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Reducing Interactive Service Interruptions in Linear Infrastructure Systems (Transportation, Water/Sewer, Power) by Synchronizing Schedules for Appropriate Maintenance Activities

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REDUCING INTERACTIVE SERVICE INTERRUPTIONS IN LINEAR INFRASTRUCTURE SYSTEMS (TRANSPORTATION, WATER/SEWER, POWER) BY SYNCHRONIZING SCHEDULES FOR APPROPRIATE MAINTENANCE ACTIVITIES

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ABSTRACT

The objective of this study was to develop a framework for integrated assessment of service vulnerabilities based on individual system failure probabilities, consequences, and potential interactions transportation networks with pipeline (water and sewer) networks. A comprehensive integrated network methodology was developed to evaluate and quantify the interactions between different infrastructure networks which included transportation and pipeline systems for water and sewer services. The quantitative risks were evalueted in terms of the individual network vulnerabilities, interactions of different networks (traffic, water, sewer), affected service areas, number of vehicles, and delays in transportation (vehicle-hours) using ArcGIS. The interactive vulnerability and quantitative risk assessment methodology was demonstrated by a case study using the transportation and pipeline infrastructure for the service area in downtown Miami, Florida. The impacts on traffic flow were evaluated by segmentation methodology using node-based connections and visualized using ArcGIS. Based on the analyses, analyses showed that the case study area (about 3.15 square miles) is vulnerable for service interruptions which will affect traffic flow significantly. This corresponds to about 58,805 people in the service area. The integrated methodology developed can be used for asset management for developing effective maintenance programs to improve service quality in areas served by multiple infrastructure networks.

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CHAPTER 1: INTRODUCTION

Lifeline systems provide the main utility or transportation services to a community (i.e., electric and potable water transmission and distribution, wastewater collection and treatment, highways, railroads, seaports and inland waterway ports). The interdependent nature of the linear infrastructure systems due to accidents, periodic upgrades, service demands, system limitations, and environmental factors often result in major interruptions in service delivery and economic loses. Linear infrastructure systems (roads, water/sewer/power lines) are often located in parallel manner, to form a network which provides the necessary services. The key impacts of bottlenecks in interdependent linear infrastructure systems (ILIS) are reduction of system reliability and oscillations in service delivery capacity and quality. Failure in one infrastructure network can result in service disruptions or increase in demand in other infrastructure networks. For example, when a segment of the water transmission fails as a result of pipe breakage, the water needs of a community may be met through the transportation routes. Similarly, when there is a pipeline repair, the road closures can create disturbances in transportation network due to road closures (partial or full closures).

Risk is defined as the likelihood of an undesirable event happening that will have measurable impacts (i.e., consequences). For quantification purposes, risk can be expressed by the following equation (Masse and Rollins, 2007):

$$R = T \times C \times V \qquad (1)$$

where,

R : risk,

T: threat,

C: consequence, and

V: vulnerability.

The studies on failure risks can be grouped into two categories as deterministic and probabilistic (Bonvicini et al., 1998). For deterministic studies, the focus is on the mechanical behavior of the network (e.g., pipes, valves, pumps) (Brémond, 1997; Clark et al., 1982; Constantine et al., 1993; Kettler and Goulter , 1985). In studies related to probabilistic approach, different statistical methods are used for failure estimation (e.g., Poisson model, Bayesian approach, Markovian approach) (Kleiner and Rajani, 2001; Magelky, 2009).

For parallel infrastructure networks (i.e., transportation, pipeline), analysis of the infrastructure topologies individually does not adequately reflect the actual vulnerability of different types of infrastructure networks due to the significant interaction between the networks from service delivery perspectives. There are only a few studies which address the interdependent layers of networks and their interactive nature. Fuzzy logic approach has been used to assess the risks of hazardous materials transport by road and pipelines to evaluate the uncertainties affecting both individual and societal risks (Neutens et al., 2012). Integrated spatial analyses have been used by only a few studies for quantitative risk assessment (Ouyang and Dueñas-Osorio, 2011; Shamir and Howard, 1978; Walski and Pelliccia, 1982).

Prediction of failures and maintenance strategies have been studied extensively (Chughtai and Zayed, 2008; Al-Barqawi and Zayed, 2006; Halfawy et al., 2008; Johansson and Hassel, 2010; Koonce et al., 2008; Michaud and Apostolakis, 2006; Wang et al., 2012). Most of the studies focused on one infrastructure network. Chughtai and Zayed (2008) proposed a framework for sewer pipeline condition prediction considering material class, bedding material, and street category on existing structural and operational condition of sewers; Al-Barqawi1 and Zayed (2006) developed a rating model for water mains using the artificial neural network approach to predict and assess the condition of water mains by considering pipe type, size, age, breakage rate. Halfawy et al. (2008) proposed a step-wise integrated approach that could potentially assist municipal professionals in developing optimized plans that would identify the most appropriate compromise of renewal solutions while simultaneously optimizing the renewal costs, condition state, and risk of failure of the sewer network. The three main criteria considered in the planning process were condition, risk, and cost.

The objective of this study was to develop a framework for integrated assessment and visualization of vulnerability of the transportation and pipeline networks based on the individual network characteristics, failure probabilities, failure consequences, and interactions with other networks. A comprehensive integrated network methodology was developed to evaluate and quantify the interactions between different infrastructure networks, identify and visualize vulnerable areas. The analyses were conducted for transportation and pipeline systems for water and sewer services. The quantitative risk analyses were performed in terms of the individual network vulnerabilities, interactions of different networks (traffic, water, sewer), affected service areas, number of vehicles, and delays in transportation (vehicle-hours) using ArcGIS. The interactive vulnerability and quantitative risk assessment methodology was demonstrated for by case study for the Miami downtown area in Florida. Affected links and expected traffic delays due to pipeline failures were analyzed and visualized using ArcGIS.

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CHAPTER 2: RESEARCH APPROACH

A multilevel quantitative risk assessment methodology was developed to quantify the impacts of pipeline failures (i.e., water and sewer) on transportation networks. Vulnerability of the service networks for transportation and pipelines systems were identified based on the failure characteristics of each network. Consequences of service failures were quantified and visualized by integrating the failure data into ArcGIS to estimate the traffic impacts. Figure 1 presents the general framework of the quantitative risk assessment methodology.

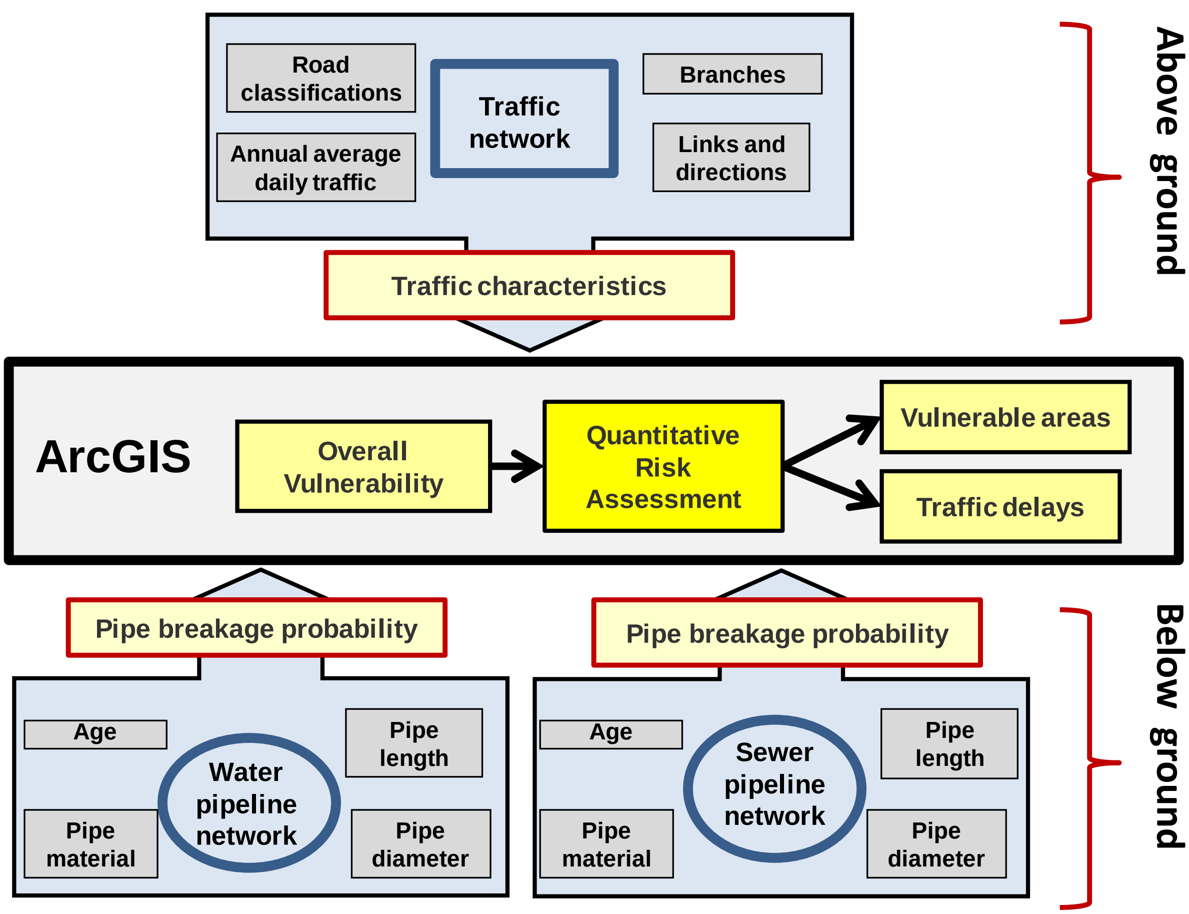

Figure 1. Framework for the interactive vulnerability assessment of transportation and pipeline networks.

A rating system (metrics) for service quality and/or interruption probabilities and consequences for traffic were developed based on service interruptions in pipeline infrastructure. The rating system included the following considerations:

1. Failure frequency: Frequency of occurrence in relation to failure mechanisms of pipeline infrastructure.
2. Consequence rating and quantification: For the purpose of quantification, the degree of severity was quantified in relation to service quality reduction and duration, and population affected.
3. Potential impacts on functioning of other co-located linear infrastructures: Service quality interruption in terms of their potential impacts on transportation services.

VULNERABILITY ASSESSMENT

Risk management for co-located linear infrastructure systems (i.e., roads, water/sewer lines) involve considerations for reducing hazards both above and below ground as well as risk reduction for services provided by other linear infrastructure systems which can affect the service quality.

The vulnerability for service interruption in parallel infrastructure networks is higher due to their interactive nature. Table 1 presents the possible interactions between three infrastructure networks; transportation, water utility, and sewer utility lines. Depending on the failure characteristics in each network, service interruptions can range from minor to long term impacts. The interactive vulnerability and quantitative risk assessment methodology was demonstrated by a case study by integrating failure information for pipeline systems with traffic information.

Table 1.Interactive vulnerability of transportation and pipeline networks.

Scenario	Road Network[a]	Water Utility	Sewer Utility	Description	Severity
1	+	-	+	Road may experience mild congestion, it would be closed for a few hours for pipe repairs	Low
2	+	-	-	Road may experience from mild to high congestion, it would be closed for a few hours for pipe repairs	Low to Medium
3	-	-	-	Service restoration would take longer time than expected due to road closures	High
4	-	+	+	Potential severe consequences may occur due to damage to pipelines during road repairs (Scenario 3)	Low to High

[a] Negative sign (-) indicated failed, positive sign (+) indicates functional.

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CHAPTER 3: CASE STUDY

The quantitative risk assessment methodology was demonstrated by a case study for the downtown area in Miami, Florida. The quantitative risk analyses were conducted for the impacts on transportation network as results of pipeline network failures in water and sewer utility lines. The analyses focused on identifying the vulnerable areas for pipeline failure which can interfere with the traffic flow during the repairs. Affected links were identified and expected traffic delays were estimated and visualized using ArcGIS based on the characteristics of the transportation network.

TRANSPORTATION NETWORK

For the analyses, it was assumed that the main highways will have higher priority over collector roads and collector roads over the local roads. Table 2 presents the assigned vulnerability factors for the transportation network components. Figure 2 presents the case study area and the traffic network.

Table 2. Assigned vulnerability factors for the transportation network components.

Transportation Network Component	Vulnerability	Assigned Vulnerability Factor
Main Highway	High	0.5
Collector	Medium	0.3
Local	Low	0.2

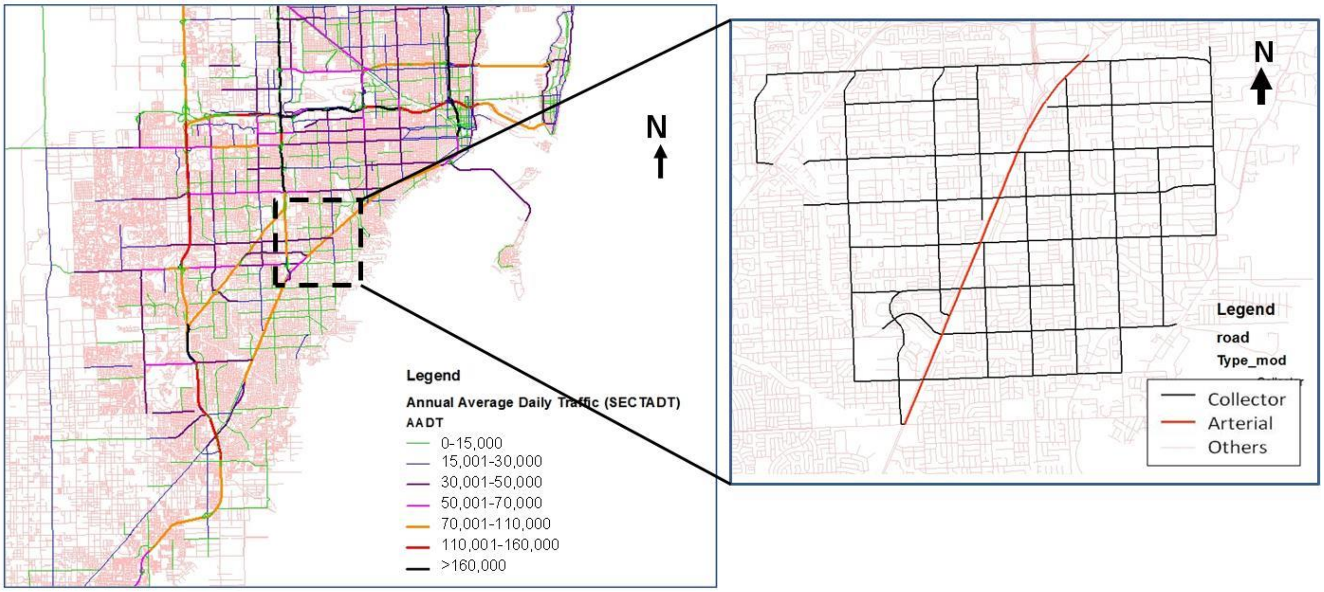

Figure 2. Annual average daily traffic flow and classification of roads in the study area.

Pipeline Failure Model

The probability of pipe failure depends on characteristics of pipe (i.e., age, pipe materials, pipe diameter). The probability function of pipe failure for the water and sewer pipe can be expressed as follows (Eq. (2)):

$$f(X_{pipe}) = f(X1) \times f(X2) \times f(X3) \tag{2}$$

where,

$f(X_{pipe})$: overall probability of pipe failure,

$f(X1)$: probability of pipe failure due to pipe material type,

$f(X2)$: probability of pipe failure due to pipe diameter, and

$f(X3)$: probability of pipe failure due to pipe age.

For the analyses, the probability of failure due to age was assumed constant for the study area. Pipe breakdown may be caused by other factors such as installation related or component failures. Analyses in this study focused on pipe failures due to age, pipe materials, and pipe diameter.

Pipeline Network Failure Probabilities

For the study area, the failure probability functions for the pipeline systems were developed based on the data and information provided by Miami-Dade Water and Sewer Department (MDWASD). Pipe Maintenance and Repair Unit of MDWASD maintains a service and emergency response database for both water and sewer pipelines in the service area.

The pipe maintenance and repair data for water pipeline network database included information on failure incidents, types of failures, and pipe characteristics for water system. However, the maintenance data for the sewer pipelines were compiled in different format which could not be translated in a similar manner. Therefore, the sewer pipeline failure probability data were developed based on the data available in the literature and personal communications with the Miami-Dade Water and Sewer Department.

The probabilities of failure for polyvinyl chloride (PVC), cast iron (CI), ductile iron (DI), asbestos cement (AC), steel, galvanized iron (GI), reinforced concrete (RC), and vitrified clay (VC) pipes were developed separately for water and sewer systems. It is important to assign the failure probability functions separately for the water and sewer pipes. Even if they have the similar pipe material and pipe diameter, water and sewer lines exhibit significantly different failure profiles due to the differences in the materials transported in the pipes.

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CHAPTER 4: RESULTS

Tables 3 and 4 present the failure characteristics of the water and sewer pipes based on pipe material and pipe diameter, respectively. The values for failure per mile were estimated by multiplying failure occurrence to the fraction of pipes for each column. Probability of failure was calculated by dividing the failure per mile by the sum of the failures per miles for all the pipes. For asset management, a pipe type with a relatively low and consistent probability of failure is preferred. For the water pipeline network, cast iron pipes followed by ductile iron pipes had the highest probabilities of failure per mile. For the sewer lines, galvanized iron pipes followed by ductile iron pipes had the highest probabilities of failure. In general, the probability of failure increases with decreasing pipe diameters for both water and sewer pipes.

Table 3. Failure characteristics of water and sewer pipes based on pipe materials.

Water pipes	Pipe material						
	Polyvinyl chloride (PVC)	Ductile iron (DI)	Cast iron (CI)	Asbestos cement (AC)	Steel	Galvanized iron (GI)	Reinforced concrete (RC)
Failure occurrence	8	27	46	15	1	3	2
Fraction of pipes	0.2	0.15	0.35	0.05	0.10	0.05	0.10
No. of Failure/mile	1.60	4.05	16.10	0.75	0.10	0.15	0.20
Probability, P(X1) (Failure/mile)	0.070	0.176	0.702	0.033	0.004	0.007	0.009

Sewer pipes	Pipe material						
	Polyvinyl chloride (PVC)	Ductile iron (DI)	Cast iron (CI)	Asbestos cement (AC)	Steel	Galvanized iron (GI)	Vitrified clay (VC)
Failure occurrence	1	16	12	1	4	70	6
Fraction of pipes	0.1	0.2	0.2	0.025	0.025	0.3	0.15
No. of Failure/mile	0.10	3.20	2.40	0.03	0.10	21.00	0.90
Probability, P(X1) (Failure/mile)	0.004	0.115	0.087	0.001	0.004	0.757	0.032

Table 4. Failure characteristics of water and sewer pipes based on pipe diameter.

Water pipes	Pipe diameter (in)								
	8	**12**	**16**	**30**	**20**	**24**	**36**	**48**	**60**
Failure occurrence	61	25	5	2	2	3	1	2	1
Fraction of pipes	0.3	0.2	0.15	0.1	0.05	0.08	0.02	0.05	0.05
No. of Failure/mile	18.30	5.00	0.75	0.20	0.10	0.24	0.02	0.10	0.05
Probability, P(X2) (Failure/mile)	0.739	0.202	0.030	0.008	0.004	0.010	0.001	0.004	0.002

Sewer pipes	Pipe diameter (in)				
	8	**10**	**12**	**16**	**30**
Failure Occurrence	70	4	12	3	1
Fraction of pipes	0.3	0.15	0.3	0.15	0.1
No. of Failure/mile	21	0.6	3.6	0.45	0.1
Probability, P(X2) (Failure/mile)	0.816	0.023	0.140	0.017	0.004

IDENTIFICATION OF VULNERABLE AREAS BY SPATIAL ANALYSIS

The failure probabilities for water, sewer and traffic networks were compiled as presented in Table 5 to develop the ranked maps for each network (i.e., water pipeline network, sewer pipeline network, traffic network) using ArcGIS. The overall network vulnerability scores were developed based on the individual network scores for each infrastructure system.

The spatial analyses were conducted by overlaying the ranked maps and using ArcGIS. The vulnerable points were identified based on the ranking of the cells analyzed in ArcGIS.

Figures 3 and 4 present the pipeline network risk maps for water and sewer, respectively. 5 presents the overall vulnerability map for transportation, water and sewer pipeline networks.

Table 5.Vulnerability summaries of network branches.

Branch ID	Water network vulnerability characteristics (P1)					Sewer network vulnerability characteristics (P2)					Traffic network vulnerability (P3)	Overall probability[a]
	Type	Dia (in)	Prob. X1	Prob. X2	Prob. X3	Type	Dia (in)	Prob. X1	Prob. X2	Prob. X3		
1	CI	12	0.05	0.7	0.2	GI	12	0.76	0.14	0.2	0.3	0.100050
2	CI	12	0.05	0.7	0.2	GI	12	0.76	0.14	0.2	0.3	0.100050
3	CI	12	0.05	0.7	0.2	GI	12	0.76	0.14	0.2	0.3	0.100050
4	CI	12	0.05	0.7	0.2	GI	12	0.76	0.14	0.2	0.3	0.100050
5	CI	12	0.05	0.7	0.2	GI	12	0.76	0.14	0.2	0.3	0.100050
6	CI	12	0.05	0.7	0.2	GI	12	0.76	0.14	0.2	0.3	0.100050
7	PVC	8	0.179	0.07	0.2	PVC	8	0.004	0.816	0.2	0.3	0.100001
8	DI	8	0.179	0.176	0.2	CI	8	0.087	0.816	0.2	0.3	0.100030
9	DI	8	0.179	0.176	0.2	CI	8	0.087	0.816	0.2	0.3	0.100030
10	PVC	8	0.179	0.07	0.2	PVC	8	0.004	0.816	0.2	0.3	0.100001
11	DI	8	0.179	0.176	0.2	CI	8	0.087	0.816	0.2	0.3	0.100030
12	DI	8	0.179	0.176	0.2	CI	8	0.087	0.816	0.2	0.3	0.100030

[a]Calculated as: $P1= (X1\cdot X2\cdot X3)_{water}$, $P2= (X1\cdot X2\cdot X3)_{sewer}$, overall $P = (P1+P2+ P3)/3$

a. Water pipes material

b. Water pipes diameter

c. Water Overall Risks

Figure 3. Risk allocation map for water network based on pipe material and diameter.

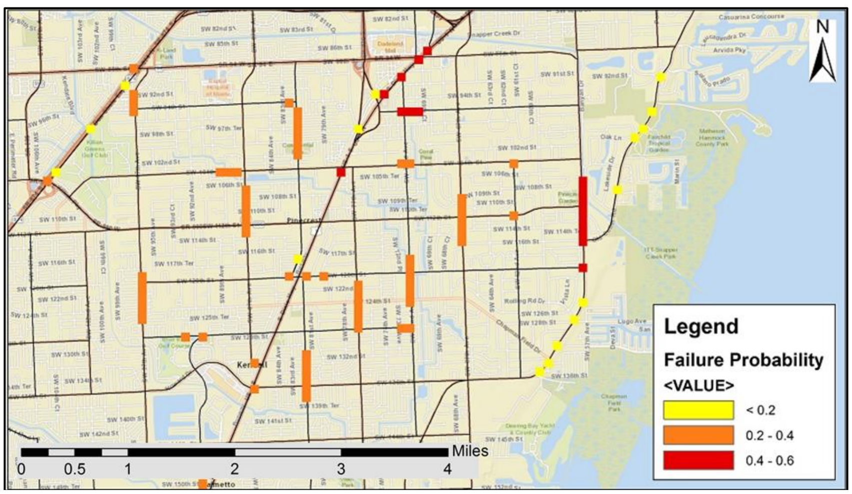
a. Sewer pipes material

b. Sewer pipes diameter

c. Sewer overall risks

Figure 4. Risk allocation map for sewer network based on pipe material and diameter.

a. Traffic network



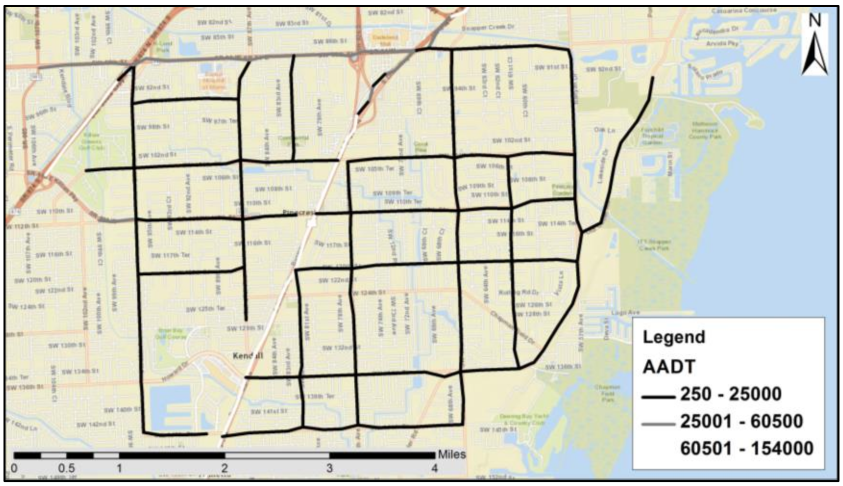
b. Overall vulnerability for the three networks

Figure 5. Overall vulnerability map based in transportation and pipeline network characteristics.

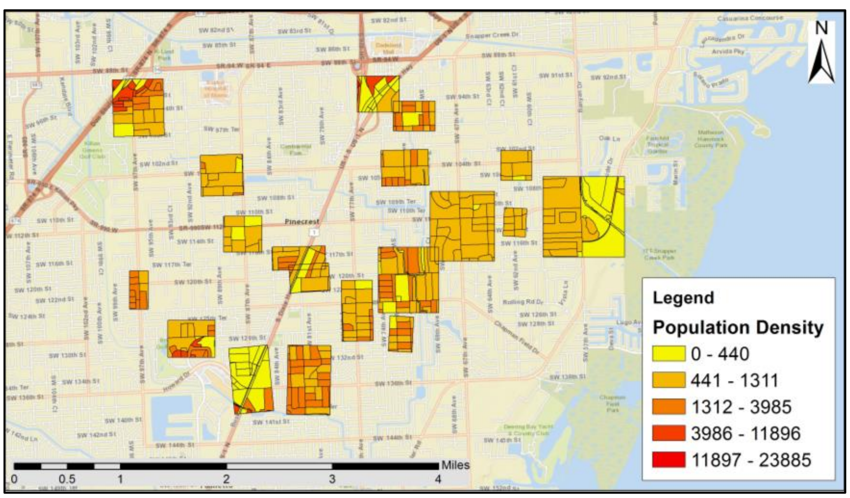
QUANTITATIVE RISK ASSESSMENT

The vulnerability analyses were conducted by buffer analyses to estimate the affected areas and population (Figure 6b). Since the impacts of traffic congestion due to incidents are not easily quantifiable, a simple but practical approach was used to quantify the impacts on traffic flow. The impacts on traffic flow were evaluated by segmentation based on the node based connections. The

Annual Average Daily Traffic (AADT) data (Figure 6 (a)) was used to assess the traffic impacts for affected links. The AADT associated with each link was multiplied with the average incident duration to estimate the hours lost corresponding to each incident. Figure 7 presents the methodology for integration of vulnerability information with the traffic flow data (AADT) by segmentation.



a. Annual Average Daily Traffic



b. Population density whithin affected areas

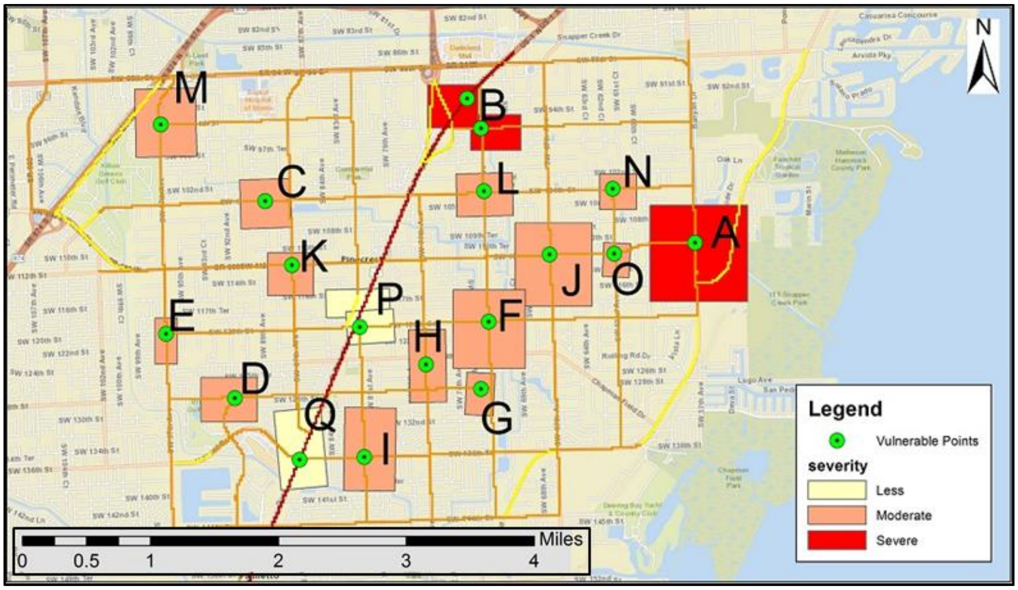
Figure 6. AADT and population density data.

AFFECTED AREAS AND POPULATION

The ArcGIS analyses were performed to estimate the affected areas, population and potential impacts on traffic flow. The spatial analyses were conducted by assuming that failed pipelines will affect half of each block they are located on. Table 6 presents the categorized impact levels, the estimated impact areas and affected population.

Table 6. Affected areas and population by impact severity categories.

Impact Level	Total Area (sq mi)	Affected population
Low	0.434	8554
Moderate	2.280	38110
Severe	0.830	12143



a. Vulnerable areas and level of vulnerabilities.

b. Segmentation of transportation network.

Figure 7. Integration of vulnerability with traffic flow impacts by segmentation.

TRAFFIC IMPACTS

For the traffic analyses, the annual average daily traffic (AADT) data were obtained from the Florida Department of Transportation (FDOT) website. Impacts on the traffic flow were estimated by nodes and segmentation approach. The AADT of the affected links were used to estimate the delay characteristics (as vehicle-hr) as presented in Table 7. Based on the spatial analyses, about 3.15 square miles in the case study area is vulnerable for service interruptions which will affect traffic flow significantly. This corresponds to about 58,805 people in the service area.

Table 7. Affected links and expected traffic delays due to pipeline failure.

Affected area	Affected Links (area-direction)	AADT (no of vehicles)	Duration (hr)	Delay (Veh-hr)
A	A-N	130000	0.125	16250.0
	A-S	10000	0.125	1250.0
	A-W	3900	0.125	487.5
B	-	-	-	-
C	C-N	10000	0.125	1250.0
B	-	-	-	-
E	E-N	250	0.125	31.25
	E-S	250	0.125	31.25
	E-E	250	0.125	31.25
	E-W	250	0.125	31.25
F	F-E	5000	0.125	625.0
	F-W	5000	0.125	625.0
G	-	-	-	-
H	H-E	4700	0.125	587.5
	H-W	4700	0.125	587.5
I	I -N	8300	0.125	1037.5
	I -S	8300	0.125	1037.5
	I -E	7200	0.125	900.0
	I -W	7200	0.125	900.0
J	J-N	11000	0.125	1375.0
	J-S	11000	0.125	1375.0
	J-E	7000	0.125	875.0
	J-W	3900	0.125	487.5
K	K-N	19200	0.125	2400.0
	K-S	15300	0.125	1912.5
	K-E	15700	0.125	1962.5
	K-W	11000	0.125	1375.0
Total				37425.0

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CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

A quantitative risk assessment methodology was developed for estimating vulnerability and impacts for linear infrastructure networks (traffic, water and sewer pipelines). The pipeline networks were mapped based on service failure in pipeline systems which can impact the traffic network. The vulnerabilities and potential impacts on traffic flow were quantified using ArcGIS. The methodology developed can be used as a management tool for allocating maintenance efforts to reduce the potential service interruptions and related impacts on the population served and/or to reduce the traffic delays due to pipeline repairs. The spatial analyses in ArcGIS allowed visualization of the vulnerable areas, identification of the areas with different levels of vulnerabilities, as well as quantification of the potential impacts (i.e., area, number of people, traffic delays).

The integrated methodology developed can be used:

- To develop strategies to minimize service interruptions in lifeline systems (i.e., identifying areas where agencies can coordinate maintenance schedules to maximize maintenance efficiencies to improve service quality and reduce cost),
- For developing effective maintenance programs for asset management to improve service quality in the areas served by multiple infrastructure networks,
- For decision-making to improve service quality under dynamic (technical, environmental, social, economic) factors, and
- For improving service quality by smart maintenance planning for integrated transportation and water/sewer infrastructure network service and maintenance programs.

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