these systems, their interdependencies and how they can be monitored dynamically on three different levels (census block, municipality, sub-county region) of the study area. This examination will afford a better understanding of how disasters begin and evolve. The goal is to aid survival, response, and recovery by increasing the accuracy of risk assessment, the amount of warning time and degrees of preparedness at multiple levels of operation in a regional response system.

1.1 SIGNIFICANCE OF THIS STUDY

Disasters have been studied for many years. Practitioners are well versed in the development of static hazard assessments and plans for response to that specific hazard. What they have learned through experience is that there are a myriad of other factors associated with the specific triggering agent. These secondary events are not commonly associated with the event by those who have not experienced them first hand. That knowledge set is often used by experienced managers and relayed from generation to generation anecdotally or in the damages following a disaster.

While several researchers have explored the roles of systems in disaster genesis (Mileti, 1999), (Perrow, 1984) there has not been an operationalization of the concept to actual practice. This is an important step in both the validation of the concepts and in moving from a conceptual basis to application in managing risk in vulnerable communities. Because of the complexity of both the events and the interdependent physical, built and human systems, a comprehensive approach to address all hazards is not feasible for this study. Rather, a single hazard agent, flooding, will be analyzed as a template for further research.

1.1.1 Research Questions

The following research questions guided this exploratory study:

1. What methods can be used to model the interdependencies that create a community's vulnerability to risk?

2. What are the macro spatial and functional interactions among the physical, built and human systems that characterize a community's vulnerability to risk?

3. What are the micro spatial and functional interdependencies among the components (topography, buildings, transportation, utilities, populations, organizations) of these systems that characterize a community's vulnerability to a specific hazard, e.g. flooding

4. What are the critical conditions and interactions that affect a community's capacity to respond to threat?

5. What types of policies and operational programs increase or decrease the vulnerability of the community?

2.0 HAZARD ASSESSMENT IN THEORY AND PRACTICE

Given the multidisciplinary nature of this study the literature review will address briefly nine different approaches to hazard assessment.

2.1 PRESENT METHODS OF HAZARD ANALYSIS

Hazard analysis is the basis for emergency management; planning cannot begin without a firm knowledge base of the types of hazards. The terms hazard and vulnerability have often been used interchangeably, though in many cases, inappropriately. For this study, a hazard is defined as a threat to people and things they value (Cutter, 2001). Vulnerability is defined as the exposure a community has to the occurrence or impact of a hazard. This study will focus on flooding as an example of middle scale calamities (Hirshleifer, 2003). Middle scale refers to events that are between individual incidents and society-wide disasters.

The traditional approach to hazard assessment, still employed by the U.S. Federal Emergency Management Agency (FEMA, 2001), is to base the assessment on the types of incidents that have occurred, their frequency and impacts, and to expect the continuation of the same if no mitigative actions are taken. This method has proved ineffective as evidenced by the continuing increase in both the frequency of natural disasters and their impact. During the 1990s, there were 84 large natural disasters worldwide. That is a three-fold increase from the number experienced during the 1960s. The economic losses increased eight-fold to US $591 billion (OFDA/CRED, 2003).

Another shortcoming of the traditional method is that it provides only a “snap shot” of the conditions. Disasters, like other complex situations, are dynamic. In addition, linear models for reducing risk repeatedly fail in dynamic environments. Estimating the cascade effect becomes a critical factor in assessing the demand for services in a disaster (Comfort, 1999). This demand for services may be thought of as a component of vulnerability. The vulnerability of a community is the difference between service demand and response capacity.

The reliance on often-antiquated information may lead to erroneous decisions with dire consequences. The dynamics of the response process are created by the “cascade effect” or interdependencies among potential or actual damaged parts and the capacity flow among the participating agencies (Comfort, 2003). Responders need a tool that considers the current state of the environment in order to make decisions that are more effective.

2.2 NEED FOR UNDERSTANDING/QUANTIFICATION OF THE INTERDEPENDENCIES AS A DISASTER MECHANISM

It is apparent that a greater understanding of the mechanisms of disaster is necessary. Mileti (1999) uses a systems approach by positing that disasters are the result of the interdependencies between three systems: physical, built and social. While this theory provides a greater understanding, it falls short of a providing a practical application as it lacks operational delineation of the elements within the systems cited, and consequently lacks a quantifiable method of measuring the status of the systems.

2.3 NEED FOR MULTIDISCIPLINARY APPROACH

While many hazard assessment models include a wide variety of vulnerabilities, a multidisciplinary perspective is lacking in many. As noted by Tierney (2001), the bulk of disaster research has been done by sociologists focusing on social dimensions. This singular perspective does not facilitate single discipline researchers to recognize any potential interdependencies or interactions with factors from other areas. From necessity, practitioners have taken the lead in applying multidisciplinary thinking by considering physical conditions, vulnerable groups and organizational issues (Tierney, 2001).

2.4 SHORTFALL IN METHODS OF HAZARD QUANTIFICATION

One of the earliest attempts to employ a multidisciplinary, quantifiable method of assessing hazards was developed by Susan Cutter for the State of South Carolina. In her Geographic Information System (GIS) based Hazard Assessment, Cutter (1997) quantifies primarily two systems: social and physical. A score for each of the vulnerable population cohorts is created by comparing the census block value with the population for the entire county. These scores are summed to provide a social vulnerability score. The hazard score is based on a summation of the probabilities of the hazards. For example, an area with a 1% chance of flooding would receive a score of one. If the same area had a 5% probability of wind damage, the total hazard score would be six. This becomes a multiplier for the social vulnerability scores. The limitation of Cutter's method is that it does not take into consideration the infrastructure of the area being studied nor does the simple multiplication of the scores accurately reflect the interdependency of the data sets of multiple hazards. The vulnerabilities of a population vary with the type of hazard agent and summing them for multiplication presents an overly simplistic model.

Community infrastructure includes a number of lifelines, such as public utilities, communications systems, transportation, etc. While Cutter's work is an improvement over previous methods of assessing of hazards, this deficiency is significant. The status of the infrastructure is a vital component to disaster response (USFA, 2003), as demonstrated by the actions taken by FEMA, the US Department of Homeland Security (DHS) and state, county and local governments along with industry to develop infrastructure protection programs. The omission of this measure leaves a large gap in the hazard analysis and the status of the community.

FEMA has developed a hazard assessment model titled HAZUS–MH. This computer model is essentially an impact-modeling program. It contains three levels of analysis that vary in their degree of granularity and specificity. Across the levels, the methodology remains the same. It is essentially an inventory of the three systems mentioned by Mileti over which is laid the effects of a modeled incident. Missing from the data set is the interaction among the data sets and the capabilities of the public safety agencies to address the hazards. The HAZUS model was originally designed in the mid-1990s for planning related to earthquake mitigation but was later expanded to include an all-natural hazards approach with the latest version including flood and hurricane damage models. The flood model is limited in scale because the software allows the evaluation of a maximum of three waterways during one model run. Multiple model runs could be completed to evaluate a wider area of potential impact, but because they are isolated studies, they do not take into consideration the interaction between the individual study areas. While it does a better job than most with the economic and social impact, it does not include interdependency in the models nor does it account for the decrease in the impact due to public safety intervention.

2.5 NEED FOR A SYSTEMS APPROACH

Missing from much of the literature is a systems view. Many researchers acknowledge that there are social systems and the physical scientists acknowledge terrestrial systems, but few put the two together. Phillips (1999) explores the earth's surface as a series of integrated non-linear dynamic systems while Comfort (2001) does likewise for organizational systems in situations of seismic risk. Comfort (2003) goes further by bringing in the role of information into the complex environment by pointing out that the effective response to a disaster requires not only adaptive organizations but also a method of procuring the necessary information on which the response can be based. This information must not only be acquired but also disseminated throughout the response organizations. These communication pathways are best established prior to the incident and are built on existing non-emergency communications.

Additional information and communications are not a panacea. As Quarantelli (1998) points out, an incident can be exacerbated by relying on technology or providing too much information, thereby overwhelming the decision makers. Communications and information must be interpreted and used to enhance decisions based on human experience. Comfort (2002) adds to this premise by stating that without relevant information to form a system wide perspective, individual units make separate decisions that are appropriate for them locally but may conflict with system-wide goals. Under these conditions, relationships tend to fail under the pressure of time critical events (Comfort, 1999).

This study addresses Wildavsky's (1988) two methods of improving safety by using strategies of anticipation and resilience. The strategy of anticipation calls for a need to know the characteristics of the adversity, the consequences and probability of the event and the existence of effective remedies. Using precursor factors involved in the initial conditions, the goal is to increase the ability to anticipate the event, or at least recognize its initiation soon enough in the event time line to take action that will positively influence the outcome. The strategy of resilience is used in evaluating the organizational capacity, knowledge and communications in order to respond appropriately when adverse effects occur. Together these strategies, operationalized through parameters delineated by Comfort (1999) and Mileti (1999), provide a method to understand the genesis of disasters and thereby enhance assessment of risk, warning times, and opportunities for preemptive action.

2.6 SYSTEMS AND COMPLEXITY

The study of systems and networks has developed from the initial studies by E. N. Lorenz (1963). Since then, network and systems theory has been expanded in both scope and application to a wide variety of disciplines. A pivotal work relating systems and accidents was Charles Perrow's (1984) book Normal Accidents, in which he uses this term in part to describe "inevitable accidents." This categorization is based on a combination of interactive complexity and tight coupling as system features. Normal accidents in a particular system may be common or rare, but it is the system's characteristics that make it inherently vulnerable to such accidents, hence their description as "normal". While this work focused on the nuclear industry, it was very insightful for other applications. Perrow describes the way in which a system with two or more discrete failures can interact in unexpected ways, or are "interactively complex." In many cases, these unexpected "interactions" can affect supposedly redundant sub-systems. For example, the loss of electrical power in the blackout affecting the northeast US in 2003 resulted in the loss of water service.

Another important point is that normal accidents occur in a complex system, which has so many parts that it is likely that something is wrong with more than one of them at any given time. It involves interactions and interdependencies that are not only unexpected, but are incomprehensible for some critical period of time. These interdependencies and interactions are an integral part of vulnerability because they are the connections that allow failure of one system to affect another. This expansion of failure can exploit several different relatively minor points of vulnerability resulting in a much larger cumulative effect.

Unfortunately, the accumulating impact of the interdependencies and interactions is often increasing during the same time that response organization interventions would be most effective. This builds on Simon's (1945) concept of bounded rationality that posits that humans are capable of handling only limited additional information.

2.7 INTERDEPENDENCE

Perrow (1984) refers to four levels within the system of linkages between various levels of interaction. This study will use a similar structure to look at the scalar issues involved in understanding the interactions among the various system segments.

Perrow's Scaling

1. Parts
2. Units – a collection of parts that perform a particular function within a subsystem. (Events whose disruptions are restricted to a single part or unit are usually called "incidents.")
3. Subsystems, made up of a number of units.
4. Complete system, composed of perhaps one or two dozen subsystems

This study will apply that concept using the following subsystems:

	Organizational	Physical/Spatial	Built
1.	Individuals	Census tract	Element (roadway, building, functional node)
2.	Organizations	District	Aggregation of built elements within tract

3.	Municipalities	Municipality	Aggregation of tracts within municipality
4.	Sub-County Region	Region	Aggregation of municipalities within Region

This leads to Comfort's (1999) work regarding shared risk. In it she defines public risk as one that affects all residents of a risk-prone community, whether or not they have contributed to the conditions producing the threat. The interdependencies in the systems being examined are one of the primary methods by which these complex systems parse the risk among the residents and communities. These complex systems will be examined first as individual units but as the scale of the aggregation increases it should be more evident that the risk producing conditions are of a nature that endorses Comforts sharing premise.

One of the defining qualities of a complex system is sensitivity to initial conditions (Lorenz, 1993). The existing conditions characterize the context in which the disaster strikes, how it evolves and influences operations. This evolution occurs in iterative, sequential processes of information search, information exchange, and organizational learning (Comfort, 1999).

The human and organizational sections are not the only complex systems in the study. As Charles Phillips (1999) points out, the earth's surface environment is active and complex. It is marked by a web of interrelated components dynamically linked which result in complex changes in initial conditions. To be manageable we need to break it into chunks called earth surface systems. For this study, we will limit the scope to those associated with flooding. Phillips (1999) goes on to delineate four factors necessary to understanding earth systems, which are equally relevant to the other systems in the study:

1. Basic mechanisms and process-response relationships involved
2. Knowledge of the influence of individual factors
3. Mutual adjustments and interactions among components
4. Measures of how each major component affects and is affected by the other components.

2.8 INTER-ORGANIZATIONAL COOPERATION

An important aspect of organizational interactions is how they reflect on the ability of the organizations to combat the untoward effects of the physical and built systems. The small degree of agency interaction at the municipal level is found typically in the area of public safety and public works. Sharing resources under mutual aid agreements facilitates the interaction. One of the difficulties in including this interaction in the model is its idiosyncratic nature. These relationships are often based on the politics and personalities involved.

Management of the flooding hazard is a single perspective on a much bigger issue. It provides an example of the overall management issue in not only disaster response but also public management in general. The management of flooding has been a long-standing problem from the time of initial settlement. The management of the problem, as with other problems, is often viewed at the local level or even at the subdivision level. Each organization has an independent view and acknowledgement of the problem, as well as associated planning and training.

This localized view does not consider the impact to their jurisdiction from beyond their boundaries nor the coordination of the response with support agencies. This view does not take into consideration the potential indirect impacts from an event in a neighboring community. Each agency prepares itself for a response without considering a coordinated effort. This method of preplanning is inefficient. This planning in isolation places the plans at risk because many of the agencies rely on the same organizations that, in a wide spread disaster, will be quickly overwhelmed.

Non-linear dynamics shows us that chaotic behavior is “globally“ stable but “locally” unstable (Kiel, 1994). While local organizations need to embrace this chaos in order to retain viability in service provision, nonlinear dynamics also illustrate that when dealing with complex systems, events that are outside normal local parameters and therefore unmanageable may indeed be manageable from a larger scale. This scalability is central to this study. An example of scalability used in disaster response is the concept of mutual aid between jurisdictional levels. When the resources of two or more municipalities are insufficient or depleted, local officials call for assistance from the next higher jurisdictional level, in this case the county. The allocation of these assets from the county usually does not significantly deplete their resources so that level remains stable. In many cases these higher-level resources are not involved in the assessment of risk within a specific municipality. By acknowledging the non-linear characteristics of disasters and the complexity of the interdependent organizations within the study area, I will assess their individual and combined impact on the vulnerability of the community and the region.

A fundamental issue in the organizational ability to work together is their patterns of organizational communication/interaction. Comfort et al (2003) found that the sharing of resources without coordination in allocating resources appeared to have little effect on the efficiency of disaster response activities. The communication among organizations at various levels of response is critical to response efficiency. Iterative patterns of communication transmit information among subsets of actors within the community, permitting adaptation to changing conditions via mutual adjustment (Nichols and Prigogine, 1989). The presence of multiple organizations, or actors, creates constraints within the system, producing dependency relationships among the organizations. These recurring patterns of communication allow non-linear systems to reproduce self-similar patterns (Comfort, 1999). These patterns of communication and their impact on the efficiency of interorganizational coordination must be considered in the ability of the response system to provide adequate resources for disaster response.

To understand the nature of the interorganizational response we need to examine the interaction for the presence of an established network. Interaction patterns will be the roadmap for communications and decision-making among disaster response organizations. This study uses a proxy measure of frequency and quantity of response interaction to estimate the interorganizational communication patterns. This familiarity often adds to the resiliency of their combined efforts. As Karl Weick (1993) points out, one of the four sources of organizational resiliency is a respectful interaction. Based on the assumption that a continued relationship would only exist with a respectful interaction, we can determine which of the agencies have adopted this method based on relationship length of at least three months.

The identification of networks among organizations within a given geographic region exposed to disaster risk is important to the advancement of improving the capacity of interorganizational decision support in disaster management (Comfort, 2003). The critical aspect in regard to hazard assessment and response capacity is the ability to identify the organizations that function as critical nodes within the network. These may act as a “bridge” which when removed will divide the network into disconnected clusters and inhibit the ability to deploy resources. More connected populations may be better able to mobilize resources and bring multiple perspectives to bear to solve problems (Hanneman, 2001).

2.9 NETWORK ANALYSIS

To further the understanding of networks, Watts (1999) developed the Small World technique to map these networks and to provide a method of quantifying them. The technique uses the several different methods of evaluating networks such as edge complexity, clustering and the development of neighborhoods. The use of this technique provides both a graphical representation of the quantification and facilitates understanding through measurement. Another convenient aspect is that the development of clusters and neighborhoods may lend itself to aggregation as the scalar level rises. There appear to be both spatial and organizational clusters and/or neighborhoods in the study area. One focus of the study is to explore whether social clusters exist and if so, how they translate into operational functionality. This could determine their impact on the hazard posed by flooding.

A third approach is the use of an agent-based framework based on the work of Axelrod and Cohen (1999). This agent characteristic information can then be overlaid on the network structure to provide additional information on how the various agents act. This will lay the groundwork for the development of computer-based modeling of the interdependency of the systems and the interactions of the organizations. This model would provide the decision-makers with additional information in an arena that is fraught with uncertainty.

While the degree of complexity and the potential for chaotic behavior are inherent in disaster situations, Simon (1996, p. 179) observed, “The ominous term chaotic should not be read as unmanageable.” The intent of this study is to apply many of the concepts from complexity and systems theories to disaster situations in an effort to promote understanding of disasters and to improve their management.

Based on the literature cited above, this study assumes that disasters are the result of the dynamic complex systems created by the interdependencies among the three systems identified by Mileti (1999). The assessment also requires a multidisciplinary approach to accommodate the range of information concerning Mileti’s systems. To provide a more accurate assessment of the risk associated with the incidents, the capabilities of the response organizations should be included in the vulnerability assessment. Because all of the systems are dynamic and complex, the assessment must be based on quantitative measures that can be readily updated in order to afford the response decision makers an optimal decision environment. By augmenting Cutter’s (1997) GIS-based assessment technique with information on the critical infrastructure, a more accurate understanding of the evolving incident can be developed. This understanding, with the inclusion of the organizational component, facilitates the creation of an agent-based model that will enhance the bounded rationality of the decision makers.

2.10 SUMMARY

This effort to assess disaster risk and enable proactive action is a long way from the early contention that disasters are random "Acts of God" that require a linear, hierarchical methodology to contain them. The realization that disasters are complex systems operating in a built, interdependent infrastructure environment that is present in a variety of states in everyday life is an important breakthrough. To effectively manage them requires a different methodology than has been used in the past. Through the increasing economic losses to disaster, from $20 Million in 1976 to $100 Million in 1994 (Mileti, 1999), we can see that present methods of disaster management are proving ineffective despite a recent emphasis on mitigation. This study will attempt to provide some additional insight through modeling those systems. This increased understanding will provide a decision support tool for those interesting in disaster response, recovery and mitigation.

3.0 METHODOLOGY

3.1 STUDY TYPE

This study is an exploratory, small n-case study based on four contiguous municipalities within eastern Allegheny County, Pennsylvania. Given the scalability of the problem, from census tract through sub-county region, the study area will be explored at each of these levels to investigate the effect of scale on the area's vulnerability. Both quantitative and qualitative methodologies will be used. The design of this research encompasses several different issues and perspectives. It will examine the interdependencies among those three systems in reference to a specific study area and one selected hazard, flooding. The problem structuring tasks for the proposed study are as follows:

1. Determine the areas within the study area which are vulnerable to flooding.
2. Determine the population that is at risk and its relevant characteristics.
3. Determine the built environment of the study area and how it could be affected by flooding.

4. Determine the various organizations involved in disaster response and their response capacity.

5. Understand what factors contribute to the interdependencies among the above systems.

6. Map the various agents involved in the threat of flooding.

7. Map the interdependencies among the agents and develop a model demonstrating the impacts of changes among the agents.

3.2 PRELIMINARY ASSUMPTIONS OF THE RESEARCH QUESTIONS

A primary assumption of the relationship between the organizational capability and the hazard vulnerability involves the ability of a response organization to positively intervene in the incident as it occurs. Disasters, like other events, have a time line continuum of their own and often the degree to which a response organization can alter the natural progression of the incident depends on where in the event continuum the organization is notified and intervenes. An example of this concept can be seen in Figure 1.

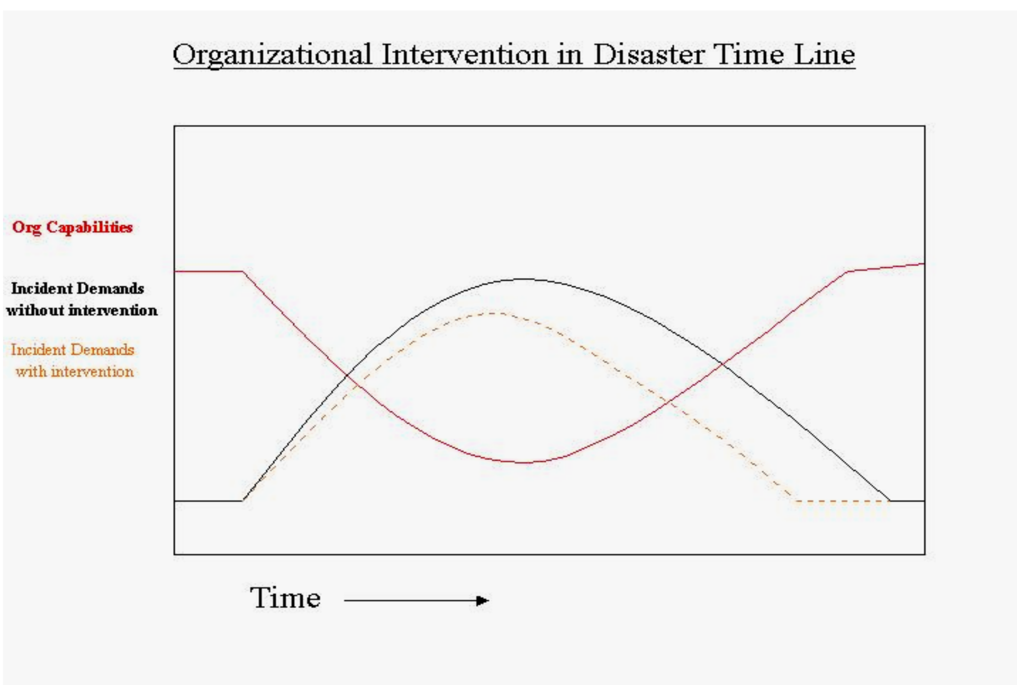


Figure 1. Organizational Intervention in Disaster

For demonstrating property conservation, the choice of flooding as the disaster agent is not optimum because once the water rises, most submerged property is effectively lost. In this study, we are operating under the assumption that lives are salvageable and that some degree of property loss can be reduced. Salvage operations do expedite the cleanup operations and a return to functionality, but the direct property loss is often irreversible due primarily to hygiene reasons.

With sufficient warning time and resources, mitigative actions can be taken that would reduce water inundation. Local experience has been that either a lack of resources or warning time has limited the ability to perform such actions. The personnel and equipment resources for an event with sufficient time are considered in the secondary responder category.

3.3 SELECTION OF CASES

The municipalities (Municipality of Monroeville, Municipality of Penn Hills, Wilkins Township and Wilkinsburg Borough) can be seen outlined in green in Figure 2. They and their associated organizations were chosen based on several factors:

1. They are all contiguous so there is continuity, among not only the geophysical environment elements but also in elements of the built environment.
2. History of interaction among most of the response organizations.
3. While spatially close, the communities differ in demographic and economic characteristics.
4. The communities range in both flash flood and riverine flood experience.

5. Diversity in public safety organization types (career, combination, volunteer) and sizes.

Table 1: Municipal Profiles

Municipality:	Monroeville	Penn Hills	Wilkins	Wilkinsburg
Area (square miles)	19.54	19.08	2.75	2.02
# of Census Tracts	7	10	2	8
Miles of Streams	35.60	40.74	4.80	0.00
% area within 100-yr floodplain	5.50	2.12	2.00	0.00
Population	29,349	46,809	6,917	19,196
% of population minority	14.4%	26.4%	0.7%	70.7%
65 years of age or over	20.3%	19.7%	25.8%	15.8%
Education: BS or higher	35.6%	21.0%	30.3%	22.4%
Speak English Less Than Well	3.0%	1.3%	2.1%	1.7%
Housing Units	13,159	20,355	3,432	10,698
Owner Occupied	69.7%	79.7%	69.0%	41.6%
% At/Under Poverty Level	6.6%	7.5%	6.4%	18.6%
Per Capita Income	$ 24,031.00	$20,161.00	$24,515.00	$ 16,890.00
Fire Department				
Staff	115	133	66	22
Type	volunteer	volunteer	volunteer	career
Stations	5	7	3	1
Police Department				
Staff	45	55	12	24
Type	career	career	career	career
Stations	1	1	1	1
Emergency Medical Services				
Staff	60	21	38	46
Type	combination	career	combination	combination
Stations	4	1	1	1

Study Area

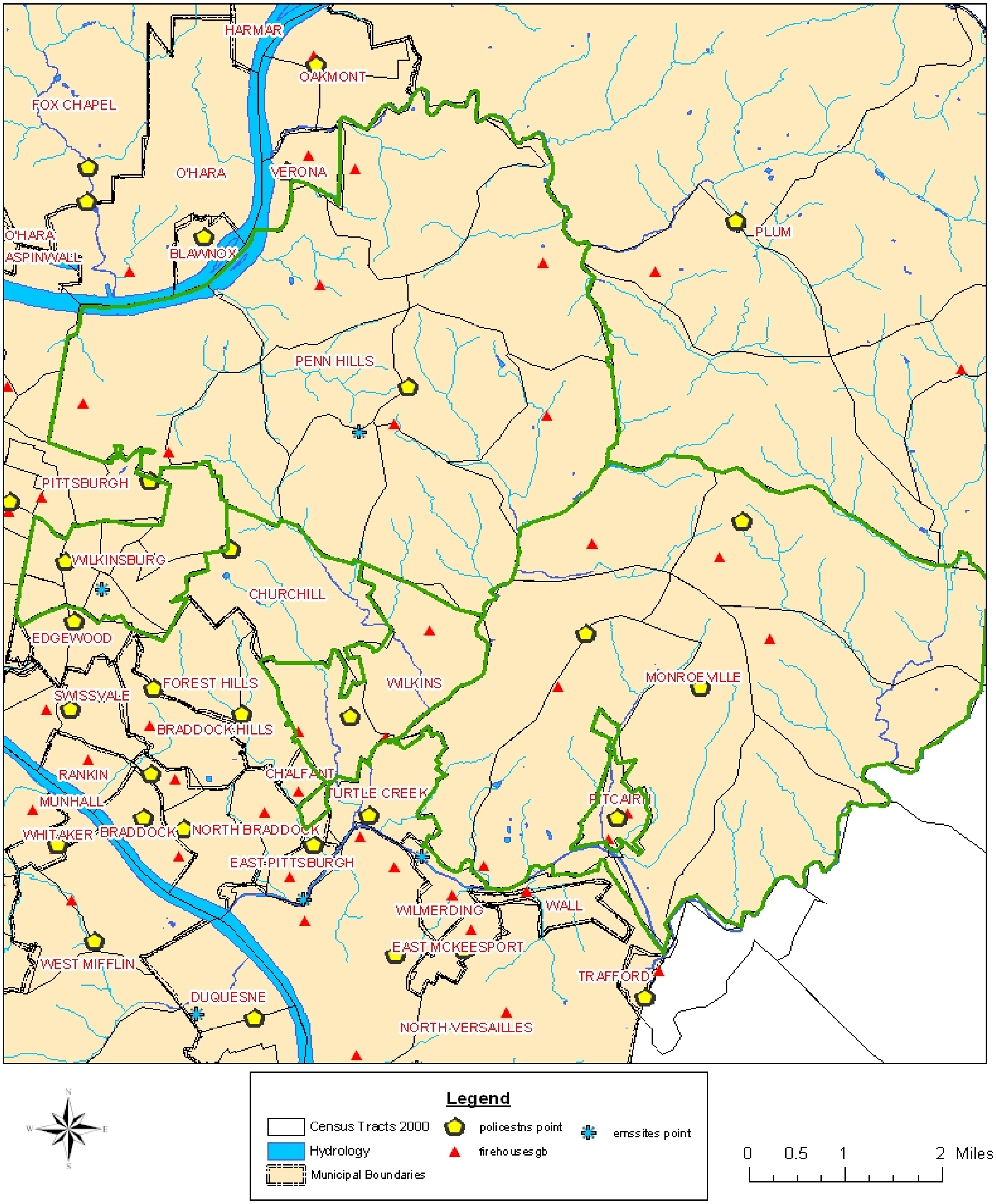


Figure 2: Study Area

The four areas involved in the study vary from a small, urban, economically depressed area with all career public safety agencies and little direct impact from flooding through a medium sized primarily bedroom community with areas of light industry to two large suburban municipalities with significant resources and a history of major flooding. This variety increases the applicability of the results to a variety of areas.

3.4 UNIT OF ANALYSIS

The unit of analysis for this study is the organization. While the majority of the organizations will be located in four municipalities, their interaction within their jurisdictions, between municipalities, and as a sub-county region will also be included in the analysis.

The unit of observation for the organizations will include the managers of the various organizations or organizational associations. For additional information, training and staffing records of the organization will be assessed to determine their present capabilities.

3.5 METHODOLOGY

The study will be broken down into four sections.

1. Creation of a knowledge base

2. Interdependency mapping

3. Determination of community resiliency through response organizations reducing the risks

4. Development of a model of the system to increase understanding of the systems and their impact on vulnerability.

The first section is the creation of a knowledge base of the initial conditions (geophysical, built, social and response organizations) so important to the understanding of a complex system. This is accomplished through a combination of data acquisition and mapping. The first map characterizes the geophysical area including the watershed and the hydrology of the area. The second map presents the built environment. The content includes the critical facilities required for the maintenance of services and habitation, such as roadways, utilities, communications assets and structures. The third map represents the human/social organizations. This map takes two perspectives. The first cohort is that of the population within the area, focusing on "at-risk" populations developed from Cutter (1997) with some modifications. The second cohort is that of the public safety response organizations. The organizational information attribute table will include: resources (staffing, training, experience, etc).

While the maps show the various systems independently, the representation does not indicate that these systems are independent in nature. It is portrayed in this way for visual clarity only. These systems interact on a variety of levels. The first is spatial. By virtue of co-location, these systems share any interdependencies that may occur in that space. For example, in one area the topography and soil types create an area of high landslide potential. On top of that hillside is a communications tower and under the surface is a gas transmission line. Should the hillside slide, it could undermine the tower and rupture the pipeline. To add to the hazard, dropping electrical lines could be an ignition source for escaping gases. While a portrayal of this type of interdependency does not lend itself to visual display on a map, it can be shown in mathematical form. A mathematical model also allows us to investigate the changes that occur when the model is scaled through the three levels (tract, municipal, and sub-county region) that will be investigated in this study.

To develop the mathematical model we need to begin with the elements to be included at each of the levels. This knowledge base will begin on the tract level and aggregate through the upper levels. Because each level will use the same technique and metrics, comparison among the levels of changes is facilitated and relatively simple. The following section will address these elements and their metrics through the generation of a common knowledge base.

3.5.1 Introduction to the Model Equation

To model the dynamic vulnerability of the communities an equation is needed that will take into consideration the deficiencies noted above. The vulnerability equation for the model reflects the three systems designated by Mileti (1999) but quantifies the systems through the measurement of elements contained in those systems. These measurements are aggregated to produce a final score for the system. Within each of the systems, each element is standardized by the area of the census tract to facilitate comparison among the tracts. Each of the three vulnerability system's elements is aggregated into a single variable that is the initial vulnerability. For example, the built environment variable is composed of three elements (transportation, utilities and buildings). Each of those elements includes three to six sub-elements. The values for the sub-element variables will be computed by straight aggregation.

During the analysis of the data it was found that the interdependent nature of some of the system elements could be examined by using the concept of networks, specifically network centrality. The two methods examined were cutpoints and betweenness. Betweenness measures the number of paths between actors, in this case census tracts, which pass through that point. The higher the score the more connections between tracts rely on that connection. The other measure examined was cut points. Cutpoints are nodes; again referring to census tracts, which if removed would disconnect part of the network. Because both are measures of centrality I decided to use only one measure in the calculation of the equation. Using betweenness provided a better measure interdependency, because it considered the entire network and is not just sectioning off of parts. Because the sizes of the systems vary, using the measure of nBetweeness would be optimal. This measurement applies to linear elements so it was included in the measures of utility lines, roads and bridges. To reflect the impact of the betweenness on the original measure, I multiplied the measure by the betweenness factor to amend that element score. Because some of the nBetweeness scores were less than 1.0, I added 1 to each betweenness factor score. Because not all edges generated betweenness scores, the default value is set at 1.0.

Once the information is collected, it can be expected that some of these variables will be correlated and the number of variables (15 for built, 4 for geophysical, 9 for social and 6 for response organizations for total of 34) in the final equation will be reduced. To examine these variables for correlation within each system, I performed a factor analysis. From the output of the factor analysis, it was clear that the non-linear nature of the variables made the use of the technique inappropriate for this use.

The total of the three elements and their components is the vulnerability posed by the three systems within the area measured. The values for the municipalities are an aggregation of the tract values. The sub-county region is an aggregation of the municipalities.

The other component of the initial vulnerability equation is the capacity of the public safety organizations to respond and mitigate the hazards. Each organization's capacity for managing emergencies is measured. The exact method is discussed fully in the next section. The capacity of those organizations is subtracted from the vulnerability of the tract. The capacity score is modified for its distance from the tract so the further away it is the less value for a particular tract. The equation is shown in Equation 1. See Figure 3 for a diagram of all of the components of the vulnerability equation architecture. The equation to determine total initial vulnerability is:

Equation 1 $$V_{initial} = VGeo \times VBuilt \times Vsoc / \sum(\text{Response Capacity}/\text{distance})$$

Vinitial = Initial Vulnerability

VGeo = Vulnerability contributed by the geophysical environment

VBuilt = Vulnerability contributed by the built environment

VSocial = Vulnerability contributed by the social environment

The term initial vulnerability is used because this is the vulnerability when all of the response assets are available to respond. If those assets are not available their value is deducted from the divisor and the vulnerability of the area increases accordingly. This is explained in more detail in the Section

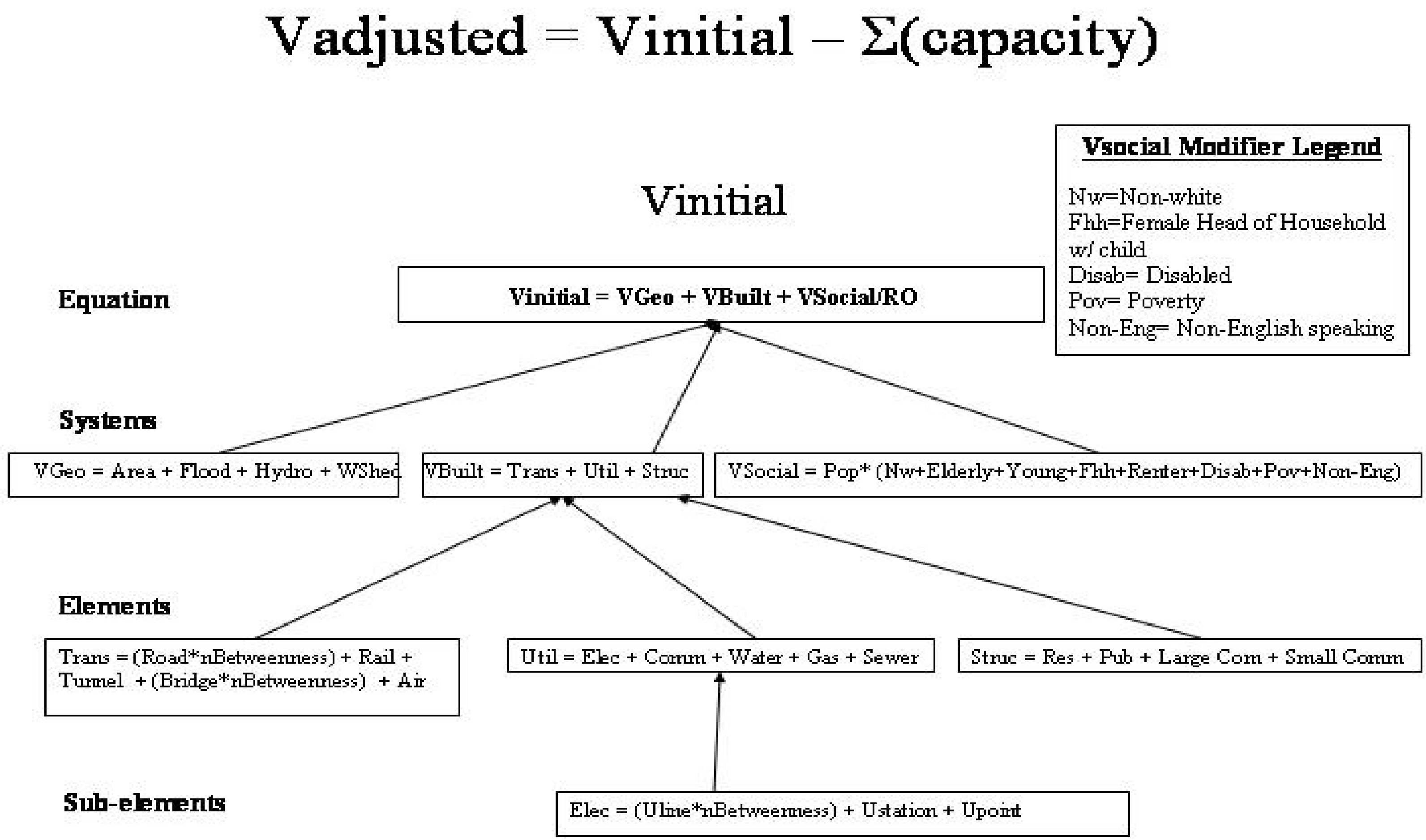


Figure 3: Vulnerability Equation Architecture

3.5.2 Creation of the Knowledge Base

The knowledge base documents the initial conditions for the study area. In complex systems the establishment of initial conditions is critical. These metrics define the initial conditions for each of the environments, their relevant elements and sub-elements. For comparison purposes the score from each element is standardized by dividing it by the area of the tract containing the elements. This did create some difficulties due to the extreme variation in the area of the tracts, .143 – 4.07 square miles, because the values for the small tracts while presenting a smaller actual vulnerability load when standardized became quite large numbers. While initially perceived as problematic, it can been seen as a valuable happenstance because the close proximity increases the potential for cascading failure or other nonlinear interactions.

3.5.2.1 The Geophysical Environment

The vulnerability of the study area begins with the geophysical environment because the remaining systems are literally built upon it and it is the source of the triggering agent being explored. While the majority of this environment is relatively static, the dynamic nature of the disaster results from the changes in the area's hydrology.

The following are the specific data that were considered within the geophysical environment.

- Area (A)
- Stream Length (SL)

- Area of the 100-year floodplain. (FP)

- Number of watersheds within the study area. (WS)

The equation for the calculation of the geophysical component is simply an aggregation of the elements:

Equation 2 $$VGeo = A + SL + FP + WS$$

VGeo = Vulnerability contributed by the geophysical environment

A map of the study area showing a ranking of the vulnerability contributed by the geophysical environment can be seen in Figure 4.

3.5.2.2 Built Environment

The built environment has significance for several reasons; it contains the system vital to habitation and the infrastructure that supports “normal” life. It also contributes to the vulnerability when these elements are placed in areas endangered by flooding.

The calculation for the vulnerability of the built environment is more complicated due to the nature of the environment.

The following are the specific data that were considered within the built environment.

- Occupiable Structures (St)

- Utilities (Ut)

- Transportation (Transp)

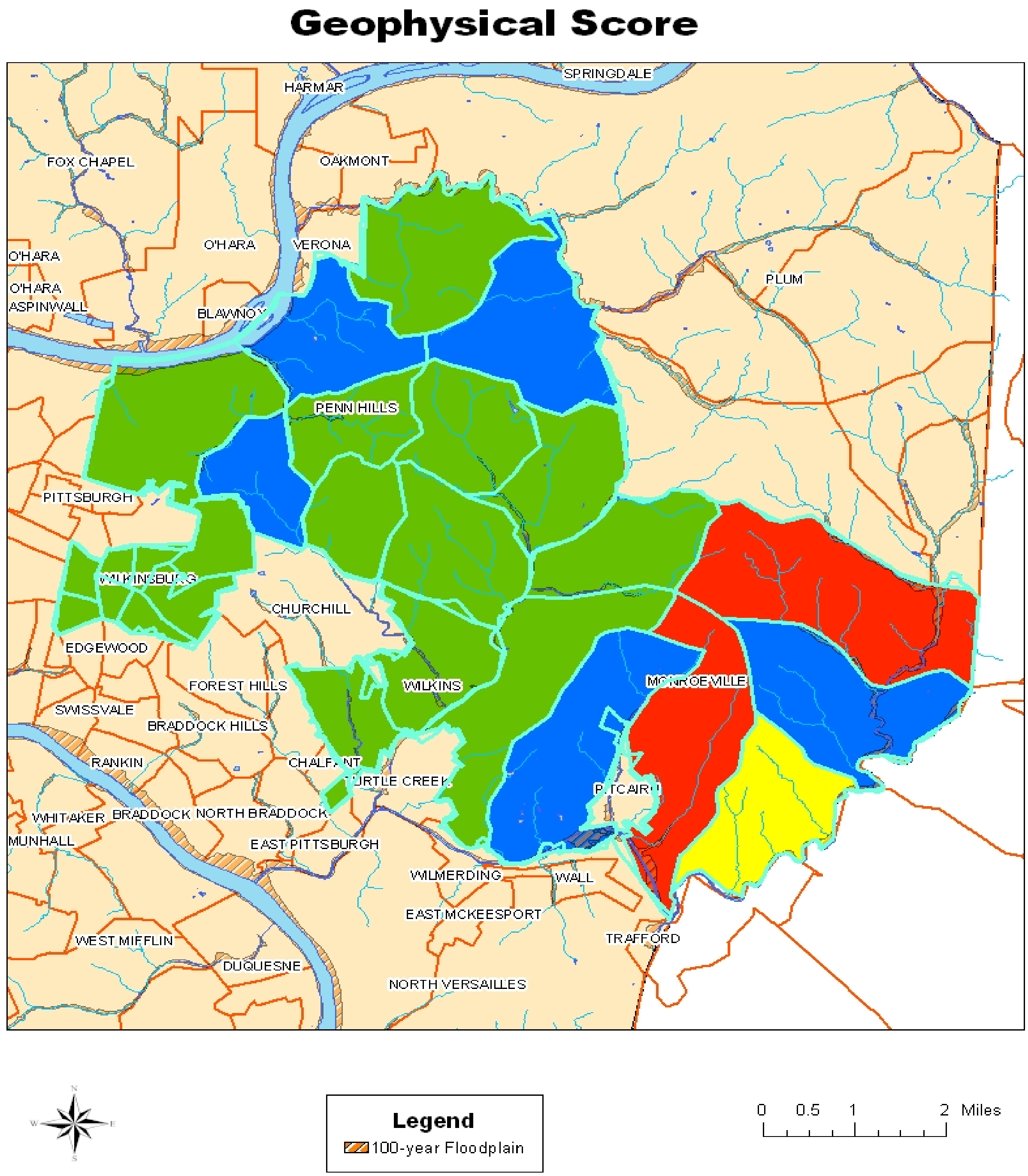


Figure 4: Map of Geophysical Contribution to Vulnerability

Each of theses is made up of elements. In one case there are sub-elements that make up the element score.

Equation 3 VB = St + Ut + Trans

VB – Vulnerability contributed by the built environment

Equation 4 St = Public + Residential + Small Commercial + Large Commercial

Equation 5 Ut = Electricity + Gas + Communication + Water + Sewer

The electrical element has sub elements indicating the various parts of the electrical system. These are:

Equation 6 Electricity = Lines + Stations + Points (poles/pylons)

A map of the utilities and their spatial relations to geophysical vulnerability can be seen in Figure 5.

The third element in the built environment is transportation. Like the others it is made up if sub-elements. These include:

Equation 7 Trans = Road length + Rail length + Tunnels + Bridges

Trans- transportation elements

The major roads for the study area are shown in Figure 6. The data guided the type of measurement made of the elements. If the data was linear then length was used. For point data a count of the points within the census tract were used. As in VG the data was standardized by tract area for comparison purposes.

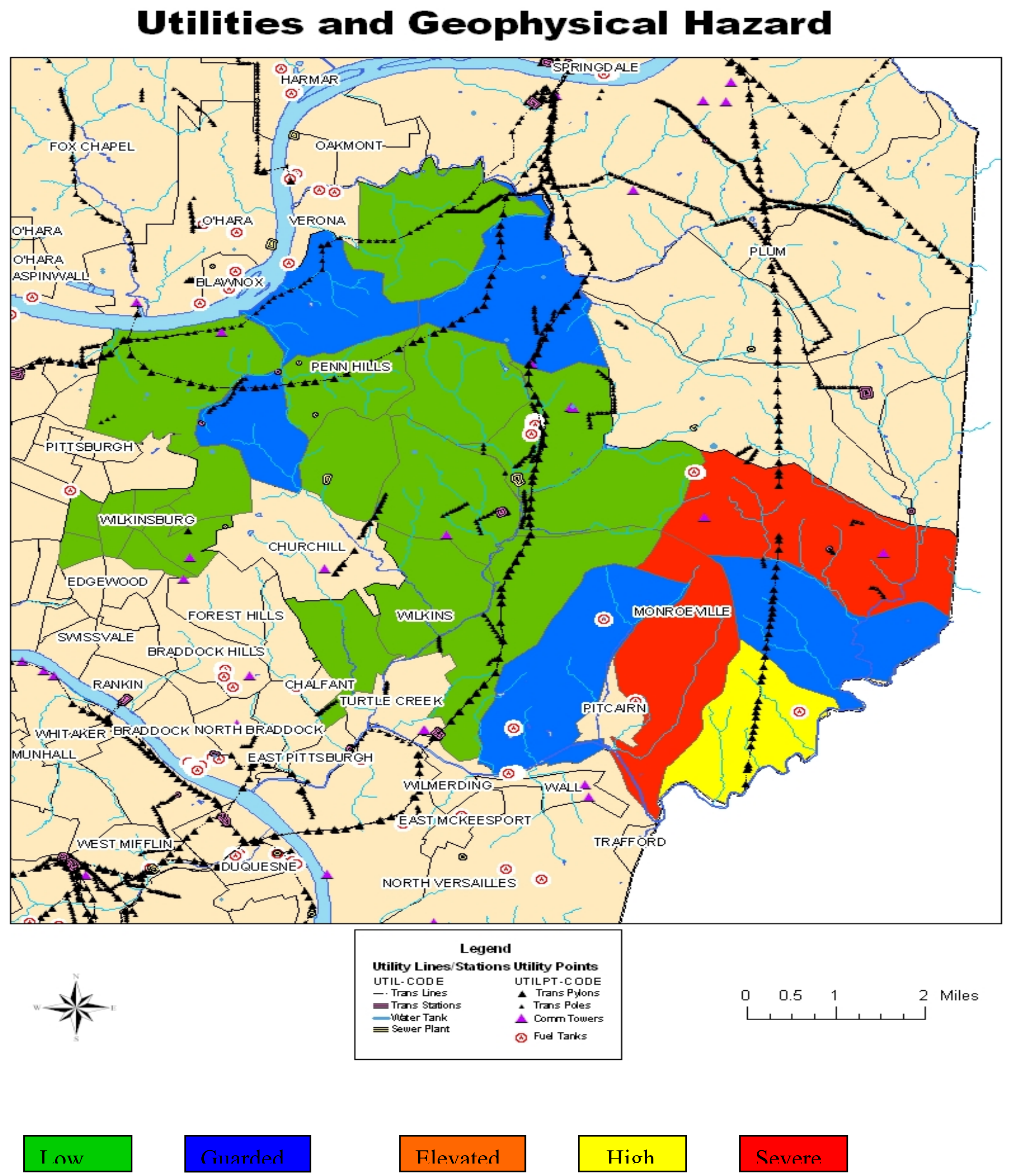


Figure 5: Map of Utilities Features over Geophysical Contribution to Vulnerability

Major Roads

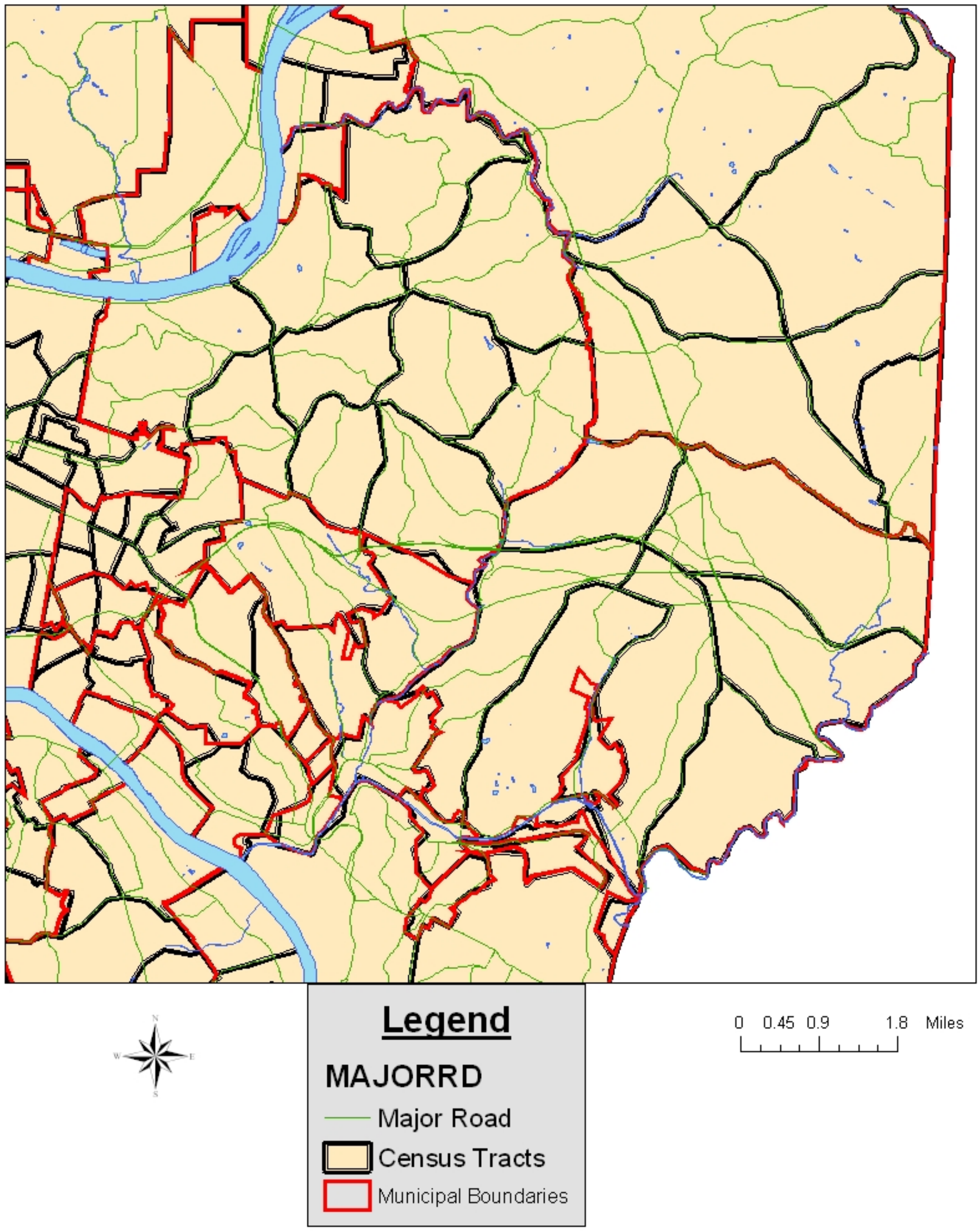


Figure 6. Map of Major Roads

3.5.2.3 Social Environment

The social environment is the most critical of the three as it relates to the lives endangered by the floodwaters. While the population as a whole is included in the variable, cohort risk factors that are known to be particularly susceptible to disaster are broken out to reflect a general decreased ability to absorb or respond to an emergency. These conditions create an increased demand for response resources.

The following are the specific data that were considered within the social environment:

- Total Population (TP)
- Nonwhite (NW)
- Young - under 18 years of age (Yng)
- Elderly - 65 years of age and older (Eld)
- Female Head of Household with Child (Fhh)
- Renter (Rnt)
- Disabled (Dis)
- Non-English Speaking (Nes)
- Poverty (Pov)

While it may appear that there would be some multicollinearity involved in making this calculation because all but the total population numbers are risk factors rather than direct counts of individuals, multicollinearity is not an issue. A single individual may indeed have more than one of these factors which puts them at an increased risk. To address this problem, the number of risk factors for each tract were tallied and then standardized by the mean number of risk factors for all tracts. This operation allows comparison of risk factors across all tracts. The resulting value was used as a modifier for the total population for the tract, producing the measure in the equation denoting vulnerability. The use of the total population in the equation allows it to reflect those who do not have any of these characteristics.

The calculation for the social vulnerability (VS) is as follows:

Equation 8 $$VS = TP*((NW + Yng + Eld + Fhh + Rnt + Dis + Nes + Pov)/\text{Mean for all tracts})$$

TP- Total Population	Yng – Under 18 years of age
Eld – At or over 65 years of age	Fhh – Female Head of Household with child
Rnt – Renter	Dis – Disabled
Nes – Does not speak English well	Pov – Income at or below poverty level

The study area was chosen based partly on the diversity of the municipalities and tracts. The social environment was an excellent example of this reason. The results of the assessment of the social environment can be seen in the map contained in Figure 7.

In evaluating the descriptive statistics the following surprising show the most variation in the geophysical environment and not the social environment. This indicates the heterogeneity of the tracts sizes and hydrological features.

Table 2. Environmental Score Statistics

Environment	Mean	Std Deviation
Geophysical	110.21	229.01
Social	2,776.34	2,264.26
Built	1,434.14	1099.16

Based on the large standard deviations in comparison to the mean none of the environments show a level of variation that should be interpreted as homogeneous.

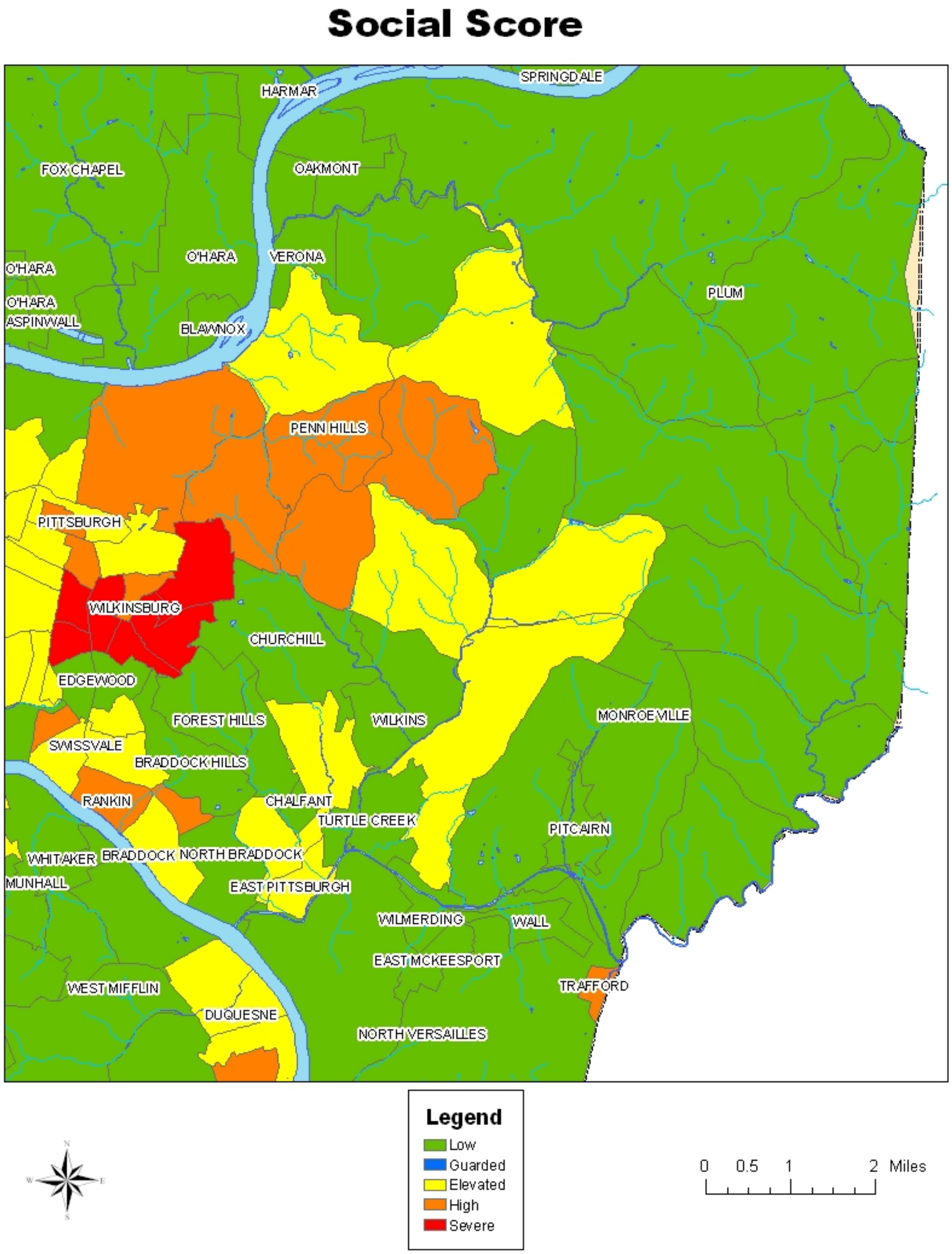


Figure 7. Map of Social Environment Contribution to Vulnerability

3.5.2.4 Response Organizations

The organizations involved in the disaster response could be many and range from the local level up through the levels of government and include many non-profit public safety agencies. This study focuses on the local level emergent response because it is the most immediate and has the greatest potential for life saving and property protection. The specific organizations for the study area are listed in Table 15. The choice of the municipal level primary responders reflects the old emergency management adage that all disasters are local.

The county, state and federal governments do provide support for the local agencies serving residents, businesses and public agencies but this is typically hours, days or weeks into the event and not relevant to the immediate needs of the incident. Much of the state and federal support is in the form of funding and recovery costs and not direct assistance.

The study area contains twenty-four response organizations: four police, sixteen fire and four emergency medical services. The other local response agency, emergency management, is not included in the study. This decision was based on the fact that in all of the municipalities in the study area, the emergency management coordinator is also involved in one of the response organizations. In most cases he/she functions in the other role and also functions as the emergency management coordinator simultaneously when necessary. If the municipalities had separate emergency management organizations or clearly delineated emergency management roles, then the inclusion of the emergency management agency would be appropriate. Of the twenty-four organizations in the study area, twenty-one completed the survey. Two of the sixteen fire departments and one of the four police departments did not reply.

In determining the capabilities of the response agencies a total of thirteen (13) variables were collected during a survey of the response organization managers or their designees. Some of the variables were multi-element items consolidated into one score. While the use of this self-reporting method can be problematic, with reporting errors there is no other feasible method for retrieving the information. See Figure 8 for the specific variables in the Capacity equation.

Tract **Capacity = Σ(Org Capacity * 1/distance to tract (miles))**

Municipality **Σ(tracts in municipality)**

Organization **Capacity = Personnel + Equipment + Planning + Interaction**

Personnel = Basic Staff + (Advanced Staff *1.5) + Org. Experience + Flood Training

Equipment = Flood Equipt + (Vehicles/# Vehicle Types) + (Comm. Equip../# Equip. Types)

Planning = Mutual Aid + Resource Planning + Hazard Analysis

Interaction = Interaction Outcome + (Σ frequency by discipline)/6 + nBetweenness

Divided by the 6 disciplines (fire, police, EMS, EMA, Public works, other)

Figure 8. Response Organization Capacity Equation

An important issue that must be considered when evaluating the data is the inherent sense of competition between agencies. The survey explained the study area and because many of the organizations commonly interact there is a pre-existing sense of competition or organizational pride. Where possible, the data was corroborated with direct observation.

The thirteen variables were combined into four general area scores that represented their general characteristics as shown in the methodology section. By combining variables it is possible to arrive at a more comprehensive picture of a function within the organization and not be overwhelmed by the number of variables. The four general areas are:

- Personnel
- Equipment
- Planning
- Interaction

Each of these areas was based on elements combined to arrive at a score for that area. Each evaluated specific elements. Some of the data gathered was ordinal and some was interval depending on the nature of the data. The four areas were weighted to indicate their respective importance to the completion of the organization's missions. These weights were developed by consulting a minimum of three experienced practitioners from each discipline. Each assessed the importance of that category to the organization's ability to complete their overall mission.

Table 3. Response Organization Variable Weights

Variable	Police	Fire	EMS
Equipment (A)	20	30	30
Personnel (B)	60	50	50
Planning (C)	5	15	15
Interaction (D)	15	5	5

Equipment

The equipment score is an aggregation of the scores on the following variables:

A. Flood related equipment rating

B. Amount of communications equipment/categories

C. Number of vehicles/vehicle categories

X. Discipline specific weight.

These resulted in the following equation:

Equation 9 $((A + (B/8) + (C/5))*X$

In the above equation, the first variable (flood equipment) is a rating of the amount of flood equipment owned by the organization. The respondent could choose from four different levels of equipment from water rescue specific equipment to no equipment. This is a somewhat subjective judgment because the fire service has equipment in their standard inventory that is applicable to flooding but may not have been purchased specifically for that purpose.

Variables B and C had multiple types of equipment that could be included in those categories. If the quantities were included in their pure form their values would have a disproportionate influence on the total equipment score. To arrive at an appropriate indication of communication equipment and vehicles, the total number of units was divided by the number of types of that equipment or categories. This measure provides a mean for the group that does not overwhelm the other items.

Personnel

The personnel area used the following elements:

A. Number of field personnel trained to the discipline basic level
B. Number of field personnel with discipline advanced training weighted by 1.5
C. Percentage of field people with flood/water rescue training
D. Percentage of field personnel with flood response experience
E. Number of floods to which the organization has responded in the last ten years

X. Weight assigned for the discipline

To calculate the personnel score for an organization the following equation was used:

Equation 10 $((A + (B*1.5)) + (C*D) + E))*X$

* For the purposes of the study, all personnel were considered not just on duty personnel. This allows for the inclusion of personnel called back to work in career organizations.

The equation was constructed in this way to divide the discipline specific training, giving an added value to those with advanced training, from the flood specific training and experience. Because training and experience are both parts of a learning feedback loop, they were multiplied rather than added. The addition of E was to represent the experience of the personnel working together as an organization at flooding incidents separate from their individual experience. This is one method of taking into account, the impact of the double-hatters who may have experience from other organizations and at the same time giving credit for the organizational members working together. The number of people trained in management was included to address the administrative aspects of the organizational, which may not be critical to the direct provision of service but may be an indicator of the organizational stability and structure.

Planning

The Planning component is a compilation of a variety of factors used to indicate the amount of preparation the organization has made for emergency response. The planning area used the following elements:

A= Organizational Planning and Exercising

B= Completion of Hazard Vulnerability Assessment

C= Resource Planning (by jurisdictional level)

These variables were used in the following equation to create the Planning score:

Equation 11 $$(A+B+(C/4))$$

Variable A indicates the amount of planning that the organization has completed regarding responses in its area. The value of the variable was coded with the higher levels indicating a higher degree of preparedness.

Variable B indicates whether the organization has completed a hazard vulnerability and its degree of formality.

Variable C provides a measure of what resources from other jurisdictional levels were considering in their planning. The score is a compilation of four jurisdictional levels that are then averaged to prevent this one variable from dominating the score for the variable.

Interaction

Interaction among the agencies is critical to efficient and effective response operations. While this is necessary for emergent operations the groundwork for the efficiency is laid in developing pre-existing relationships. To determine the amount of interaction that the organizations routinely experience, three variables were used to develop an interaction score.

A. Interaction Outcome

B. Interaction frequency by discipline

C. nBetweenness for the response organizations

These variables were used in the following equation to create the Interaction score:

Equation 13 $$(A + (\text{Sum of } B/6) + C)$$

Variable A (Interaction Outcome) is based on the manager survey in which they indicated whether they found that the relationships aided or hindered response operations in the past. This is a critical issue because it creates an expectation regarding the benefits of interagency cooperation. These expectations can manifest themselves in subtle ways that could taint interorganizational communications and efficiency.

Variable B (Interaction frequency) is an average of the frequency with which organizations interact with specific disciplines. They were given three choices (frequently, occasionally, rarely) to indicate their perceived frequency of interaction. For the purpose of the model, an average was used to provide a general picture. However the granularity of discipline specific information was used in the analysis.

Each score is independent of the others in that the scale does not allow comparison between areas but only across the organizations individually, by discipline, and by municipality. While they share the same mission, their specific discipline, implementation and available resources differ significantly. In the study area, the organizations range from large, well funded, career organizations to small, struggling, volunteer organizations. While this diversity makes comparisons difficult, the standardization of the organizations by comparing their service capability to area served provides a reference similar to that used in the hazard sections.

3.6 MAPPING OF THE INTERDEPENDENCIES

The second section begins once the baseline information is obtained. The data will be used to create interdependence matrices. The first task was to identify the nodes and the spatial linkages among the nodes. There were also the linkages between non-human (geophysical and built) and demographic elements. Because these elements are connected spatially, co-location will be the primary source of determining interdependency. This was represented in the aggregation of the vulnerability by tracts rolling up to the sub-county region.

Using network analysis on the linear elements between the tracts included an additional facet of interdependency. Network maps were created allowing the determination of two important indices. The first was the betweenness measure for each node. Betweeness is the indication of how important that node is in the flow between all of the other nodes in the system. Because betweenness is sensitive to the size of the network, the value of nBetweeness was used because it is standardized to remove the impact of network size.

The second aspect included concerned the public safety response organization elements. Each organization uses the assistance of other organizations to respond to larger incidents. This is termed "mutual aid" because it is often a two-way relationship, although it may not be equal in frequency or reciprocity. These relationships are both intra- and inter-municipal. The frequency of these interactions increases familiarity and brings additional resources to the incident. In addition, organizations from multiple disciplines often respond to the same incident. All of the response organizations within a discipline were mapped to illustrate proximity. The interdependency of these organizations is reflected in the model used to simulate responses. The exact nature of the interaction will be explained in detail under the model section.

3.6.1 Interaction Data

1. How do the areas within the Knowledge Base and within the Interdependency maps interact? Are these direct or indirect interactions?
2. How do the organizations in the Capabilities Section interact?

Each organization was scored using as a reference the mean of the entire group for this specialized field. The qualitative aspect of the study came through interviews with the managers of the various response organizations, including chief officers and organizational managers. Their experience and information was added to the quantitative information to develop an overall picture of the organization's response capacity. There are twenty-eight primary response organizations providing service to the study area. The smallest area has four organizations while the largest has ten. With this limited number, it was hoped that all of the managers could be interviewed, but three of the organizations did not respond to multiple requests for information. These three were all in one municipality and two disciplines.

3.7 DETERMINATION OF RESILIENCE

The third phase is to examine the impact of public safety organizations, their interactions and their response capabilities on the vulnerability of the study area. These agencies are the first form of community resilience in that they provide a direct and timely method by which the impact of the incident can be reduced. In addition, they are typically the first to move the incident from response to recovery. This is especially the case in flooding incidents because they have the tools to save lives, minimize water damage, and assist the home and business owners with the initial stages of salvage.

Response organization capabilities will be determined at the tract level and then aggregated up to each of the two jurisdictional levels above tract. The aggregation of all response organizations' scores, this is where the mutual aid mentioned above is manifested, over their distance to the tract will be subtracted from initial vulnerability (Vinitial) for the tract to arrive at an adjusted vulnerability (Vadjusted) for the tract.

Equation 14 VGeo x VBuilt x VSoc= Vinitial (initial vulnerability conditions at the tract level)

VGeo = Vulnerability contributed by the geophysical environment

VBuilt = Vulnerability contributed by the built environment

VSocial = Vulnerability contributed by the social environment

Equation 15 ∑(RO/distance to tract) = Ctract

RO = Response Organization Capabilities

Ctract = Capabilites for the specific tract

Equation 16 Vinitial – Ctract = Vadjusted

For those tracts that are not wholly contained within an organizations response district the percentage of their area within the tract will be used to modify the score to adequately reflect response capabilities. Models, especially those of complex interdependent systems, are simplifications of reality. The goal of the models is to provide us with an increased understanding of the nature of the systems and are to be probabilistic not deterministic. The model and the simulation that provides data based on the model are the best representations possible within the limitations of the data and available technology.

3.8 DEVELOPMENT OF THE SIMULATION

In order to gain an understanding of how the interactions among the vulnerabilities and the response organizations can change over time, a series of simulation iterations were done using historical data from the National Weather Service (NWS), the local dispatch center and the Allegheny County 911 dispatch system. The development of the flood service demand template was done using actual emergency calls received during Tropical Storm Ivan on September 7th and 8th of 2004. The service demands represent not only flooding calls but also the routine 911 calls. This allows the simulation to run a much more accurate representation of the service demand placed on response organizations.

While the 100-year flood plain will be used as the planning threshold, many of the floods occurring below this level affect the systems being studied. This is particularly true of flash flooding. The emergency response officials who worked during the event validated the accuracy of the service demand model.

The methods outlined above for the three systems (geophysical, built and social) provide the initial conditions. The next step is to use agent based modeling as the method to effectively create a computerized version of the systems and their interdependencies. Agent based modeling allows the creation of simulated organizations or elements that are assigned characteristics that represent the relevant parts of their environments. The information collected in the previous sections of the study will be used to construct these agents. Once constructed, the agents follow preprogrammed rules, based on the defined characteristics, when interacting with other organizations and their environment. The three systems will create the environment around which the modeled response organizations will respond. Using the initial conditions as the starting point, the waters will rise affecting certain elements. By iterating the model, we can simulate the affects over time.

NetLogo, an agent-based model computer program was initially intended to be used as the platform for this part of the study. As the model evolved it appeared that NetLogo was overly simplistic and therefore not adequate to represent the complexity of the model. A colleague, Adam Zagorecki, became interested in the model and agreed to program the simulation in a C++ base. In this section I will describe the methods we used in creating the simulations.

3.8.1 Tracts

The initial vulnerability (Vinitial) for each tract was coded into the program. This value does not change throughout the simulation. This score was then ranked to provide an incident modifier for the simulation's incident service demands. That exact application of the modifier will be explained more fully under the incidents section.

The inclusion of the summation of all response organization capabilities, as shown in Equation 3, for each tract is applied to determine the Vadjusted for the beginning of the scenario. This score changes as the availability of response assets changes by assignment to incidents. Because the Vadjusted is calculated based on all response assets, when a single unit is assigned the Vadjusted value for each tract changes to reflect the loss of this asset. For the determination of impact to the municipal and sub-county regions the tract values are aggregated up to the appropriate level.

3.8.2 Time

In most simulations time is not a relevant parameter but in the case of modeling these incidents time is a critical factor. For this simulation each step was modeled to reflect a four minute time step. The entire simulation runs for one hundred time steps, reflecting the initial six hours of an incident. While flooding incidents can run longer than the six hours modeled, the majority fit within that time. By choosing the six-hour time frame, larger sections of time can be readily modeled for longer periods of time by extending the simulation run. Since the purpose of this study was to develop the model, simulating the impact of extended operations was considered beyond the present study scope.

3.8.3 Incidents

The systems create a complex environment. To effectively model this complex system, the initial conditions must be established. The scores for the geophysical, built and social systems were used for that purpose. This number serves as a modifier to the service demands created when an emergency occurs. The number is standardized based on the lowest value in the area. In the case of the study area tracts, the range for the modifiers is from 1 – 16.7.

For example, a person calling for an ambulance may require one ambulance and one police car. In an area where the standardized vulnerability is 4, the service demands would increase by four reflecting the “cost” of the incident in that area. The rationale behind this modification is that in areas where there are more vulnerable initial conditions, the resources required to mitigate the incident are more valuable when compared to areas that are less vulnerable. This is an oversimplification of a specific incident but allows a standardized approach to combining all of the vulnerability factors.

Emergencies, by their nature, occur at a specific time and place. Some of the events can spread both temporally and spatially. This is often the case with flooding events that can have impacts for days, months or years, depending on the scale of the flooding. There may also be multiple incidents occurring simultaneously. These additional incidents may be flood related or could be “routine” emergencies. The use of the advanced simulation allows the inclusion of both aspects into the model. This is much more realistic than the single incident focus required with the software that was initially proposed. The software also allowed us to program 249 different incident types directly from the Allegheny County Computer Aided Dispatch (CAD). This provides a representative range of incident types. Using the CAD data and the first 24 hrs of the incident, the probability of receiving the various types of calls was determined. For each run of the simulation, a random list of incidents was created based on the probabilities. The storm from which the data were taken affected the entire county resulting in a Presidential disaster declaration. Because the study area was not served by Allegheny County 911 at the time of the storm, the data was distilled down to probabilities based on population of the area served. Population was chosen as the measure of standardization rather than area because people make the calls, and areas with more area but less people will generate fewer calls. The probabilities were then applied to the population of the study area to generate the probabilities used in the simulation.

For each type of incident a “run card” was created, denoting the amount and type of resources (police, fire, EMS) typically dispatched to that type of service demand. Each type of resource was modified by the tract ranking to determine the response capability level required of the incident. This does result in additional units being initially assigned but that the total capacity of that type of resource required is elevated in order to mitigate the incident. All units assigned to an incident remain on scene, and therefore out of service and out of the capacity calculation, until the incident is resolved.

One modification that was made to the simulation-created incident list was the assignment of flooding incidents to specific known problem areas. During interviews the response organization officials identified areas where flooding commonly occurs. These areas were specifically included in the simulations to more accurately reflect their experience.

It was shown through the work of Comfort, Ko, and Zagorecki (2004) that emergency incident service demand is affected by increasing demand generated by cascading failure effects inherent in the environment systems. The rate used in the simulation, .01, was the same as used by Comfort, Ko, Zagorecki (2004). To reflect the variation in incident service demands generated incidents were assigned one of two trends. They had either the .01 increase or a flat trend. This reflects the two incident escalation trends common in emergency incidents. The flat service demand is typical of incidents such as medical emergencies, and vehicle accidents where the impact of the incident is completed when the call for service is made. The increase attributed to the cascade of failure is more typical of utility emergencies, weather and fires.

The application of response organization assets to these emergencies reduced the impacts and therefore the demand. To increase the realism of the simulation the above trend line in service demands were placed randomly on each incident. If the service demand was not met by the initial public safety response during the first five time steps then initial resources were called in based on the response policies chosen at the beginning of the simulation. Once the incident demands are met the unit is immediately placed back in service.

Two formats were chosen for the simulation for comparison. The flooding data as mentioned above was used to create a model similar to flash flooding while a second model depicting riverine flooding was done for comparison. Each has the background set of non-flood related 911 calls to reflect normal emergency response service demands.

3.8.4 Response Organizations

The response assets were scored as delineated in Equation 3. The scores of units dispatched, based on call type, were applied against the incident service demands at the first time step. Three different methods of dispatching units, response policies, are available when the simulation is set up. The first uses the existing dispatch policies in practice throughout the study area, Response Policy 0. The second uses a closest available unit approach, regardless of municipality, Response Policy 1. The third is a “leap frog” pattern where the initial unit to respond is the closest but the third closest unit is dispatched for mutual aid. This continues until the furthest unit is dispatched and then the policy begins again from the closest unit. To illustrate if units 1,2,3,4,5 are in order of proximity to an emergency unit 1 is sent first. If they require assistance then unit 3 goes , then 5. If additional assistance is still required then unit 2 and finally unit 4 is assigned. The rationale behind using the leap frog policy is to facilitate a more uniform distribution of response assets rather than depleting the area directly adjacent to the incident. This policy has been used in a variety of incident commanders, including myself, but is not currently in formalized use in the study area.

3.8.5 Data Collection

The majority of the GIS information used was from the Allegheny County Department of Computer Services GIS division. Additional GIS information as retrieved from the Pennsylvania Geospatial Data Clearinghouse and some was created by the investigator reflecting information from interviews with response organization managers. The interaction information is available in a variety of formats for cross validation. The Computer Aided Dispatch (CAD) and response organization manager interviews provided information to identify which and with what frequency organizations respond to calls together. The interviews also revealed an impression of how well those organizations work together.

4.0 ANALYSIS

The analysis, driven by the questions stated in Chapter 1 will investigate the findings relevant to hazard vulnerability and the development of an accurate model for simulation.

4.1 AREAS VULNERABLE TO FLOODING

In order to determine the areas within the study are that are vulnerable to flooding, we first have to define the term *vulnerable*. For this paper vulnerable is defined in two ways:

1. Direct Vulnerability - areas directly endangered within the designated 100-year flood plains.

2. Indirect Vulnerability - areas endangered because of their interdependencies with the areas directly inundated.

It may seem reasonable to only examine the structures and population in the floodplain this is one of the shortcomings of the existing hazard vulnerability assessment. The intrusion of floodwaters places additional demands on the entire area. This led the researcher to include all of the structures, infrastructure and population in the study.

As an additional facet in the development of the model, the connections between the areas were also considered. When there is a loss of infrastructure within an area not only does it impact those services/routes but also any attached to it. This aspect will be discussed more fully in the network analysis.

The first section of the analysis concerns the creation of the knowledge base. This laid the groundwork from which all of the other analysis occurred. The development of the knowledge base provided some interesting challenges. I will discuss each of the three main sections of the knowledge base and how the information was developed.

4.2 KNOWLEDGE BASE

The measures for the previously specified three (3) environments were collected from a combination of the GIS and interviews with response unit managers for the area. It was determined that standardizing them using density would allow for a ready comparison of the jurisdictions on a spatial basis. This was done initially on the lowest level, census tracts, and then rolled up through the municipalities and then the sub-county region.

The area surrounding streams and drainage pathways most prone to flooding is known as the 100-year floodplain, or the base flood elevation (BFE). This is determined by the Federal Emergency Management Agency. This area has a history of flooding with the defining parameter being a 1% annual probability that the area will experience a flood reaching the BFE. Another way to look at it is that the designated area can expect a flood of that level once every 100 years.

While admittedly there is the possibility that floodwaters will reach higher levels, this measure was considered the optimum for representing the planning threshold, and therefore modeling threshold, for likely flooding. Buildings within this area are required by US CFR Title 42 to purchase the insurance when they are located in National Flood Insurance Program participating communities. Three of the four municipalities in the study area participate in the program. Wilkinsburg Borough, the one non-participating municipality, has no above ground streams although they have experienced flooding due to backup within the storm water system. This type of flooding is beyond the scope of this study.

Since flooding begins with the geophysical environment, that is the best place to begin the development of the knowledge base.

4.2.1 Geophysical Knowledge Base

There were four variables included in the geophysical environment of the census tracts: area (sq miles), flood prone area (sq miles), stream length (miles), watershed (count). Each of these factors is relevant to the determination of the vulnerability of flooding.

All of the municipalities in the census tract have a history of flooding, although one contains no flood plains or open streams. In that case it was found that the flooding was due to the back up of storm water through the storm water drainage system during periods of extreme rain such as Tropical Storm Ivan (Colella, personal communication, May 22, 2005).

To understand the diversity within the study area and compare the direct vulnerability inherent in the tracts a scoring system was devised to compare the tracts. Density was used to standardize the information for comparison. The first thing that is apparent is that the top four tracts contain no floodplain and no streams. However because they are small areas with several watersheds that will funnel storm water, they scored at the top of the ranking. These conditions, in addition being the most urbanized area with considerable amounts of impermeable soil coverings, may explain part of the reason for the flooding due to the overwhelming of storm water system carrying capacity.

The tract with the largest area of floodplain ranks twenty third (23^{rd}) in the ranking. This may seem unrealistic but when you consider that flash flooding is a stream and urban flooding issue the concept becomes more tenable. To further validate this finding the National Weather Service office in Pittsburgh was contacted. Meteorologist Robert Davis stated (personal communication, May 31, 2005) that there is a connection between the basins and urban/stream flooding. The steep topography of the area not only results in more basins but also increases the speed of the flow and causes the water to be deeper at the collection points than an area with flatter topography. This results in quicker and more extreme flooding.

4.2.2 Social

While the population residing in the floodplain is small these individuals will generate the most immediate need for public safety assistance and could potentially draw away resources in a temporal shift, from other more populated areas that will later be endangered as the incident evolves.

The percentage of people residing in the 100-year flood plain is actually quite small.

Municipality*	Residential Structures	Estimated Population at Risk	Total Population	Percent of Population in Flood Plain
Wilkins Twp	36	40.29	6,917	0.006
Monroeville	85	94.47	29,349	0.003
Penn Hills	30	47.07	46,609	0.001

Table 4. Population residing within the flood plain

The number of people residing in the flood plain was estimated by first determining the number of residential structures located within the floodplain in that municipality from the GIS. The average household size for that census tract, based on the U.S. 2000 Census, was multiplied by the number of structures to arrive at the population estimate.

There is no correlation between the total population and the number of people residing in the floodplain.

Correlations

		Residential Structures in flood plain	Total Population
Residential Structures in flood plain	Pearson Correlation	1	-.025
	Sig. (2-tailed)	.	.984
	N	3	3
Total Population	Pearson Correlation	-.025	1
	Sig. (2-tailed)	.984	.
	N	3	3

Table 5: Correlation of Total Population and Residential Structures in the Floodplain

There is however, a positive correlation between the density of the population in a municipality and the number of people residing in flood plains. While the number of cases is small, the correlation warrants noting.

Correlations

		Residential Structures in flood plain	mean pop/sq mile
Residential Structures in flood plain	Pearson Correlation	1	.892
	Sig. (2-tailed)	.	.299
	N	3	3
mean pop/sq mile	Pearson Correlation	.892	1
	Sig. (2-tailed)	.299	.
	N	3	3

Table 6: Correlation of Population Density and Residential Structures in the Floodplain

Most people will evacuate during a flood, when possible. There are occasional exceptions when people opt to remain. This usually results in either rescue efforts creating an increased public safety demand or increased morbidity/mortality of victims, rescuers and those who might have needed the additional resources, which are now not available. Increasingly in cases where people are advised to evacuate and knowingly refuse to do so, they are advised that should they call when conditions are not safe to retrieve them public safety agencies will not respond until conditions will improve. The impact generally remains, but is merely delayed.

The census data reflects only residential numbers but there may be larger numbers of people working, shopping or traversing the area that would be at risk. This factor will be addressed more fully in the section on the built environment but it should be remembered that flooding is the Number 1 weather-related killer in the US and 50% of those fatalities are vehicle related (NOAA, 1992). While the characteristics of the cohort do not necessarily apply to those traveling through the area, because the areas are contiguous many of the characteristics of the study area in general may apply.

The social vulnerability was developed from the 2000 Census data at the tract level. Each cohort represents a risk factor that, based on the literature, places an individual at a higher impact risk from a disaster. The list of risk factors, the number present in each tract and the total population for the tract is shown in Table 7.

The social vulnerability layer was built using the following steps:

1. The demographic risk factors are gathered from the 2000 census data.

2. This score was then normalized by dividing it by the area of the tract to facilitate comparison among the tracts.

3. To categorize the tracts the normalized scores were divided into five groups using natural breaks (Jenks) in the data assigned each of the tracts to one of five divisions. The Jenks method was chosen because it is commonly regarded as the best for visual representation of distribution. The five divisions were color coded to coincide with the US Department of Homeland Security threat levels (US DHS) since it is a generally recognizable by the public.

This method provides an accurate portrayal of emergency resource demand given the limitations of the data available. Person with multiple risk factors can be expected to have an increased need for emergency resources because they have fewer assets available to apply to their situation (Blankie, Cannon, Davis, Wisner, 1994). These individuals would place an increased demand on the response resources of the public safety and support agencies.

Municipality	Tract	Total Pop.	Non-white	Young	Elderly	FHH w/ Child	Renter	Disabled	Non-Eng	Poverty	Score
Wilkinsburg	561400	4775	3409	983	991	243	1337	1127	76	1055	8970.05
Wilkinsburg	561500	3655	2543	895	559	206	771	863	58	810	7200.25
Wilkinsburg	560600	1636	1275	459	205	114	576	386	26	362	5674.56
Wilkinsburg	560500	2286	606	353	236	72	755	539	37	506	5640.21
Wilkinsburg	561200	1744	1611	44	285	107	442	412	28	386	5494.77
Wilkinsburg	561000	1916	1497	572	229	153	486	453	31	424	4852.12
Wilkinsburg	560400	1770	1297	366	316	113	740	418	28	392	4662.69
Wilkinsburg	561100	1414	1343	417	218	112	230	335	23	313	3655.57
Penn Hills	523400	5229	900	1047	1118	140	491	967	63	472	3155.76
Penn Hills	523200	4423	2083	1131	674	209	359	818	53	399	3024.40
Penn Hills	523501	5160	1545	1158	850	149	355	955	62	466	2366.55
Penn Hills	523300	4592	858	908	1242	94	263	851	55	415	2303.63
Penn Hills	523100	5067	4413	1278	962	201	296	937	61	458	2297.40
Penn Hills	523600	5276	868	1020	1093	83	454	976	63	476	1874.81
Monroeville	521100	4768	1116	1204	768	94	104	731	159	374	1751.93
Penn Hills	523702	5718	826	1192	931	165	848	1058	69	516	1723.21
Penn Hills	523800	5086	222	937	1336	77	463	941	61	459	1670.56
Wilkins	520002	3515	223	638	729	66	539	490	71	263	1478.51
Monroeville	521200	4498	710	769	890	87	976	689	150	352	1072.93
Penn Hills	523701	4555	413	1067	687	115	260	843	55	411	1034.97
Wilkins	520001	3402	276	532	1055	38	465	473	68	255	991.31
Monroeville	521302	4291	683	729	907	120	1063	658	143	334	942.3
Monroeville	521301	4118	591	781	1119	147	925	631	137	321	941.38
Monroeville	521402	4140	575	1014	647	43	57	634	139	325	915.99
Monroeville	521500	4708	337	972	949	75	281	722	157	369	650.60
Monroeville	521401	2826	219	510	668	26	350	433	98	220	373.13
Penn Hills	523502	1703	238	402	338	47	161	317	20	153	241.67

Table 7: Social Environment Scores by Tract

* Red denotes Risk Factors

It is evident that the heterogeneity in the study area is not evenly spatially distributed nor is it confined to a specific municipality. The areas of high and severe risk are clustered appearing to emanate from Wilkinsburg. The vulnerability levels generally decrease as you move away from the area but it is interesting to see that this decrease is not uniform. This is a spatial representation of the homophily in the area (McPherson, Smith-Lovin, Cook's, 2001) and demonstrates the populations tendency to group with others with similar characteristics. In this case it extends to those who are more vulnerable to disasters and may be of benefit to emergency management planning. The map also shows that these clumps are not generally limited by political borders but in some cases do coincide. For instance, Wilkinsburg borders Churchill borough. The contiguous sections are orange and green respectively. The number of people at or below the poverty level in the Wilkinsburg tract is 1198 while on the Churchill side of the line it is 146. The associated variable, such as rent vs. own homes, varies similarly. It is not as simple as looking at income levels.

4.2.3 Built Environment

The built environment contains 15 variables. Each was placed into one of three categories based on similarity of function: transportation, utilities and buildings. While these categories are arbitrary they are helpful in conceptualizing the infrastructure on which the population relies for normal day to day life.

Transportation	Utilities	Buildings
Road	Transmission Lines	Residential
Rail	Stations	Public
Tunnels	Points	Small Commercial
Bridges	Comm. Towers	Large Commercial
	Gas Wells	
	Sewer Plant	

Table 8: Built Environment Variables

4.2.3.1 Transportation

The most readily apparent day-to-day use to the majority of people is transportation. That group included roads, rail, bridges and tunnels. The road and rail variables used length as the measure while bridges and tunnels used a straight count for the tract. The total length of roadway in the area is the most normal distribution of the transportation group with a mean of 13.5 miles of roadway/tract with a standard deviation of 7.4. See Table 9. As intuitively expected, the amount of roadway is positively correlated with the population of the area.

Municipality	Roads	Railroads	Bridges	Tunnels
Wilkins Twp	1.73 (6.0%)	.31 (5.7%)	3 (27.3%)	1 (100%)
Monroeville	6.88 (34.7%)	1.94 (62.3%)	2 (4.4%)	1 (100%)
Penn Hills	2.91 (1.6%)	2.59 (12.6%)	3 (11.1%)	0 (0%)
Total	11.52	4.84	8	2

* Wilkinsburg had no designated flood plains and therefore no direct vulnerability.

Table 9: Transportation Environment Direct Vulnerability in miles (% total for tract)

The majority roads and railways in the study area are indirectly vulnerable. There are road routes through the area that do not enter floodplains but approximately half of the major routes traverse through a floodplain. While the actual area impacted is small, as shown in the Table 7 the inundation of those areas disconnects much of the heavily traveled traffic routes. This would delay both evacuations and response of public safety assets into the area. It should also be noted that virtually all of the rail routes through the area at some point cross the floodplain. In a widespread event impacting the entire area it is conceivable that all rail traffic would be shut down.

In a recent discussion with a representative of the Norfolk Southern railroad regarding the financial impact of shutting down rail traffic, a colleague was quoted the number of $1million/hr as the cost of stopping rail traffic on a single line (R. Conely, personal communications, 2005) . Not all of the rail lines through the area are Norfolk Southern so the actual costs may vary.

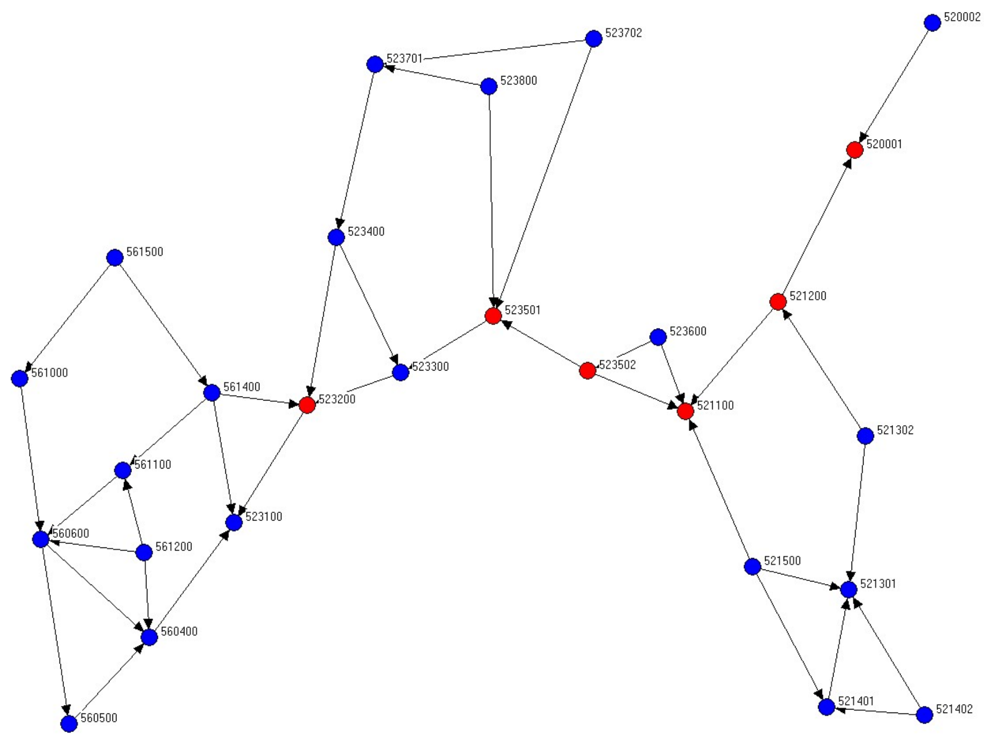
4.2.3.2 Utilities

The group includes electricity, gas, water impoundments, sewer lines and mobile communications towers. Much of the information on the local level is secure proprietary data so the information was not attainable from any sources. However, there was some information available from several GIS sources. All available data sources were used. The data are primarily information on the distribution system, which has applicability not only to the local area but also to many areas in the surrounding region and in some cases in other parts of the country.

Some of the utilities have several indicators. For example, electrical service is a combination of transmission lines, utility poles/pylons and substations. For the linear functions, length was used as the measure and for points it was a total count. Admittedly, the electrical system does not include the local distribution lines. That data are considered secure by the utility companies so access to it is even denied to public safety officials. The use of the proxy measure of roadway length was considered but with the increasing use of buried lines it was determined that the use of the proxy would be too inaccurate to include in the study.

In examining the utilities there would appear to be little direct vulnerability to the transmission network because little of it is located directly in a flood plain. However using network analysis we can see that there is a vulnerability that is not readily apparent. By evaluating the links between the census tracts made by the utility line, a network matrix was developed. This matrix reveals 6 cut points that are critical links in the distribution network. Cut points are nodes in a network that if removed disconnect sections of the network. In this case the elimination of a cut point would cause a loss of service to any nodes downstream in the network. See Figure 9 for the diagram showing cutpoints shown in red.

Figure 9. Utility Line Cutpoints



* Nodes are census tracts

Another important point is the vulnerability of the sewage system. Sewage treatment plants are commonly placed along rivers to reduce the cost of disposing of treated water. As a result they are very vulnerable to riverine flooding. In the case of the study are there are two sewage treatment plants. Based on the GIS flood plain map a 100-year riverine flood would result in a 50% loss of the sewage treatment facilities. Flooding of sewage treatment facilities not only reduces the capacity to provide service but often creates a public health hazard not only in the area of the plant but also in the homes unable to dispose of waste.

Municipality	Utility Points	Utility Lines	Sewer Plants	Utility Stations
Wilkins Twp	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Monroeville	2 (1%)	0 (0%)	0 (0%)	0 (0%)
Penn Hills	7 (2%)	0.67 (4%)	1 (50%)	0 (0%)

Table 10: Utilities located in Floodplain

A point worth noting is the predominance of two types of energy for residential use. According to the US Department of Energy's Energy Information Administration (2005) 51.1% of the homes in the northeastern U.S. use electricity, with the majority of energy use (36.7%) for environmental control. A smaller percentage use natural gas (31.9%) but only 17% of the homes have other energy sources available. This reliance on only two forms of energy creates an increased vulnerability since the loss of those two energy sources would minimize the ability for people to control their environment. A second important use of energy is for refrigeration. The loss of electricity for refrigeration for an extended period of time could result in increased incidence of food-borne illness and a resulting burden on the healthcare system.

4.2.3.3 Buildings

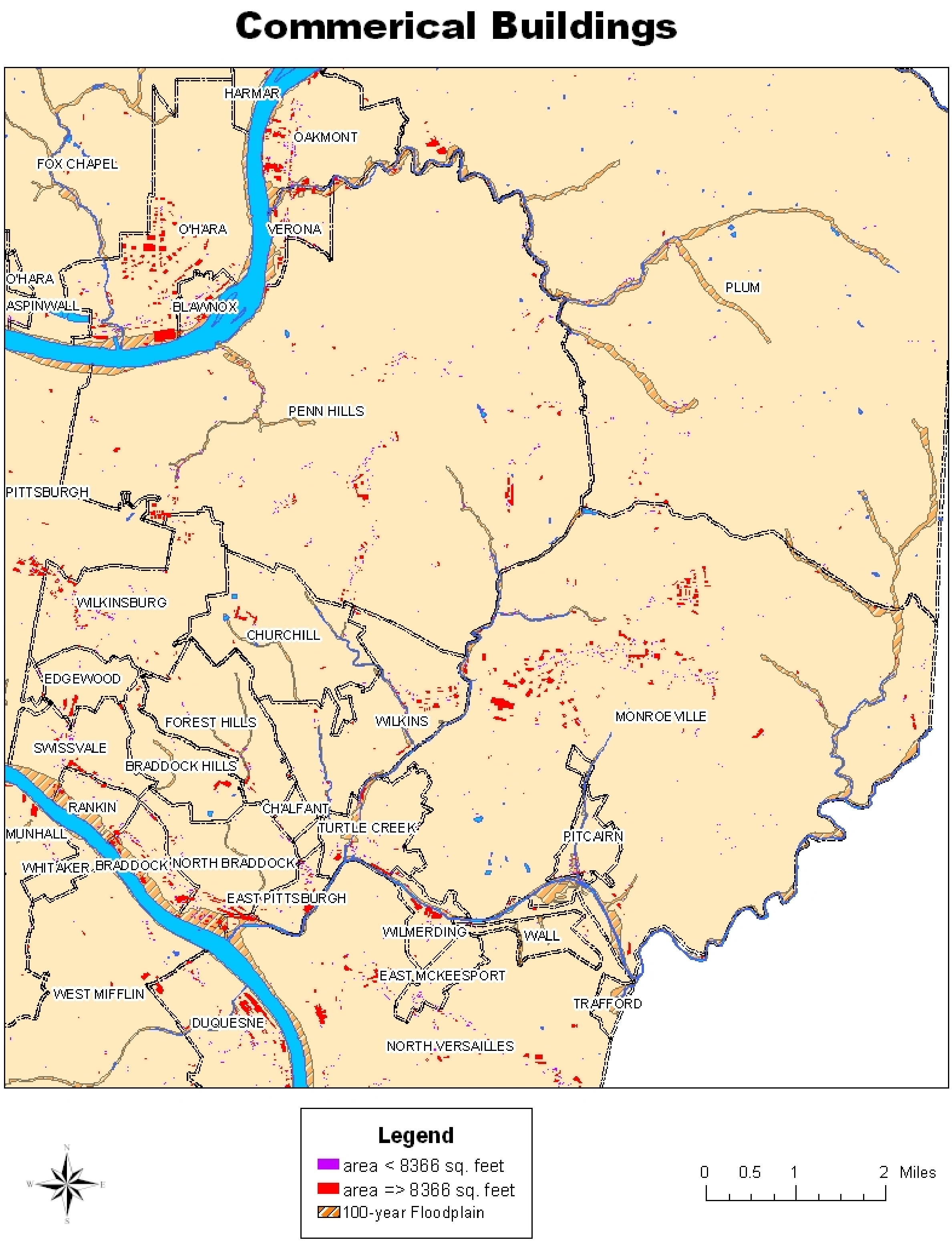
To determine the building infrastructure vulnerable to flooding the GIS building footprint layer was used. The buildings were categorized by occupancy type. Occupancy refers to the use of the building vs. the type of physical structure. The five types of occupancies included in the coverage were: residential, public, commercial/industrial, out buildings, such as garages/sheds, and unknown. The first three mentioned were included in the study since the effect of losing the remaining two categories would be minimal. Some of the buildings originally listed as unknown were recategorized based on knowledge of the area and input from the local agency managers.

One of the variables, commercial/industrial buildings, was divided between large and small structures. This was done as a method to separate the larger industrial buildings, warehouses/factories/etc, from the smaller primarily mercantile structures. It was felt that this better represented the heterogeneity of the areas delineating the main business areas from industrial park type areas. The basis for the separation was a dividing line in the distribution at the 75th percentile (8366 sq ft). The 75th percentile was chosen because it reflects a break line in the distribution of the size of commercial/industrial buildings that best delineated large warehouse/industrial buildings from smaller mercantile buildings such as single shops. Buildings at or above that line were considered large. Of the 1415 commercial/industrial buildings in the study area the large buildings accounted for 372 (26.2%) of them.

Direct Vulnerability

In looking at the distribution of the buildings in Figure 10, we can see that the larger structures are more clustered than the smaller ones reflecting the major business districts and industrial areas. No public buildings are located in the floodplains.

Figure 10. Commercial Buildings



	Small Commercial in floodplain	Large Commercial in floodplain
Wilkins Twp	6 (75.0%)	3 (13.1%)
Monroeville	15 (5.3%)	8 (9.2%)
Penn Hills	16 (43.2%)	15 (32.6%)
Wilkinsburg	0 (0%)	0 (0.0%)

Table 11: Commercial Buildings located in floodplain

(% of total for category in the municipality)

The smaller buildings are more evenly distributed across the area so as a group they are less likely to be impacted. The areas of larger commercial property are typically the larger employers and provide revenue to both the government and the population through employment. There is a roughly even distribution of small and large commercial structures in the study area floodplain, but the majority of commercial structures are outside of the floodplain.

4.3 KNOWLEDGE BASE ANALYSIS CHALLENGES

In an attempt to refine the equation to a more parsimonious form, the variables were explored using factor analysis. Both the raw data and the density data were initially tried in the analysis. Factor analysis requires both a normal distribution and independent variables. In evaluating the data it was found that neither of these requirements could be met. Because of the heterogeneity of the area, the distribution of the data had multiple outliers. Removing them to facilitate the analysis would have resulted in a diluting the heterogeneity of the areas sufficiently that the applicability would be compromised. It was decided that retaining the original variables and thereby the heterogeneity of the area took precedence.

4.4 KNOWLEDGE BASE SUMMARY

While the ability to compare tracts is useful, it does have a draw back. Using density for standardization illuminated the heterogeneity in the area, but it also skewed it. Basing the density calculation on one square mile resulted in some of the populations for that area appearing high. For this reason the densities will be used only for comparison purposes among municipalities.

Municipality	Social	Built	Geophysical
Wilkinsburg	66.67	33.23	0.09
Monroeville	58.32	41.3	0.03
Wilkins Township	92.98	6.77	0.24
Penn Hills	64.42	35.41	0.16
Percent of total	70.6	29.18	0.13

Table 12: Percentage of Environments to Initial Vulnerability

4.4.1 Response Organizations

The data from the response organizations were collected by surveying each response organization. The surveys were completed by the organization’s manager, chief or designee. All organizations were given the same survey. See the Appendix. Three organizations did not respond to the survey. Some of the data for those organizations was gathered from other sources such as employees and direct observation. Each variable score was developed using the same parameters. Once calculated, the variables were weighted according to a discipline specific number. The assigned weight was based on the input of experienced managers from within that discipline reflecting the relative importance of that category to the organization being able to complete its mission. The total sum for all weights is 100.

While EMS and the fire service rely heavily on their personnel, they value equipment and planning more highly than do police agencies. This makes intuitive sense because police can still complete much of their work without relying on equipment as heavily as the other disciplines. They do however rely more on interaction than the others that are more operationally autonomous

4.4.1.1 Personnel

Personnel were the most valued asset by all of the survey respondents and the experienced public safety managers from whom the variable weights were derived. Because of its weight of 50-60 it can be expected that there is a statistically significant correlation with the final score. While this may seem to skew the total score the inclusion of the components of experience and training give the result more validity than a straight count of personnel.

Correlations

		Total Score	personnel score
Total Score	Pearson Correlation	1	.887**
	Sig. (2-tailed)	.	.000
	N	21	21
personnel score	Pearson Correlation	.887**	1
	Sig. (2-tailed)	.000	.
	N	21	21

**. Correlation is significant at the 0.01 level (2-tailed).

Table 13. Correlation of Response Organization Score and Personnel Score

An interesting discovery was that this assumption of a significant correlation was accurate for fire (.867, .000) and EMS providers (.968, .032) it was not the case for police (.964, .171). This is despite the police weighting personnel higher than the other disciplines. One of the reasons for this may be the inclusion of the training in the equation. In the calculation of the equation the number of personnel with advanced training are weighted an additional fifty percent. Both the fire service and EMS have relatively large amounts of personnel with advanced training, 104 and 83 respectively. Police agencies have only 16 so the impact on their score would be much lower.

One other problem that ties into the value of training is the double-hatters. These are people who are trained for, and function depending on time or circumstances, in more than one position, or in some cases, disciplines. In a few cases there are triple hatters within the study organizations. Because the random assignment of these people is dynamic, not only within a jurisdiction but on a individual scene, any double counting would be considered an augmentation of the score based on personnel flexibility.

This study area includes both career and volunteer agencies. In general, volunteer agencies are much larger, but less available at any particular time. One resolution to this problems used by the Insurance Services Organization (ISO), a fire service rating organization, is to standardize fire department staffing using four volunteers to one on-duty career fire fighter equivalency. Additional career staff can be called in and volunteers may become available as an incident progresses, so the total number of personnel with the agency was used for this study.

4.4.1.2 Equipment

Correlations

		equipt score	Total Score
equipt score	Pearson Correlation	1	.833**
	Sig. (2-tailed)	.	.000
	N	21	21
Total Score	Pearson Correlation	.833**	1
	Sig. (2-tailed)	.000	.
	N	21	21

**. Correlation is significant at the 0.01 level (2-tailed).

Table 14. Correlation of Equipment Score and Organization Total Score

The correlation between equipment and the total score demonstrates several things. First, on average these organizations are well equipped, reflecting the importance they attribute to having the tools necessary to do the job. Police put less emphasis on equipment, choosing to weight it by 20% vs. the 30% chosen by EMS and the fire service. Despite the lower weight, it remains an important part of the capability shown by its rating second only to personnel. The equipment score accounted for an average of 53% of the police department's score while only 23% and 33% for fire and EMS respectively in the unweighted scores. In investigating this relationship further, it can be seen that some departments can be spoilers for the utility of the average. The size of the department needs to be considered in evaluating these scores. This is logical because the larger the department, the more equipment they would be expected to own. Using a mean equipment/field person was considered, but because some of the larger departments have more equipment than the number of people they routinely field. I used the total for equipment because a neighboring department in a single municipality incident could use this excess equipment.

There were some interesting discoveries. First, each discipline was compared internally as shown below.

Agency	Field Staff	Equip. Score	Equip./staff
Monroeville PD	45	144.75	3.22
Wilkins PD	12	25.75	2.15
Wilkinsburg PD	24	49.00	2.04
Monroeville EMS	60	125.37	2.09
Wilkinsburg EMS	46	50.12	1.09
Penn Hills EMS	21	18.12	0.86
Wilkins EMS	25	18.37	0.74
Monroeville VFD 3	10	15.10	1.51
Monroeville VFD1	15	17.62	1.18
Monroeville VFD 6	20	19.00	0.95
Wilkins VFD 1	13	10.62	0.82
Wilkins VFD 3	25	14.50	0.58
Monroeville VFD 4	35	20.27	0.58
Penn Hills VFD 5	15	8.05	0.54
Monroeville VFD 5	35	17.87	0.51
Wilkinsburg FD	22	11.21	0.51
Penn Hills VFD 1	15	6.75	0.45
Wilkins VFD 4	28	12.22	0.44
Penn Hills VFD 4	25	10.80	0.43
Penn Hills VFD 7	38	13.07	0.34
Penn Hills VFD 3	40	11.80	0.30

Table 15. Response Organization Staff compared to Equipment Score

The initial review of the data shows the Monroeville is in the top position for all three disciplines, and further, that for the fire service Monroeville occupies the first three slots. The other two Monroeville stations, while lower, have more staff resulting in their lower equipment/staff positions. At first review, it would appear that there is a strong correlation between the number of staff and the amount of equipment. There is a strong correlation as would be expected for reasons mentioned earlier.

Correlations

		field staff	raw equipment score
field staff	Pearson Correlation	1	.672**
	Sig. (2-tailed)	.	.001
	N	21	21
raw equipment score	Pearson Correlation	.672**	1
	Sig. (2-tailed)	.001	.
	N	21	21

**. Correlation is significant at the 0.01 level (2-tailed).

Table 16. Correlation of Field Staff and Equipment Score

These results would not surprise someone who knows the area. Monroeville is the more affluent community with the highest median income of the four communities in the study area. These results may suggest that the higher an agency scores, the better equipped their staff is to do their jobs. When the equipment score is standardized by dividing the score by the number of field personnel, the correlation disappears.

Correlations

		field staff	raw eqpt score/field staff
field staff	Pearson Correlation	1	.212
	Sig. (2-tailed)	.	.356
	N	21	21
raw eqpt score/field staff	Pearson Correlation	.212	1
	Sig. (2-tailed)	.356	.
	N	21	21

Table 17. Correlation of Field Staff and Equipment Score per Field Staff

This finding shows that the larger departments do not necessarily equip the individual responder better. In the cases of police and EMS the assumption does hold, but in the fire service it does not. Also interesting, in Tables 19 through Table 21 show that there appears to be no direct correlation between the median income of the community and the equipment score. This is likely due to the large number of volunteer organizations that raise their own funds.

Correlations - EMS

		equipt score	MEDINCOM
equipt score	Pearson Correlation	1	-.101
	Sig. (2-tailed)	.	.899
	N	4	4
MEDINCOM	Pearson Correlation	-.101	1
	Sig. (2-tailed)	.899	.
	N	4	4

Table 18. Correlation of Community Median Income and EMS Equipment Score

Correlations - police

		equipt score	MEDINCOM
equipt score	Pearson Correlation	1	.637
	Sig. (2-tailed)	.	.561
	N	3	3
MEDINCOM	Pearson Correlation	.637	1
	Sig. (2-tailed)	.561	.
	N	3	3

Table 19. Correlation of Community Median Income and Police Equipment Score

Correlations - fire

		equipt score	MEDINCOM
equipt score	Pearson Correlation	1	.505
	Sig. (2-tailed)	.	.066
	N	14	14
MEDINCOM	Pearson Correlation	.505	1
	Sig. (2-tailed)	.066	.
	N	14	14

Table 20. Correlation of Community Median Income and Fire Equipment Score

4.4.1.3 Planning

Despite an intuitive link between planning and organizational capacity statistically, there is no correlation between the Planning score and the Total score of the agency. This may be the result of two factors:

- The self-reporting nature of the survey can skew the objectivity of the manager's assessment.
- By not using actual observations of the impact of their planning the true importance of it to achieving their mission may be understated.

Correlations

		Total Score	planning score
Total Score	Pearson Correlation	1	.139
	Sig. (2-tailed)	.	.548
	N	21	21
planning score	Pearson Correlation	.139	1
	Sig. (2-tailed)	.548	.
	N	21	21

Table 21. Correlation of Response Organization Score and Planning Score

There were some interesting points found in the responses. For this study, planning was focused on flood responses. The majority of the burden for a flood response is within the domain of the fire service. This is not because of the incidence of fire but through their mission of property conservation. To meet that mission fire agencies typically carry equipment for protection from water such as salvage covers and pumps. The results reflect that the fire service does plan more extensively for flooding with a mean score (2.49) followed closely by EMS. The police plan little (1.33).

4.4.1.4 Hazard Vulnerability Assessment

Most organizations (76%) had not completed a hazard vulnerability assessment. Of the three disciplines, the fire service was the most likely to have completed a hazard vulnerability analysis with a mean score of 1.4 followed by EMS at 1.25 and police with literally no planning at 1.0. Given that the fire service will face the greatest overall demand in most common disasters they are most in need of the analysis. While a score of 1.4 is the highest among the disciplines when converted back to the survey categories, it translates to between none and an informal hazard assessment. Only two of the twenty-one organizations had completed a formal hazard assessment.

4.4.1.5 Resources Considered in Planning

The results for this variable held a few surprises. The most prominent is that of the four jurisdictional levels, the county level was relied upon more heavily than the other three levels by two of the three disciplines, EMS being the exception. EMS considers local assets more often than county assets and does not take state or federal assets into consideration. Given the recent emphasis in the media on the reliance of local level agencies on federal assets this does not appear to be the case for these organizations.

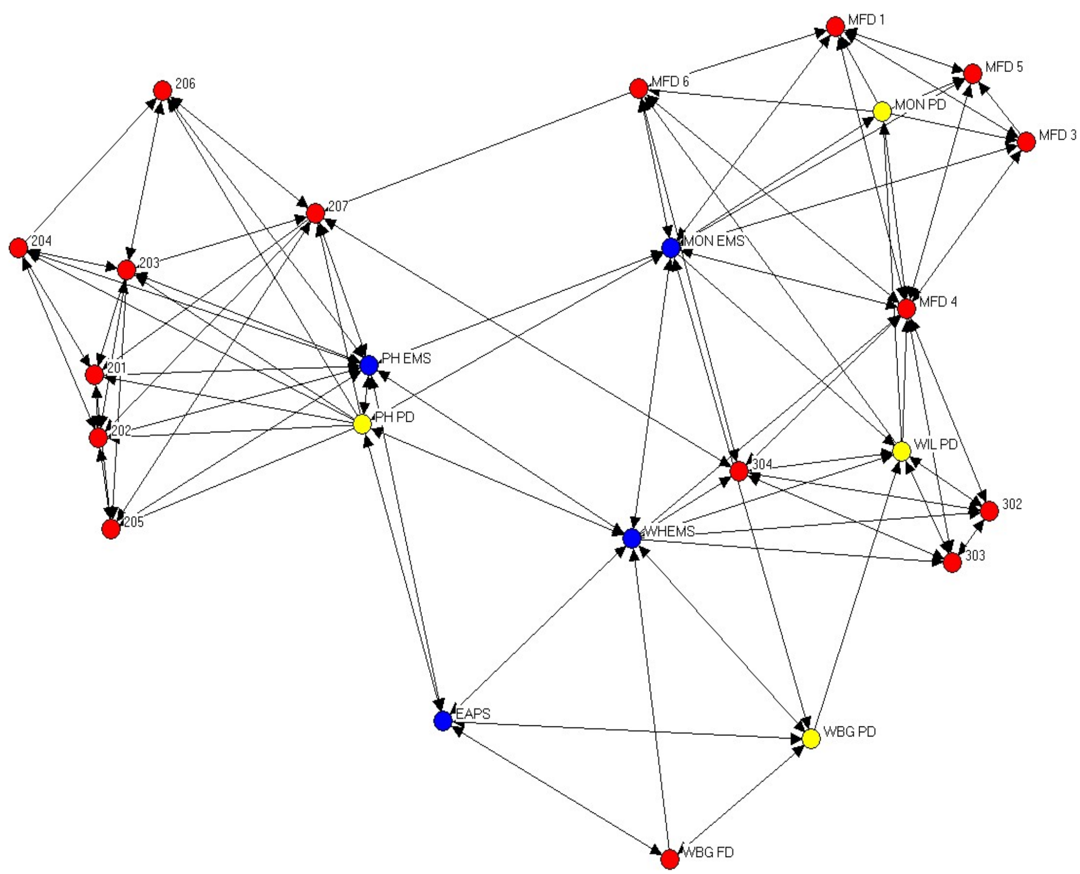
This is logical for EMS because of two local factors. The first is that county response only takes the form of incident management support. The county does not operate ambulances. State and federal assets would take up to twenty-four hours to put in place and these agencies have not experienced an incident that required an EMS commitment of that length of time since the late 1980s. Most of the EMS responders who participated in that event have left the field. The second factor affecting the result is the large number of hospitals in the area. There are 11 hospitals within four miles of the study area. With that number of hospitals nearby, they could make multiple trips relatively quickly for mass casualty incidents. For that reason, resources beyond neighboring municipalities are given little or no consideration.

Law enforcement considered assets beyond the local level more than did EMS. When asked about this practice, the survey respondents stated that they rely on specialized assets such as helicopters from the state level and advanced investigative assets from the federal level. They also consider assets like the National Guard, a state asset, for large-scale incidents. The survey results do indicate a higher consideration of state assets than federal. One other factor to consider in this is that often a federal response is only for incidents that are within their specific jurisdiction and local involvement after that point is minimal.

4.4.1.6 Interaction

While the Police officials reported that among the disciplines, they interact most often with the Fire Service it is interesting that the relationship is not reciprocal. The Fire Service reported interacting more with EMS agencies. Police agencies ranked second. All of the agencies reporting interacting with emergency management agencies (EMA), the least of municipal agencies, but scored "Others" as the lowest category. Agencies in the "Other" categories include county agencies such as hazardous materials teams, fire investigators, health department, hospitals and upper levels of government. This is expected because these resources are only needed for a small percentage of calls.

Figure 11. Response Organization Interaction Network



Nodes are the study area response organizations

In examining organizational interaction each organization was asked to rate their frequency of interaction with another discipline using a five-point Likert scale ranging from a score of 1 for infrequently to 5 for very frequently. Table 22 shows the variation among the disciplines.

	Frequency of Interaction					
Rating	FD	Rescue	EMS	Police	Emergency Mgt.	Other
FD	5.0	4.0	4.0	4.0	3.0	2.0
EMS	4.5	4.5	4.8	4.3	4.0	2.5
Police	4.0	3.7	3.8	4.7	2.7	2.0
Mean	4.5	4.1	4.5	4.3	2.9	2.2

Table 22: Frequency of Interaction by Discipline

Table 22 shows that response organizations interact more within their discipline than with other disciplines.

4.4.2 Impact of Public Safety on Vulnerability

One of the initial premises made in this paper is that public safety response organization capacity or capability is a mitigating factor in the vulnerability of an area. The method used for tract levels will be discussed in the section on modeling. While the sample size for this study is very small, and therefore only illustrative, it does provide an example of how this impact is portrayed the table below shows the impact on the municipal level. Because this table provides a summary of the capacity only within the confines of the municipality, it is somewhat misleading because response organizations within a municipality may include mutual aid from outside their area on some responses. This will be explained more fully in the model section which allows for the inclusion of mutual aid.

	Initial Vulnerability	Response Capacity	Adjusted Vulnerability
Wilkinsburg	69,224.94	10,399.21	58,825.73
Penn Hills	30,570.83	16,986.66	13,584.17
Monroeville	11,398.90	29,080.84	-17,681.94
Wilkins	2,656.23	11,905.86	-9,249.63

Table 23. Impact of Public Safety on Initial Vulnerability

From the above table it can be seen that half of the municipalities have some residual vulnerability, although Monroeville and Wilkins have a negative adjusted vulnerability indicating that these municipalities have response capabilities in excess of that required to meet its initial vulnerability level. This does not indicate that the capacity is excessive because this does not take into account the demand placed by incidents within the municipality. It is a comparison of initial vulnerability vs. initial capacity. It does indicate that Monroeville and Wilkins are in a better position than the others to absorb the impact of the demands for emergency response service given the area served. There are special hazards within those jurisdictions that require mutual aid for specialized equipment.

It might be expected that areas with increased initial vulnerability would have additional resources to meet their needs. An analysis of the data reveals no correlation between vulnerability and response capacity. In fact while not statistically significant a negative correlation is present indicating that the reverse might be the case.

Correlations

		initial vulnerability	resp org capacity
initial vulnerability	Pearson Correlation	1	-.416
	Sig. (2-tailed)	.	.584
	N	4	4
resp org capacity	Pearson Correlation	-.416	1
	Sig. (2-tailed)	.584	.
	N	4	4

Table 24. Correlation of Initial Vulnerability and Response Organization Capacity

There is also no statistical correlation to the adjusted vulnerability levels and the response organization capacity.

Correlations

		adjusted vulnerability	resp org capacity
adjusted vulnerability	Pearson Correlation	1	-.502
	Sig. (2-tailed)	.	.498
	N	4	4
resp org capacity	Pearson Correlation	-.502	1
	Sig. (2-tailed)	.498	.
	N	4	4

Table 25. Correlation of Adjusted Vulnerability and Response Organization Capacity

While it might be expected that there would be a statistically significant correlation, due to the corresponding decrease in the vulnerability with the capacity that does not appear to be the case. The presence of a negative correlation indicates that response agency capacity has an impact on vulnerability. The value is derived by subtracting the response agency capacity from the initial value, this is expected. The lack of correlation may be an indication that the impact of the response organization is not sufficient, considering the size of the vulnerability, to produce a statistically significant correlation.

There are two perspectives from which to analyze the interaction among the systems: spatial, both macro and micro, and functional. On the macro level, all three environments interact, if not all of their elements, while a micro interaction is in a localized area or small set of individuals or structures. Functional interaction occurs when one system relies on another to continue operating. This is a common occurrence but is often less well understood by the public. In the following sections, each environment and its elements will be discussed.

4.4.3 Geophysical

Often we think of the physical world around us as a static entity, but that is far from the case. It is “an active and complex place..marked by webs of interrelations, mutual adjustments, chain reactions and complex responses” (Phillips, 1999). There are dynamic processes in progress continually although perhaps not at a temporal scale that is readily apparent to the casual observer. From the fast end of the spectrum with weather and water movement to perhaps the slowest being plate tectonics, many components are in movement and interacting not only with each other but also with all of the other components.

Many of these elements have both macro and micro facets to them. Weather is one of the most dynamic interdependencies that trigger interactions with other systems on a regular basis. It can have a direct effect by dumping millions of gallons of water as rain or snow, inundating populated areas and in some cases changing the path of streams not only temporarily but in some cases permanently. While weather is traditionally viewed on a macro scale, the National Weather Service office has stated that the weather in Allegheny County can be quite localized with some areas experiencing severe weather and others remaining relatively calm. These variations, while appearing macro, can cause interactions as the result of micro interdependencies with individual streams and surrounding areas.

Heavy rainfall is the primary trigger for most flooding events but that is not always the case. In the case of the study area, winter ice jams can result in riverine flooding. In Allegheny County, winter (November-March) flooding accounted for only 18.5% of the flooding incidents reported by the NWS but accounted for 56.7% of the damage (NOAA, 2003). Not all of these incidents were the result of ice jams but environmental conditions were certainly a major factor in the increased damage.

The question here is what geophysical features are interdependent with rainfall and how does it affect flooding. The most obvious is that the same topography that created the hydrological features of streams and rivers creates watersheds to funnel precipitation. When the correlations among the geophysical and hydrological features were compared, there were significant correlations among all the features with the exception of the number of watersheds and the area of the floodplain. Correlations are shown in Table 26.

	Area (Sq Miles)	Floodplain area (Sq Miles)	Stream Length (Miles)	Watershed (Count)
Area	X	**.491 (0.009)**	**.891 (0.000)**	**.475 (0.012)**
Floodplain area	**.491 (0.009)**	X	**.473 (0.023)**	.129 (0.522)
Stream Length	**.891 (0.000)**	**.473 (0.023)**	X	**.395 (0.042)**
Watershed count	**.475 (0.012)**	.129 (0.522)	**.395 (0.042)**	X

Values shown indicate r^2(p<X)

Table 26. Correlation of Geophysical Elements

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
tract area	27	.14	4.07	1.6299	1.10923
floodprone area	27	.00	.57	.0570	.11424
stream length	27	.00	7.76	2.8653	2.56059
watershed count	27	1	6	2.74	1.483
Valid N (listwise)	27				

Table 27. Geophysical Element Descriptive Statistics

What can be seen from the above descriptive statistics of the geophysical features is the great amount of variety present in the study area indicated by the large standard deviations relative to the means. While the results would seem rather obvious, the fact that the number of watersheds does not correlate to the floodplain area indicates the hilly topography does not readily translate into an area having a flooding hazard. This also does not address the issue of urban flooding.

There are also geological factors that interact with the other environments. Some of the most obvious is the undermining of transportation paths and structures. Because of the topography, many of the older roadways are located along the flatter valleys that were carved by the streams and creeks. This proximity increases their vulnerability to flooding due to micro-scale interdependency. There is not however a statistically significant correlation between the size of the floodplain area and the length of the roadways in this area, as shown in Table 28.

Correlations

		floodprone area	road length in miles
floodprone area	Pearson Correlation	1	.338
	Sig. (2-tailed)	.	.085
	N	27	27
road length in miles	Pearson Correlation	.338	1
	Sig. (2-tailed)	.085	.
	N	27	27

Table 28. Correlation of Floodplain and Road Length

This relationship will be addressed below in the discussion of the built environment interdependencies. Direct damage to roadways can be easily seen, less evident is the removal of soil and the deposition of silt that may clog water intakes, change the courses of stream beds into new, more populated areas and require diversion of traffic around the flooded areas. This damage creates additional traffic congestion and may route hazardous cargo that is normally transported along major roads through residential neighborhoods increasing the risk of contamination should an accident occur. In the study area 17.33 miles (14%) of the major roadways are located in or adjacent to the floodplain.

The functional interaction of the geophysical environment is evident in the maintenance of the surface under the built environment. In this way it interacts with all of the other environments. Those interactions will be discussed in the analysis of that environment.

4.4.4 Social Environment

The population of the study area is affected by most, if not all, of the systems. Essentially all of the systems, with the exception of the geophysical, are created to support the population. The geophysical typically interacts on a macro level, but there are occasions where there are microlevel interactions. For example, people construct buildings that are served, ideally, by utilities to protect them from the environment and in some cases each other. This building then affects them, their environment and the demands on other built systems. If the built environment doesn't protect them, their health status deteriorates. Those people in the more vulnerable cohorts are less likely to have a resilient health status, but also less likely to have environmental control systems. This lack can have a serious impact and cost hundreds of lives as was seen in the Chicago heat wave (Klingenberg, 2002). This interaction stresses the public safety system, further adding to their vulnerability because those resources can not be used to combat other emergencies.

The geophysical environment also interacts with the social on a continual basis. As mentioned above, weather is one of the main physical factors with which we contend daily. The hydrological cycle is a part of the weather system. Both the weather and the hydrological systems interact to produce the flooding studied here. Geological elements move at a different pace but still affect the social environment. It is the base on which all of the other elements exist. As it moves, buildings are endangered, utilities uprooted and the transportation system is compromised. Earlier it was shown that there is a strong positive correlation between the hazards posed by the geophysical environment and population density. Urban flooding has long been a known killer in densely populated areas. This is the result of the nature of the topography, the amount of precipitation and the propensity for people to choose to settle in floodplains or other low lying areas.

The interaction of the population occupying the area at the time is affected by the loss of the utilities as mentioned above. Electricity is the utility most commonly used for environmental controls. Water is another critical utility. The recommended amount of water per day is one gallon per person (FEMA, 2005). The study area has a total population of 102, 271 so provision of water would require a monumental effort. A standard over the road tank truck carries approximately 8,000 gallons of liquid. To provide water to the study area would require 13 tank trucks per day and a monumental distribution mechanism.

There is also interaction between the social environment and the other systems. Emergent citizen groups (Stalling, 1985) develop in crisis into useful organizations that can assist in response operations during an incident. In areas where residents have increased their readiness or have increased resiliency they may be able to devote their time to participating in these emergent groups.

There are a few citizen groups that are formed ahead of time specifically for public safety response or support. These include municipal Community Emergency Response Teams (CERTs), National Weather Service Skywarn members and amateur radio teams (Radio Amateur Civil Emergency Service). While these groups have a more formal structure they are not dedicated (designated volunteer or career) public safety responders and voluntarily participate when the emergency notification is made.

4.4.5 Built Environment

4.4.5.1 Transportation

Transportation is series of networks of roadways, and associated tunnels and bridges, along with railways. There are no active air travel facilities in the study area, so it was not included in the analysis. There is a large volume of overhead air traffic in commercial and medical aircraft, but with the exception of a plane crashing in the area air travel is not an issue.

Each system, road and rail, has unique characteristics, both as a functional network and in the interdependencies of that network with other systems. Transportation is vital to the social environment, because it encompasses the routes by which people and goods move around the area. This critical function can be compromised in several ways. The most obvious is the flooding of roadways and the undermining of rail beds. These are localized events and were discussed in the direct vulnerability section. What is less obvious is the impact that the flooding has because traffic is rerouted through other parts of the system.

In the transportation sector many of the roadways can be easily be rerouted, provided there are no choke points limiting access to alternate routes. These choke points most commonly occur at bridges, tunnels and when crossing the limited access highway that traverses the study area. In the study area there is only one limited access highway. While it would seem that the other routes take on a higher importance in maintaining traffic flow, this route is a high volume roadway into and through the municipalities in the study area.

	Betweenness	nBetweenness
523200	20.000	3.077
523300	19.000	2.923
523501	15.000	2.308
560600	9.000	1.385
561400	5.000	0.769
523400	3.500	0.538
521200	3.000	0.462
561100	3.000	0.462
561000	3.000	0.462
520001	1.500	0.231
520002	1.000	0.154
523502	1.000	0.154

* remaining nodes had a score of 0

Table 29. Betweenness Scores for Transportation

DESCRIPTIVE STATISTICS FOR EACH MEASURE

	Betweenness	nBetweenness
Mean	3.111	0.479

Std Dev	5.690	0.875
Sum	84.000	12.923
Variance	32.377	0.766
SSQ	1135.500	26.876
MCSSQ	874.167	20.690
Minimum	0.000	0.000
Maximum	20.000	3.077

Table 30. Descriptive Statistics for Transportation Betweenness

Table 30 shows a considerable amount of variation in the traffic flow, based on the size, the standard deviation in comparison to the mean, and range of scores. This variation indicates that some nodes are more important to the maintenance of the network connections than others. The use of measure, cutpoints or betweenness, alone would be insufficient to measure the importance of the interdependence within the roadways, but combined, they provide an idea of the critical areas. By comparing the scores for the tracts, to the mean of the network, we are able to rank the importance of the tracts. This ranking can then be compared with flood risk to provide a relative level of risk to the entire network, should the roadways in that area be compromised. The correlation is not significant ($r = -.032$, $p<.876$) so it does not appear that there is interdependence between the tract's betweenness scores and the area of floodplain present in those tracts. There is also no correlation between the nBetweeness score and either the geophysical hazard score ($r^2 = .125$, $p< .543$) or social vulnerability ($r^2 = -.0911$, $p<.956$). In referring to the map, it is interesting that the tract with the highest nBetweeness is adjacent to the municipality with the highest social vulnerability score. While it is not the only means of egress, the social vulnerability map shows that the evacuation of residents with a higher at risk score to areas of lower social risk could occur through this area. With the expectation that the resident population would also be evacuating this could result in a spontaneous bottle neck of evacuees not only from that area but disabling passage through that area could compromise the integrity of the transportation network.

4.4.5.2 Rail

Rail transportation in the area is much more limited in amount and area. There are three sets of lines in the study area. Taking only a few municipalities naturally limits the assessment of the network and these three lines do connect outside of the area, but within the study areas they are distinct. The lines that run through Wilkins, Monroeville and Penn Hills each intersect the floodplain in at least one point along their lines. This could lead to a blocking of the lines by debris or by undermining the rail bed. Because this is all one line, a block in any area would effectively disable the use of the line and make the entire line a cut point.

The other line is in Wilkinsburg. It is elevated twenty feet through most of the area, and is impervious to flooding. The elevations do however place the lines above three major roadways. Should a derailment occur it would block the roadway(s). In addition, the rail line runs through the area with the highest social vulnerability scores. A combination of impacted roadways, large at-risk populations and limited access to public safety agencies could make this a calamitous situation. None of these lines carry passenger traffic, but in addition to the risk to surrounding populations should a hazardous material be released, the economic impact to the industries served by these lines could be significant.

4.4.5.3 Bridges

Given the dominating effect of topography on the study area and its interaction with the transportation system two other critical features can be seen. The Pittsburgh metropolitan area is known worldwide for the number of bridges in the county. Within the confines of Allegheny County, there are approximately 1,700 bridges depending on the information source. In the study area there are 28 bridges. Because these bridges create a connection between certain areas over water, steep topography, or busy roadways, travelers are required to use circuitous, and time consuming detours if they are blocked. This situation can cause critical delays in evacuations and public safety responses.

To identify these critical structures, a matrix was created that indicated whether two census tracts were connected by one or more bridges. This analysis revealed that fifty nine percent (59.2%) of the tracts or 16 of 27 were connected by bridges, indicating the criticality of those bridges in the maintenance of the entire roadway system. The method used to evaluate this critical relationship is betweenness. Betweenness results are:

Tracts	Betweenness	nBetweenness
523502	28.000	8.615
523100	20.000	6.154
521100	8.000	2.462
523702	8.000	2.462
523200	8.000	2.462
521301	5.000	1.538
521401	3.000	0.923

- Remaining tracts have 0 betweenness

Table 31. Betweenness Scores for Bridges

DESCRIPTIVE STATISTICS FOR EACH MEASURE

Betweenness nBetweenness

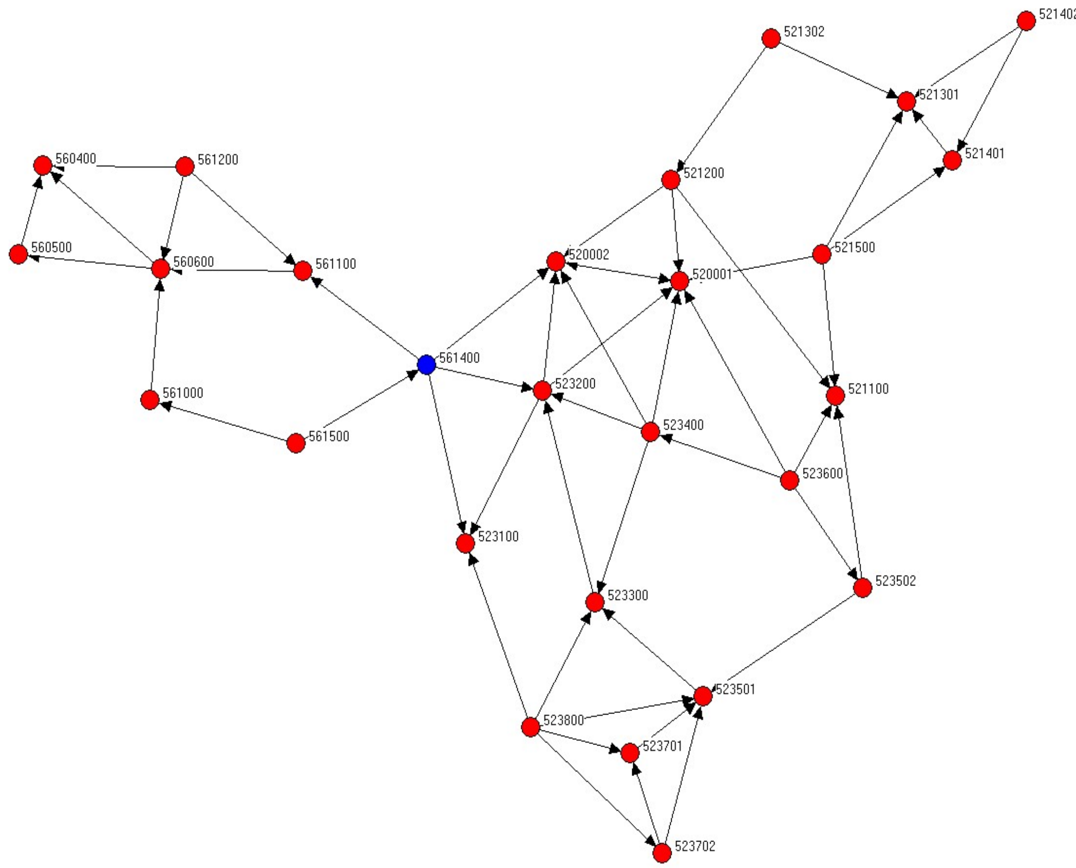
Mean	2.963	0.912
Std Dev	6.591	2.028
Sum	80.000	24.615
Variance	43.443	4.113

Table 32. Descriptive Statistics for Bridge Betweenness

4.4.5.4 Roadways

To investigate the interdependencies we need to start with exploring the system as a network. In developing the network, each tract was examined for roadway connections to other tracts. These connections are reflected in the arrows between nodes (tracts) on the graph. It was presumed that the network was symmetrical, because during emergencies law enforcement personnel could be used to direct traffic in any direction. To identify critical points that maintain the system, the network was evaluated for cut points. Cut points are nodes within a system which, if removed, will disconnect segments of the network. In essence this is the interdependency within the roadway system. The network analysis, revealed that there is a single cut point within the system, see Figure 12. While this may appear strange, the map of major roadways in Figure 6 shows that major roads link all the tracts. The result is a single cut point. This could be the reason for the large number of cut points (77.7%). This is the result of the interdependency between the geophysical environment's topography and the roadway system.

Figure 12. Roadway Cutpoints



Another measure of interdependence is betweenness. Betweenness is the measure of how often a node lies in the pathway between other nodes. Table 33 shows a comparison of the tracts, using the measure of betweenness for the road system.

Tracts	Betweenness	nBetweenness
523502	28.000	8.615
523100	20.000	6.154
521100	8.000	2.462
523702	8.000	2.462
523200	8.000	2.462
521301	5.000	1.538
521401	3.000	0.923

* Remaining tracts have 0 betweenness

Table 33. Betweenness Scores for Roads

DESCRIPTIVE STATISTICS FOR EACH MEASURE

	Betweenness	nBetweenness
Mean	2.963	0.912
Std Dev	6.591	2.028
Sum	80.000	24.615
Variance	43.443	4.113

Table 34. Descriptive Statistics for Road Betweenness

In the previous results for nBetweenness we have seen large standard deviations. In this case the standard deviation is also nearly twice the size of the mean. This makes the mean value of road betweenness questionable, but when it is cross referenced with the cut points, all but one are cut points.

There are no significant correlations between the bridge nBetweenness and road nBetweenness ($r^2 = -.181$, $p < .375$), so critical roads do not occur in areas with critical bridges. There is also no significant correlation between social vulnerability and bridges with nBetweenness scores ($r^2 = -.293$, $p < .138$) nor is there one between the geophysical hazard score and nBetweenness of bridges ($r^2 = -.239$, $p < .230$). This lack of correlation shows that bridges are not critical to the transportation network or evacuation routes for vulnerable populations.

4.4.5.5 Tunnels

While there are only a few tunnels in the study area, they do provide vital connections between areas that would otherwise require longer routes to connect. In two of the cases these areas are adjacent to the floodplains and are frequently flooded during heavy rains. While neither is located on a main route between municipalities, they are in locations where there are few alternative routes. There are also some industries in close proximity to them. This would have an indirect impact on the population in the recovery phase of the emergency. Tunnels could, in the event that large numbers of people had to move out of an area, lengthen evacuation time and create confusion.

4.4.5.6 Buildings

There is not only the interaction with geophysical environment but also anything that the weather touches. There is an interaction between buildings and the geophysical environment. Buildings create an impervious layer, either through paving or the roof of the building that enhances the run off from a storm. The water is ideally channeled into a storm water containment system, but in many cases it simply runs off and doesn't soak into the ground. This contributes to urban flooding. The geophysical environment interacts with buildings in another way. The study area has a very steep topography; elevations in the study area range from 726.5 ft to 1333.1 ft. This is reason for the large number of watersheds in the area. These elevation changes create the potential for landslides. While this study focuses on flooding, the same heavy rainfall that can cause flooding increases the chance of landslides, because of the existing shale and claystones known collectively as the Pittsburgh Red Beds. These landslides can impact buildings all along the slopes. Builders tend to place structures on the flattened out areas that have resulted from ancient landslides. (Pittsburgh Geological Society, n.d.).

To investigate the interdependency between the geophysical hazards and buildings I began with the correlation between the geophysical score and the density of buildings. A significant correlation (r^2 = .491, p< .009) was found. This indicates that the areas in which buildings are most dense are also the areas with the greatest risk of flooding.

Buildings are affected by not only precipitation but also temperature. They are also affected because the temperature may require the people in the buildings to use environmental support systems such as heating and air conditioning that affect the building and the utility demand for those appliances. During periods of extreme temperature other utility systems become stressed and critical to the survival of the population within the structures. For instance, during high heat events the load of running air conditioning equipment burdens the electrical system. High humidity also compounds the issue because it increases the heat index and supports the growth of mold in flood inundated homes causing a potential long-term recovery problem. In the 1995 Chicago heat wave 49,000 households were without power because the electrical system could not sustain the load. As a result, Chicago experienced 465 heat-related deaths in one week (Klinenberg, 2002).

In cold weather the provision of natural gas becomes critical for heating the majority of homes in the area. Wind speed complicates the cold because it lowers the perceived temperature as seen in the wind chill index. Those without redundant systems, such as residents with electrical heaters in the event that natural gas is lost, are at a greater risk. These redundant systems are an additional cost, so those in the more vulnerable social groups are less likely to have that capacity.

4.4.6 Utilities

The direct inundation of floodwaters into critical areas that are located in or around floodplains is not the only concern for maintaining utility service. Infrastructure failures can also result in the flooding of limited, but economically important, areas, such as the August 17, 2005 break of a 36-inch water main in downtown Pittsburgh that released an estimated 20 million gallons of water. There are also interdependencies among the other systems and utilities as well as interdependencies among the different types of utilities.

Beginning at the macro level of interdependency we can see from Figure 5 that much of the utility infrastructure lays in areas of guarded geophysical risk. The same concerns that were mentioned in the previous sections on buildings also come into play for the infrastructure that rests on the same ground.

Beside the interaction at the co-location (macro) level, we can examine the systems for functional interactions that are critical for the maintenance of the systems. The majority of the population in the area relies on water intakes from a single river. Increased debris and possible contamination of those facilities, as well as sewage treatment plants, can cause problems with the acquisition and disposal of water or water-borne waste. This not only affects drinking but some of the critical facilities, some hospitals for example, rely on steam heat and without water flowing into their system, they may have to shut down their boilers. In addition, the steam distribution system is also susceptible to inundation by floodwaters. While this would not be a problem in the summer, surrounding hot steam pipes with cold water during the winter floods can have disastrous affects. Many phone vaults and electrical lines run underground and an inundation of water may leak into those spaces, causing outages and transfer of the service burden to other parts of the system with the potential for cascading failures.

The study area does include the Allegheny River on which such a flood occurred during January 1996 as the result of this combination of conditions (NOAA, 2005). The resulting flood impacted 4 counties along the Allegheny River basin and caused over $1million in damage to buildings and infrastructure.

As noted above, electrical service to the area is critical to the maintenance of normal life both because of the direct impact to environmental controls but also its functional interdependence with the other systems such as water for pumping, transportation for running traffic lights, street lights and traffic warning signs, lighting and communications inside of structures to name a few. The connections among these networks are critical to maintaining normal service. To examine this set of interactions, a network matrix was created showing the electrical distribution network within the study area. The electrical system was chosen for several reasons. Foremost, virtually all other systems rely on electrical power to maintain long-term operations. Second, only the data for the electrical system was available. This analysis could conceivably be done for each of the systems should the data become available. This network can serve as an example for those subsequent analyses.

To explore this interdependency among utilities, I created a matrix that indicated which services are interdependent. This matrix was validated by experienced emergency managers. While a matrix indicating the degree of interdependence would be preferable a dichotomous matrix was used because the amount of interdependence is proprietary and the responsible utility companies would not release the information.

In Figure 5, we can see the connections between electrical transmission lines across the census tracts. While this is informative as to which area gets service from where, the truly crucial issue is which nodes, if eliminated, begin to breakup the network. The electrical distribution system is built to avoid outages and the cascade of failure. That design includes the shifting to

	Affected										
Affecting	Road	Rail	Tunnel	Bridge	Elect	Nat Gas	Potable Water	Waste Water	Phone	Comm Towers	**Tota l**
Road	X	0	0	1	0	0	0	0	0	0	**1**
Rail	0	X	0	1	0	0	0	0	0	0	**1**
Tunnel	1	1	X	0	0	0	0	0	1	0	**2**
Bridge	1	1	0	X	0	0	0	0	1	0	**2**
Electric	1	1	1	0	X	1	1	1	1	1	**7**
Nat Gas	0	0	0	0	0	X	0	1	0	0	**1**
Potable water	0	0	0	0	1	0	X	1	0	0	**2**
Waste water	0	0	0	0	0	0	1	X	0	0	**1**
Phone	0	0	0	0	0	0	0	0	X	1	**1**
Comm Towers	0	1	0	0	0	1	0	0	1	X	**3**
Total	**3**	**4**	**1**	**1**	**0**	**2**	**2**	**3**	**4**	**2**	

power service around the failed line or node onto those surrounding it to circumvent the break. Typically the only visible manifestation of this is a momentary flickering of the lights. During times of high demand however, the addition of this load onto the existing load may stress the lines to failure.

Table 35. Utility Interaction

To determine what points are the most critical to maintaining the network, the cutpoints are identified. In Figure 9 we can see that thirty three percent (33%) of the census tracts contain electrical utility cutpoints. Those tracts contain sixty four percent (64%) of the total flood plain area so any inundation into the floodplain has a 64% chance of affecting a tract that contains a cutpoint, or critical node, of the electrical distribution system.

Another measure of the importance of the electrical service through a specific tract is betweenness. This is a measure of centrality of a particular node, or in this case tract, within the network. The betweenness centrality measure characterizes tracts to the extent that they fall on the shortest (geodesic) pathway between other pairs of tracts or in network terms actors. The idea is that actors who are "between" other actors, and on whom other actors must depend to conduct exchanges, will be able to translate this broker role into power. In this case, power translates to importance in maintaining the electrical network.

In the case of the study area's electrical system the following results were found.

Census Tract	Betweenness	nBetweenness
560600	11.000	1.692
523501	10.000	1.538
523200	8.000	1.231
523300	8.000	1.231
560400	5.000	0.769
523400	5.000	0.769

Census Tract	Betweenness	nBetweenness
523502	4.000	0.615
523701	4.000	0.615
561400	3.000	0.462
561100	3.000	0.462
561000	3.000	0.462
521200	2.000	0.308

- Remaining tracts had 0 betweenness

Table 36. Electrical System Betweenness

DESCRIPTIVE STATISTICS FOR ALL TRACTS

	Betweenness	nBetweenness
	------------	------------
Mean	2.444	0.376
Std Dev	3.337	0.513
Sum	66.000	10.154
Variance	11.136	0.264

Table 37. Descriptive Statistics for Electrical System Betweenness

The descriptive statistics show a great deal of variation in the nBetweenness results, based on the mean and standard deviation. So this measure alone would be a poor indicator of the criticality of the utility infrastructure in this tract. When compared with the cut points, we see that only 2 of the tracts with betweenness are also cut points.

4.4.7 Public Safety

The interdependencies of public safety organizations occur in two ways. On the macro scale, public safety organizations interact among the different municiaplities. The majority of public safety organizations have insufficient resources to answer calls requiring more than routine levels of service. For this reason, mutual aid among the organizations is a common occurrence. Multiple organizations respond to emergencies in neighboring areas on a daily basis. On a micro level response assets within a municipality commonly respond together to address the concerns of their specific discipline and in support of the other agencies.

All response organizations interact with the geophysical, built and social environments. These environments are the genesis of the demand for their services. The public safety organizations must respond to disturbances in the balance of the systems, and in doing so, attempt to anticipate the implications of those changes so they can respond in a proactive mode rather than reactive.

This interdependency can be scaled up depending on the nature of the incident. As the scope of the event increases, assistance from higher levels of government can be requested. The most common level requested is the county. The study area is located within Allegheny County, Pennsylvania. As with many counties in Pennsylvania, the county provides hazardous materials team service. In addition, the county can provide additional assets for emergency response through their emergency services department. These assets range from logistical to information and coordination. These assets are not routinely dispatched to incidents and are therefore beyond the scope of this study.

4.4.8 Scaling up

Once the information is created for the tract level, it can be rolled up to the municipal and sub county regions. This function provides a different picture of how risk changes over the various environments and organizations. The geophysical hazard is a good example. On the tract level interactions, the only two variables that didn’t correlate were floodplain and water sheds. Table 38 shows that the case is quite different at the municipal level with only area and stream length correlating.

	Area	Floodplain	Stream Length	Watersheds
Area	X	.611 (.389)	**.993 (.007)**	.845 (.155)
Floodplain	.611 (.389)	X	.180 (.820)	-.037 (.963)
Streams Length	**.993 (.007)**	.180 (.820)	X	.873 (.127)
Watersheds	.845 (.155)	-.037 (.963)	.873 (.127)	X

Table 38. Correlation of Geophysical Elements on the Municipal Level

The reduction in analytical granularity decreases the ability to find the critical interactions that may become the triggering factor in a cascade of failure when the systems are stressed during an emergency. The initial conditions information is a straight roll up so it would be expected that areas with larger tract scores would also rank equally high. The effect of scale however changes that. For comparison purposes the use of densities from the initial assessment has been carried over to the larger areas. In the case of the geophysical rating Table 39 shows that there is a significant difference. While Wilkinsburg does not have the lowest score half of it's tracts have the 5 lowest scores.

Municipal Geophysical Scores	
Penn Hills	61.04
Monroeville	59.75
Wilkins	4.9
Wilkinsburg	16

Table 39. Municipal Geophysical Vulnerability Scores

The built environment is another excellent example of how scale changes outcomes. In the tract scores, Penn Hills ranked in eight of the ten top spots while Monroeville occupied the remaining two. It is evident that the municipal level assessment is quite different. This is because of the high population density in Wilkinsburg. Wilkins Township and Wilkinsburg are similar in size, 2.63 and 2.278 square miles respectively. Monroeville and Penn Hills only differ in size by .5 sq. miles but the difference in vulnerability scores is dramatic.

Municipal Built Scores	
Wilkinsburg	23006.89
Penn Hills	10826.47
Monroeville	4708.59
Wilkins Twp	179.83

Table 40. Municipal Vulnerability Built Scores

As a final total of the vulnerability created by the three environments we can see that the social environment takes the leading role in the determination of vulnerability on the municipal level.

Municipality	Social	Built	Geophysical	Total
Wilkinsburg	46150.21	23006.89	68.05	69224.94
Monroeville	6648.36	4708.59	41.95	11398.90
Wilkins Township	2469.82	179.83	6.58	2656.23
Penn Hills	19692.98	10826.47	51.38	30570.83

Table 41. Municipal Environment Vulnerability Scores

When compared to the contributions made by the various environments in the tract assessment, there was little change. The contribution of the social environment increased by 4.7%, while the built environment decreased by 24.8%. The geophysical input dropped the most at 75% of the original contribution. These examples illustrate the dilution effect that moving to the municipal level has in assessing the risk in these three environments. When the assessment is taken to the sub-county region, the effect is more dramatic.

Sub-county Regional Totals

Environment	Total Score	% total
Geophysical	167.96	0.01%
Built	3,8721.78	34.01%
Social	74,961.37	65.84%
Total	113,850.93	

Table 42. Sub-County Environment Vulnerability Scores

Table 43 cites the changes in the contributions of the various municipalities to the sub-county regional total vulnerability. The reason that Wilkins Township comes in above Penn Hills goes back to the density issue. Because Penn Hills has more green space, the density decreases.

Municipal	Total Score	% Region Total
Wilkinsburg	69,224.94	60.80
Monroeville	11,398.90	10.00
Wilkins Twp	2656.23	2.33
Penn Hills	30570.83	26.85

Table 43. Municipal Contribution to Sub-county Region Vulnerability

5.0 SIMULATION, EVALUATION, SUMMARY AND IMPLICATIONS

5.1 SIMULATION ANALYSIS AND EVALUATION

The simulation allows the user to program a wide variety of parameters into the model to model existing conditions effectively for the deployment of response assets to incidents within the area. The more common threat of flash flooding was used for the evaluation of the model. In this situation, a random assortment of 911 calls was used as a background for the flooding calls. Based on historical recollections of actual flood events from the response agency managers and the author, flooding calls were added to the record to reflect the locations more commonly flooded. The timing of the calls was also modeled after these actual responses. From the simulation, the municipalities were assigned the following incident service demands.

Municipality	# incidents
Wilkins	5
Monroeville	10
Penn Hills	13
Wilkinsburg	6

Table 44. Simulation Incidents by Municipality

From the flood incident template, a singular series of simulations was run using the exact same incidents but altering the response policies used in the assigning of public safety response assets. Response Policy 1 sends the appropriate resources closest to the incident while Response

Policy 2 sends the first and third closest units, leaving the second closest unit to serve all three areas. For all of the incidents, the capability levels for the municipalities mirror a graph of vulnerability levels, see Figure 13. This occurs through all the tracts although at varying degrees depending on the distance from the incident(s). It should be noted that Capacity and Vulnerability use different metrics so while related they couldn't be directly compared. Vulnerability graphs may be compared to other vulnerabilities but not capacities. The reverse is true for capacity. They are however related because they interact. Essentially, capacity and vulnerability are on opposite ends of the same seesaw.

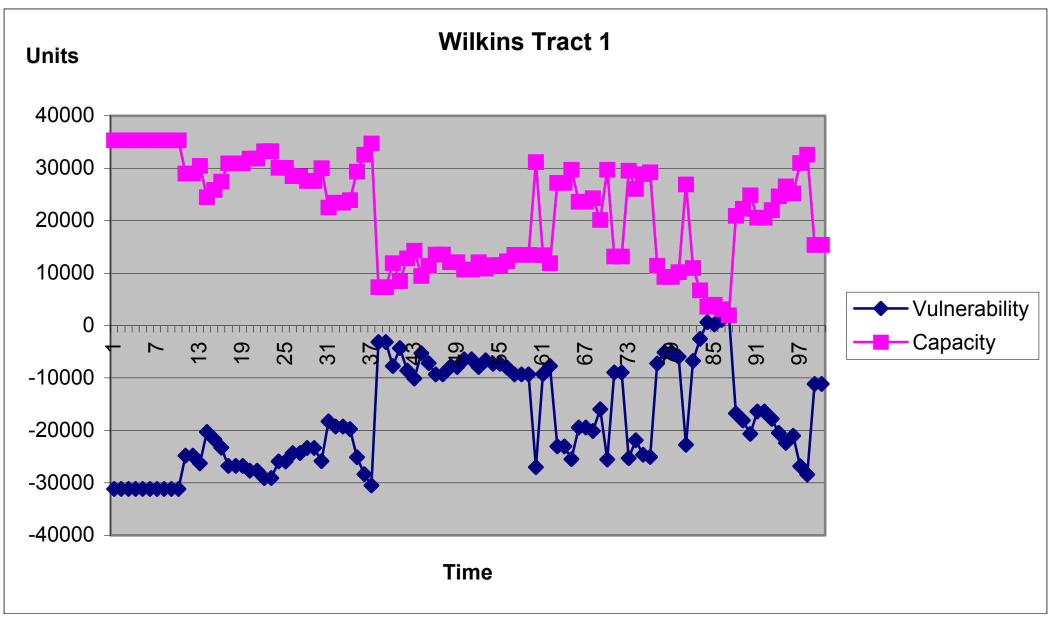


Figure 13. Simulation Results for Wilkins Tract 1

The tracts also vary depending on the location of the incidents. Because the adjusted vulnerability is the result of subtracting the capability and capability is based on a summation of available capacity, the vulnerability for each tract changes each time a unit is assigned. This is illustrated in Figure 14 using one tract from each municipality.

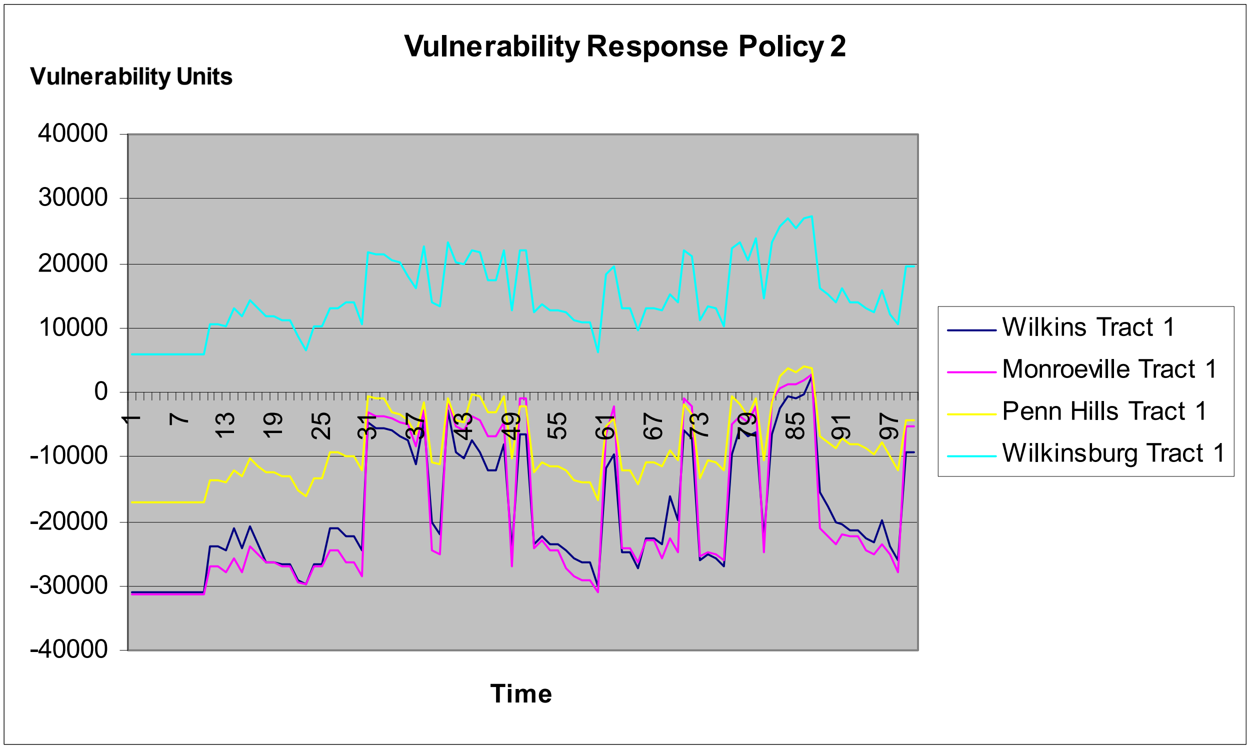


Figure 14. Simulation Results for all Tract 1s

Figure 14 shows that while the variation among the tracts is similar, the amplitude of the variation is different. The first big spike in the line is at time step 30. At that time a flood2, greater than 6" of water, occurs in Monroeville. Fire units from Monroeville, Wilkins and Penn Hills are dispatched as well as police units from Monroeville. The tracts represented had their vulnerabilities increased as seen in Table 45.

	Difference	% change
Wilkins	7537.5	-29
Monroeville	446437.0	-16
Penn Hills	2574.6	-20
Wilkinsburg	2513.3	+18

Table 45. Tract 1 changes at Time Step 30 (Response Policy 0)

	Difference	% change
Wilkins	20,091.9	-81
Monroeville	11,538.8	-96
Penn Hills	25,433.8	-88
Wilkinsburg	11,137.3	+204

Table 46. Tract 1 changes at Time Step 30 (Response Policy 2)

All of these changes are affected by the response policy. The policy determines what happens not only on the tract level, but also throughout the entire network.

While the mirroring was a constant, the amount of variation in the scores depends on the response policy used. All three response policies were run to explore the variations. The existing policy (Response Policy 0) and the closest unit policy (Response Policy 1) were identical in results for run capacity measures. Capacity was chosen for the analysis because it is the determining measure for adjusting vulnerability and resiliency for additional incidents. While municipal boundaries did not prevent the assignment of some units this is comparable to actual responses in the provision of mutual aid. The impact of the policies can be seen in Tables 47 and 48. By changing the response policy we can see that the impact on Wilkinsburg, as well as the other municipalities, is greatly reduced. This is an excellent example of the utility of this type of model. It is not possible to run this type of comparison in the real world because conditions cannot be duplicated. Not only are the increases in vulnerability reduced, but response times decreased by .4 or in real world time is equivalent to 2.4 minutes by using Response Policy 1.

When this impact is moved up a level in scale we can see that the impact direction retains, but that the scale of the changes also changes.

	Difference	% change
Wilkins	12,289.0	-27
Monroeville	38,521.0	-12
Penn Hills	37,409.0	-28
Wilkinsburg	22,174.0	+24

Table 47. Municipal changes at Time Step 30, Response Policy 0

	Difference	% change
Wilkins	38,529.3	-88
Monroeville	277,128.4	-90
Penn Hills	153,722.0	-90
Wilkinsburg	97,207.0	+118

Table 48. Municipal changes at Time Step 30, Response Policy 2

What is interesting is that the tract with the greatest increase is in a municipality, Wilkinsburg, that isn't involved in the response. Because the units assigned are also near Wilkinsburg it has an impact on that area.

Response Policy 0 & 1	Mean	Minimum	Maximum
Vulnerability Range	30,551.70	19,076.52	98,137.43
Vulnerability Std. Dev.	10,105.64	5,933.00	42,401.39
Capacity Range	30,551.71	19,076.54	98,137.40
Capacity Std. Dev.	10,105.64	5,933.00	42,401.39

Table 49. Response Policy 0 & 1 Descriptive Statistics

Response Policy 2	Mean	Minimum	Maximum
Vulnerability Range	31,144.00	20,366.63	98,219.01
Vulnerability Std. Dev.	9,787.16	5,700.38	42,038.11
Capacity Range	31,143.99	20,366.64	98,218.99
Capacity Std. Dev.	9,787.16	5,700.37	42,038.11

Table 50. Response Policy 2 Descriptive Statistics

A complete graphing of the vulnerability levels for both simulation runs for the municipal level can be seen in Figures 13 and 14.

Figure 15. Municipal Vulnerability for Response Policy 1

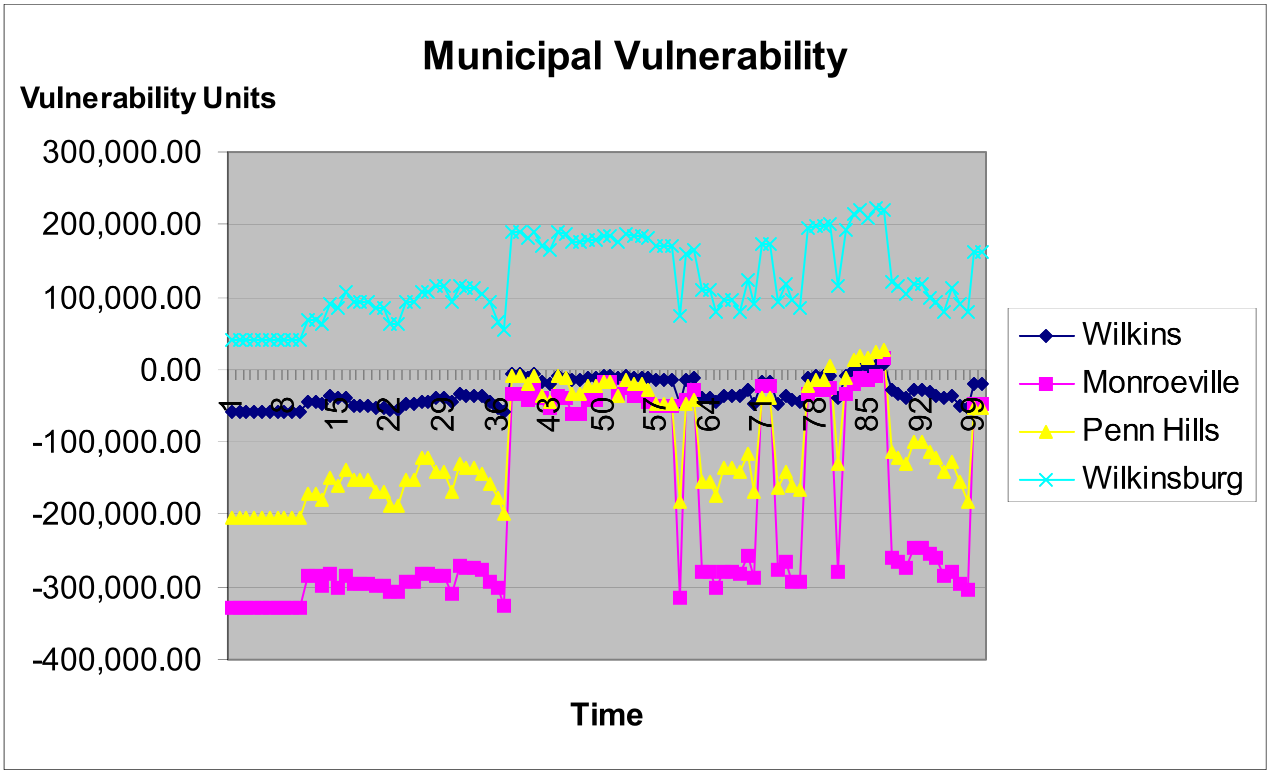


Figure 16. Municipal Capacity for Response Policy 1

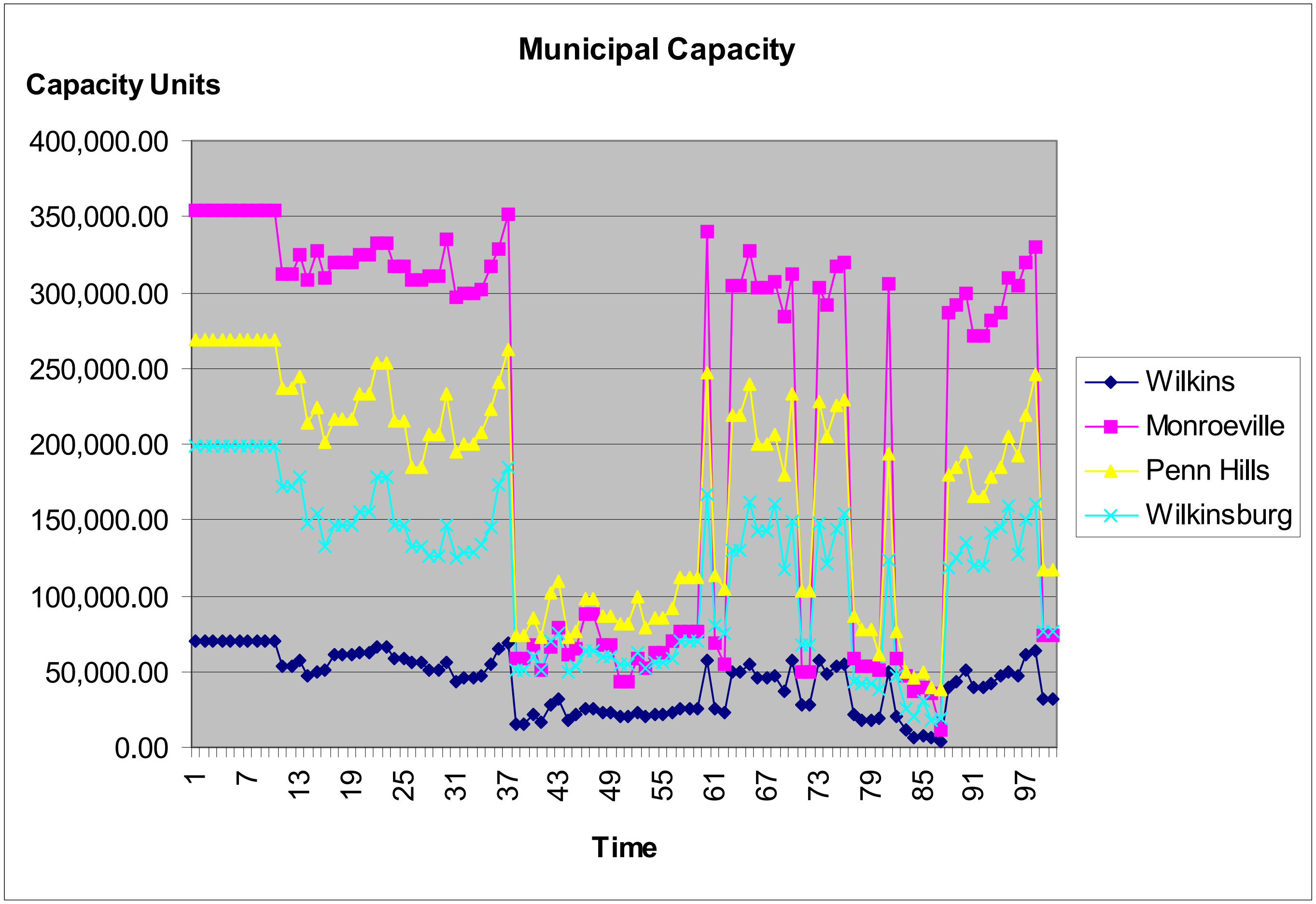


Figure 17. Municipal Vulnerability for Response Policy 2

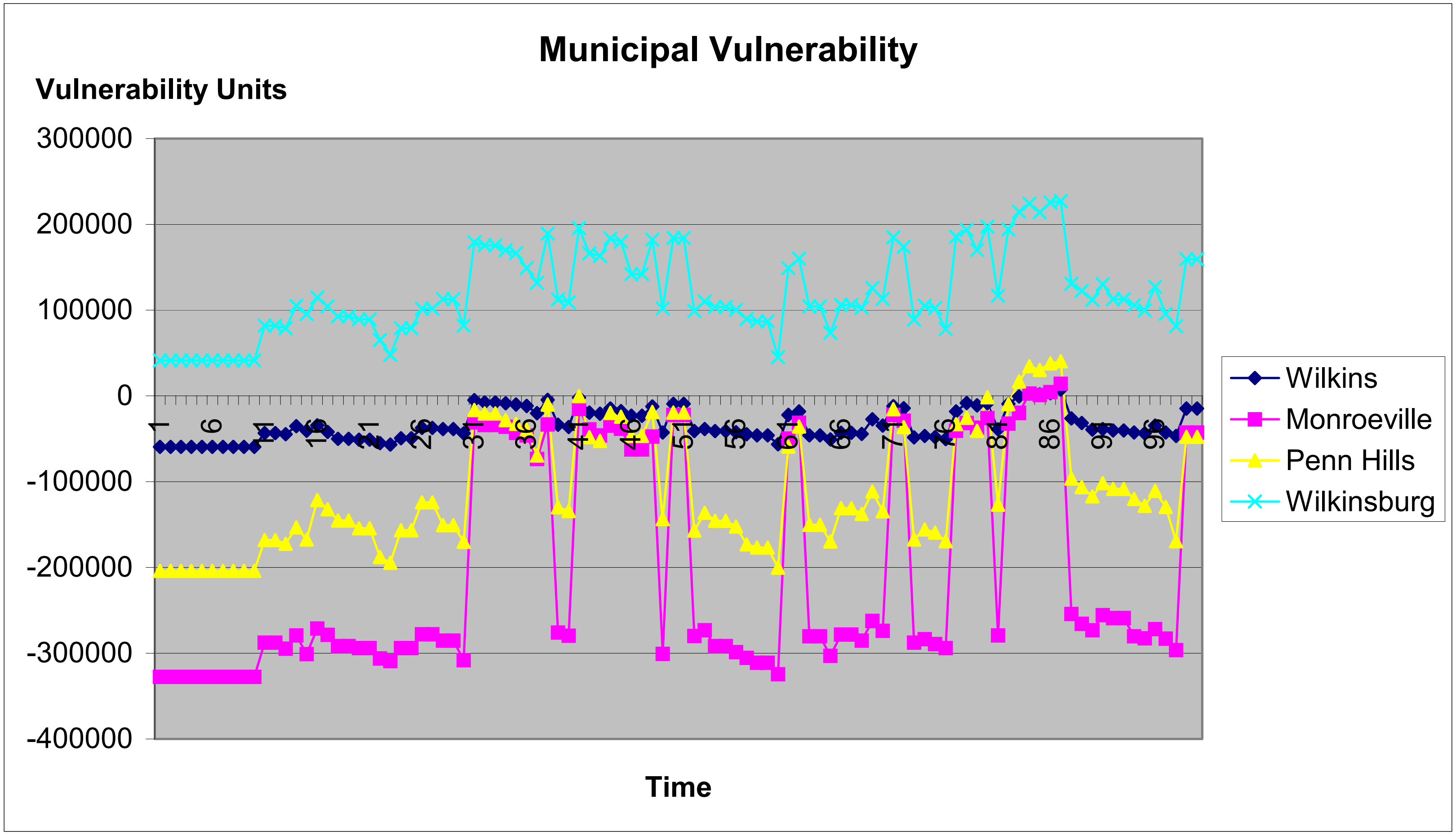
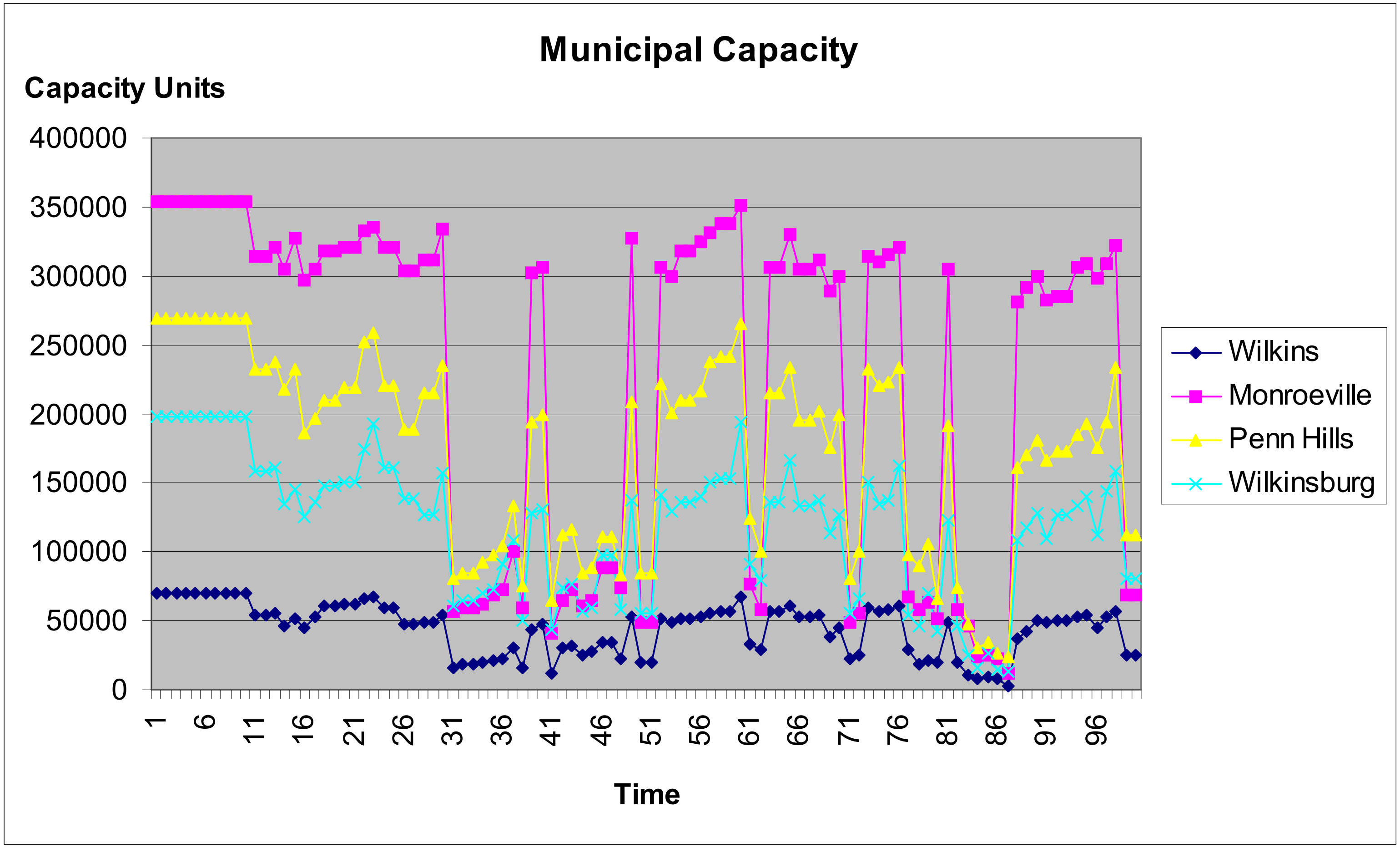


Figure 18. Municipal Capacity for Response Policy 2



The measure of capacity also serves as a proxy measure for municipal resiliency. Analysis of the tract level is difficult because the tracts are not all served by a single agency within a discipline. Many are split between fire districts and police patrol districts. Resiliency can be thought of as having sufficient response assets available to handle either an escalation of the existing incidents or additional incidents. There are two methods for measuring resiliency: a stable capability trend demonstrating that the occurrence of “routine” incidents is insufficient to cause large changes in the level of capacity or a ratio of capacity over vulnerability. The capacity measures can be seen above in Tables 49 and 50. The ratio results for both response policies can be seen below in Tables 51 and 52.

Wilkins		**Monroeville**		**Penn Hills**		**Wilkinsburg**	
Mean	-1.48	Mean	-1.38	Mean	-1.98	Mean	1.44
Standard Error	0.12	Standard Error	0.06	Standard Error	0.27	Standard Error	0.14
Median	-1.28	Median	-1.10	Median	-1.46	Median	1.15
Mode	-1.18	Mode	-1.08	Mode	-1.32	Mode	4.81
Standard Deviation	1.23	Standard Deviation	0.56	Standard Deviation	2.70	Standard Deviation	1.35
Sample Variance	1.51	Sample Variance	0.32	Sample Variance	7.29	Sample Variance	1.84
Range	13.63	Range	4.73	Range	24.73	Range	4.73
Largest(1)	2.40	Largest(1)	0.75	Largest(1)	15.22	Largest(1)	4.81
Smallest(1)	-11.22	Smallest(1)	-3.98	Smallest(1)	-9.50	Smallest(1)	0.08

Table 51. Municipal Resiliency Ratio for Response Policy 1

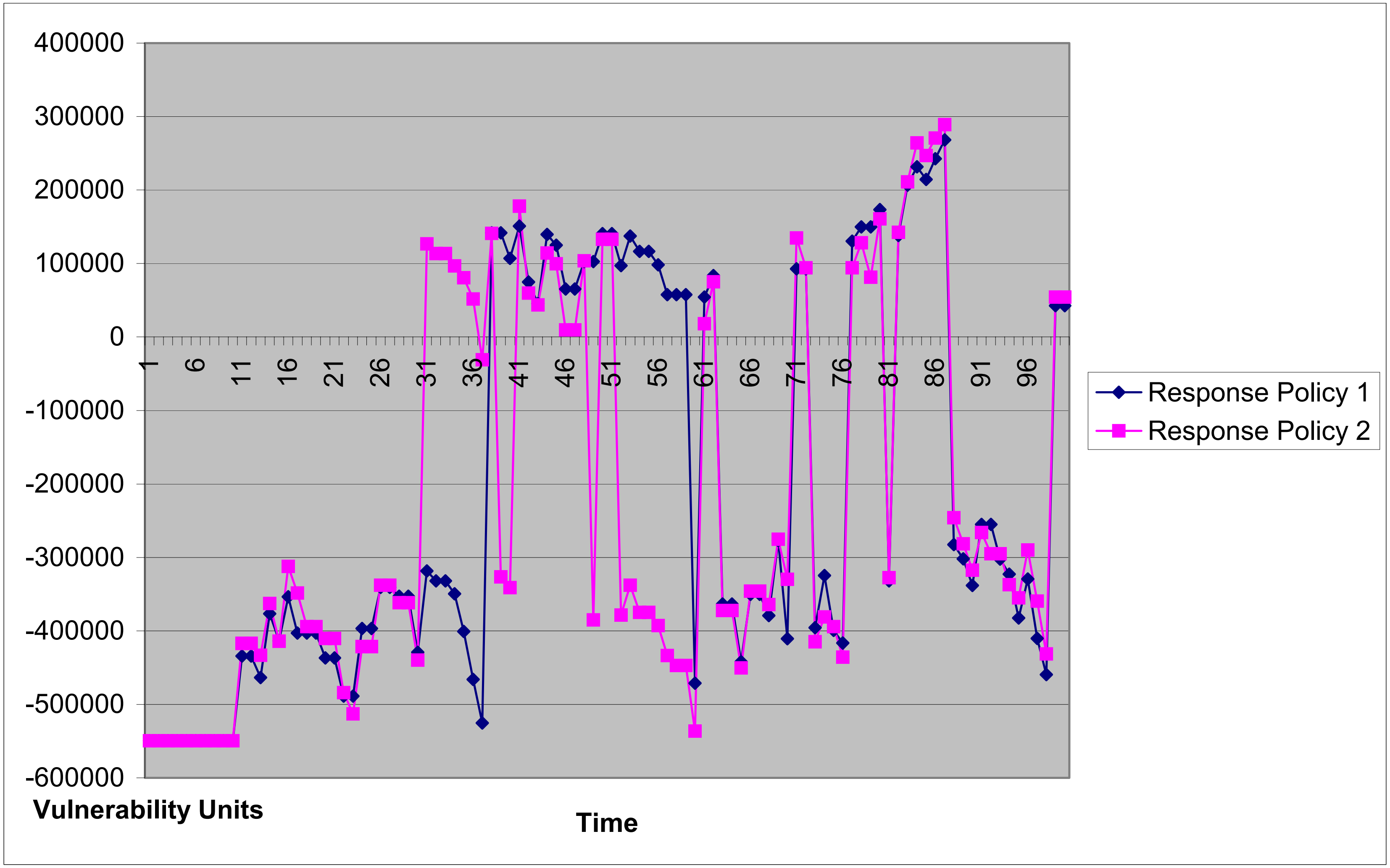
Wilkins		**Monroeville**		**Penn Hills**		**Wilkinsburg**	
Mean	-1.48	Mean	-0.87	Mean	-3.64	Mean	.47
Standard Error	0.19	Standard Error	0.29	Standard Error	1.45	Standard Error	0.13
Median	-1.26	Median	-1.09	Median	-1.48	Median	1.23
Mode	-1.18	Mode	-1.08	Mode	-1.32	Mode	4.81
Standard Deviation	1.91	Standard	2.89	Standard Deviation	14.54	Standard	1.34
Range	21.	R1nge		Range	145.60	Range	4.75
Largest(1)	5.14	Largest(1)	25.07	Largest(1)	2.85	Largest(1)	4.81
Smallest(1)	-16.	Smallest(1)	-2.73	Smallest(1)	-142.75	Smallest(1)	0.06

Table 52. Municipal Resiliency Ratio for Response Policy 2

The application of these measures need not be limited to comparing response policies, but can also be done as a before and after evaluation for policies that will change any of the measures of the either the vulnerability or capacity equations. The same can be done on the sub-county level by treating the entire area as the municipalities were in the above tables.

While the data represents a time series, it is not appropriate for evaluation using the ARIMA method commonly used in time series analysis. The data are not stationary, nor did it respond to differencing. Over a greater amount of time it may be possible to apply quasi-experimental techniques in order to determine the impact of policy changes by collecting the above data. The programming of the simulation did not provide for changing response policies during a simulation run.

Figure 19. Sub-county Regional Vulnerability



5.2 EVALUATION

The intent of this exploratory study was to examine the use of agent-based modeling for the dynamic assessment of the hazards, using flooding as the illustrative triggering agent. There are several methods to evaluate whether the goal was reached.

At the most basic level, the goal must be evaluated on its methodological foundation. The method delineated above is unique for several reasons and therefore it is challenging to evaluate. The first criterion is whether the model makes sense based on the multi-disciplinary knowledge bases provided by the literature. Chapter 2 shows that there are multiple sources from which the data are collected, and that while in some cases disparate in background, diverse measures can be integrated and applied to the research question.

The second question is whether the use of the multi-component equation to develop the vulnerability and capability scores is mathematically sound. While complex and in some cases cumbersome it does include measures that not only account for the environments outlined by Mileti (1999) but quantifies them and standardizes them so comparisons can be made between areas and organizations. While areas for expansion remain, specifically a more complete picture of functional interaction, given the data available this method does provide the additional perspective of interdependency by using the results of network analysis to reveal impacts to areas other than those directly affected by the triggering agent.

The next question is whether the application of an agent-based simulation provides a suitable tool for the effective modeling of the different environments involved in this complex response. The use of agent-based simulation is central to this study for several reasons. First is that it provides the ability to model very diverse areas and organizations, measuring each by its unique set of characteristics and at a variety of scales. While done through rather simplistic aggregation, this does allow the accurate portrayal of the environment being modeled. Agent-based modeling also enables the incorporation of the dynamic nature of the model to be used in evaluating potential outcomes. In effect it creates a time series based on historically accurate data. This addition of dynamic interaction fills one of the major gaps in existing hazard assessments as they exist in practice today.

The final methodological question concerns basing of the model on two diverse scales of measurement, vulnerability and capability. Given the disparate nature of these entities, the application of the same metrics is neither rational nor epistemologically sound. While this may initially appear to be a negating factor, I do not believe this to be the case. Each measure is applied within its domain in exactly the same way, enabling the comparison of values among their respective cohorts. This method allows the application of one domain to the other because the impact of one member of the group affects members of the other group in the same way. This common basing of the domains also allows the end user to modify the impacts to suit their own organizational culture. They can adjust or weight parameters to more accurately reflect their environment or culture. As long as the same changes are made to all of the members of the domain the impact remains relevant.

Once the methodology is shown to be sound, the most important question is whether it creates a tool useful to the end user, the public safety practitioner. Much of the disconnect between the academic disaster research community and the practitioners is over the applicability of the knowledge to the real world problems faced by practitioners on a daily basis. To evaluate whether this objective has been met, they must be given the opportunity to provide feedback.

Upon completion of the model and the simulation, the data were summarized and presented to a wide variety of response personnel and government employees with knowledge of public safety, geographic information systems or computer modeling. Some members of the audience included representatives of the agencies included in the study. An opportunity to expand the audience beyond the local level allowed the model to be presented to government representatives from eleven states around the country. A total of nineteen people evaluated the model. Of the nineteen included in the evaluation, nine have public safety practitioner experience with a mean experience of 20.6 years. The remaining evaluators were government officials primarily working in GIS and planning. They were attending a Federal Emergency Management Agency course using a GIS-based application to model potential natural disasters. The evaluators were also asked to indicate their knowledge level in developing computer models using the following scale:

0 - None 1 - Low-level (Some experience) 2 - High-level User (Modify variables) 3 - Developer

The average amount of computer modeling background was 1.05.

The evaluation focused on the advantages of expanding the concept of hazard assessment to incorporating vulnerability and public safety response capacity as well as the interdependencies and interaction. The evaluators were presented with a program outlining the simulation and supporting model. Each was then asked to complete a written evaluation consisting of the following questions. They were asked to evaluate the model on a five-point Likert scale ranging from strongly disagree (1) to strongly agree (5). The average of the response is indicated after each question.

1. The inclusion of public safety response capability into vulnerability is beneficial (4.68)

2. The model makes sense relative to your experience/background. (4.11)

3. The addition of interdependencies is beneficial (4.42)

4. The addition of dynamic evaluation features is beneficial (4.26)

5. This model provides a beneficial decision support too for emergency response or mitigation. (4.42)

6. This type of information would be useful to your agency or it's clientele. (4.26)

The overall average for the questions was 4.35, between agree and strongly agree, resulting in a positive reception for the model and simulation from the practitioners. By soliciting feedback from a widely disparate group the true applicability of the tool across the gambit of potential users is more indicative of the user population.

5.3 SUMMARY

It has become increasingly evident that current methods of hazard assessment are insufficient to prepare for and manage disaster effectively. The present practice of static hazard assessment does not take into consideration the wide variety of complexities inherent in these incidents. Our understanding of the behavior of these complex, dynamic incidents requires a multi-disciplinary approach. The development of this model provides a multi-disciplinary tool that incorporates divergent fields to provide an accurate and timely method of evaluating the vulnerability of communities at various levels of risk to a hazard.

Traditional methods of hazard assessment do not consider the capacities of the public safety response organizations as a mitigating factor in determining vulnerability. Certainly some emergencies are beyond the responders' ability to impact the incident's outcome positively, but in a majority of the cases a positive intervention is possible. This model expands hazard assessment to include the positive impact of response organizations to reflect vulnerability more accurately.

Current practice in hazard assessment has focused on a single spatial level, typically a politically based jurisdiction. This dismisses the heterogeneity inherent in many communities, a factor that can have a significant impact on the resource demands created when an emergency occurs. It also provides a template for the expansion of that assessment to other hazards that may be present beyond that specific municipality, but may have an impact through interdependent systems. This concept was applied in this study from the census tract level through the sub-county level, but it need not be limited to those scales. It could, with adjustment for scalar value changes, be applied to even larger areas. By ranging in granularity from the census tract level up through the sub-county region, and potentially beyond, it provides a method by which a practitioner can not only plan for emergencies, but also monitor conditions as the incident evolves.

The use of agent-based modeling affords the practitioner some benefits that have not been available in the past. By controlling for the nature and timing of incidents, emergency organization managers can examine the impact of policies in a controlled environment. The policies that may be evaluated range from the advantage of advanced training for personnel to resource deployment policies for large-scale incidents. They are also able to perform "what-if" scenarios to estimate the challenges posed by low-frequency high-impact events. Examples of these types of incidents include airplane crashes and weapons of mass destruction attacks.

5.4 IMPLICATIONS

When viewed from the perspective of the four segments of the emergency management cycle; mitigation, preparedness, response and recovery, there are applications at each step. During the preparedness phase, the existing vulnerability of the area can be evaluated to determine the scale of the vulnerability inherent in the community. The capability of the response organizations can also be assessed and compared, not only to other organizations within the same discipline, but also on the municipal and sub-county levels. This comparison allows practitioners at each level to manage the vulnerability and response capabilities for their specific jurisdictional level. The impact of response policy changes or station location can also be evaluated to provide a quantitative tool on which policy recommendations can be based. The use of a capability measure also allows the determination of community resiliency in the short term. This allows the practitioner a chance to modify capabilities before the incident occurs, thereby increasing their level of preparedness.

The response phase, while modeled here, can be augmented through the streaming of data from a CAD system into the model. As units are assigned to incidents, the dynamic changes in vulnerability and capabilities can be seen. Response assets can be moved to provide a more uniform coverage, decreasing the overall vulnerability of the community. Currently this is done on a predetermined format or by an ad hoc organizational manager operating without the benefit of quantitative information. This lack of information can leave the protection of the community to the anecdotally-based judgment of a person working with incomplete information.

During the recovery phase practioners now have a quantified level of vulnerability that can be used as a benchmark. The goal of recovery is to return to pre-disaster conditions. Currently determining when that return has been accomplished is left up to individual impressions of the conditions. By adopting the model, a more detailed comparison of the previous and existing states of the communities can be assessed. Because the model currently focuses on more immediate needs, the full scope of recovery is not assessed, but its application for short-term recovery is relevant. It will answer the question of whether the community has returned to its pre-disaster level of vulnerability and response capacity. By reaching this benchmark, the community can focus on long-term recovery goals and not dread an impact of additional incidents.

Finally in the mitigation phase, much like the preparedness phase, communities can run what-if scenarios when considering the potential impact of future policies. Issues that were previously relegated to strictly economic-based benefit/cost analysis can now be given the added dimension of a quantitative-based hazard assessment before making implementation decisions.

This exploratory study and the resulting model/simulation are not intended to be an complete resolution to the issue of hazard assessment, but rather a beginning. While the importance of hazard assessment cannot be overstated, it remains a problematic issue. It is inherently difficult to evaluate a complex and dynamic situation accurately and effectively. It is hoped that this model will afford practitioners a tool that will make their job easier by giving them a quantitative measure to assess the hazards in their community and thereby improve their performance in each segment of the emergency management cycle. The incorporation of additional and more dynamic data sources would greatly enhance the performance of the model, and therefore its utility in practice.

The second goal of the study was to explore the impact of including public safety response capabilities into the hazard assessment. Practitioners deal with "routine" emergencies on a regular basis, but often from a myopic perspective. Only in the rare occurrence of a large-scale disaster is the region beyond the municipality considered. Conversely, the importance of the granularity within a municipality is similarly disregarded. Because the majority of public safety and emergency management actions is based on the municipal level, the diversity at a more granular level is often dismissed. While not all public safety agencies throughout the country are municipality based, the relevance of the granularity of the model retains its relevance and should be considered by the various practioners whose work is relevant to the safety of the public.

It is my fervent hope that this study and the model will enlighten practitioners to the impact of interdependencies, granularity and the complexity of the hazards present in our communities. If nothing else, the addition of the components of the study and model will hopefully generate discussion within both the disaster research and practioner communities, ideally leading to improved hazard assessment and public safety.

Appendix

RESPONSE AGENCY SURVEY

Please answer the following questions to the best of your knowledge

Organization ____

Rank of person completing survey ____________

Response Organization Capabilities

1. What services does your organization provide? Please circle all applicable services.

   Fire

   Rescue

   EMS

   Law Enforcement

   Emergency Management

Other ____

2. How many times has your organization responded to flooding during the past 5 years?

   0 1 2 3 4 5 6 Greater than 6

3. What planning measures are in place? Please circle the most appropriate answer.

4 – formal written flood plans

3 – formal written operational plans

2 - past practice w/o plans

1 – no plan or past practice

4. What capabilities are there within your organization? Please check all that apply.

Equipment

- ☐ Equipment that could be used for flooding (portable pumps, large salvage covers, sand bags, diking tools, etc)
- ☐ Equipment water rescue response (PFDs, Polyprop rope, dive suits)
- ☐ Equipment for the discipline (if third party accreditation is available for the discipline that will be used.)
- ☐ No equipment, personnel only

Training (flooding training include water rescue, property salvage, etc)

- ☐ Greater than 75% of the personnel trained specific to flooding
- ☐ 50 - 74% of the personnel trained specific to flooding.
- ☐ 25 - 50% of the personnel trained specific to flooding
- ☐ Less than 25% of the personnel trained specific to flooding.
- ☐ In-house training for flood response
- ☐ No trained personnel

Experience

☐ Over 75% of the personnel with personal experience in flood response.

☐ 50 - 74% of the personnel with personal experience in flood response.

☐ 25 - 49% of the personnel with personal experience in flood response

☐ Less than 25% of the personnel with experience in flooding events

5. Communications/Information infrastructure

Please indicate the quantity and interoperability (will it communicate with mutual aid departments) of your equipment

Mobile Radios	Quantity_________	Interoperable___________
Portable Radios	Quantity_________	Interoperable___________
Cell Phones	Quantity_________	
Fax Machines	Quantity_________	
Mobile Data Terminal	Quantity_________	
Computer (PC/LAN)	Quantity_________	
Radio Pagers	Quantity_________	
Alpha/Numeric Pagers	Quantity_________	
Other (please specify)	Quantity_________	Interoperable___________

6. During these incidents, what type of information have you found critical to managing your response?

Weather _______ Utility Information _______ Available Resources _______

Structure Information ______ Hazard Information _______ If yes, what type?

Other ____

7. What were your sources for that information? Check all that apply.

Dispatch_____ Observation ____ Preplan_____

Other agency_______ If other agency please specify what type _______________

Other ____

8. During those events in which you had communications problems were the problems the result of :

   Incomplete information _____ Inaccurate Information _____

   Unable to access another organizations or units ____

   Required information was unavailable _____

   Other ____

9. What type of mutual aid agreements does your organization have with other organizations in the same discipline?

   Written into the preplans and exercised ___________
   Written agreements but not in the preplan/Exercised ___________
   Informal agreement/history of working together ___________
   None, we will call when needed ___________
   None, mutual aid is not permitted ___________

10. When working with other agencies did you find that the interaction improved or complicated the response?

   Improved _______ Complicated _______ No effect _____

   Varies (please explain)____

11. When developing response plans do you consider the resources of other agencies? Please check all that apply.

Mutual Aid agencies ___ County resources ___ State Resources ___ Federal Resources ____

12. Has your agency completed a hazard analysis for your jurisdiction specific to the services your organization provides?

   Formal _______ Informal _____ None _________

   If other than none, what methods did you use to determine the hazards present in your community? ____

13. Does your agency regularly interact with other municipal emergency service providers?

Yes _____ No _____ If yes, please indicate with whom you interact

Within the municipality ____ Outside the municipality ____ Both ___________

***If outside or both please put the number of municipalities you interact with in that space.**

If yes, which disciplines? Please check all that apply and indicate the frequency of the interaction.

Fire	Frequently _____	Occasionally ______	Rarely _____
Rescue	Frequently _____	Occasionally ______	Rarely _____
EMS	Frequently _____	Occasionally ______	Rarely _____
Law Enforcement	Frequently _____	Occasionally ______	Rarely _____
Emergency Mgt	Frequently _____	Occasionally ______	Rarely _____

Other (please specify)____

Frequently _____ Occasionally ______ Rarely _____

14. Please provide some information regarding your organization.

Number of field personnel ________ Number of Administrative personnel _____

Number of personnel with basic training for the discipline _______
Examples: Fire Service – Fire Fighter I/Essentials
Law Enforcement – Act 120 training
EMS – EMT
Rescue – entry level certification in a single specialty
Emergency Management – PEMA Basic level certification/FEMA PDS

Number of personnel with advanced training for the discipline _______
Examples: Fire Service – Fire Fighter II/Officer
Law Enforcement – Detective/Traffic/K9
EMS – Paramedic
Rescue – entry level certification in a two or more specialties
Emergency Management – PEMA Advanced level certification

Number of personnel with management training _______
*This may be in public safety or business

15. Age of your personnel. Please indicate the number of personnel you have in each age category.

14 – 18 ____ 19-25 ____ 26-35 _____ 36-45_____ 46-55 ____ 56-65 ____ Over 65____

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