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A decision aid GIS-based risk assessment and vulnerability analysis approach for transportation and pipeline networks

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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 with other infrastructure 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 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 by applying for the transportation and pipeline systems infrastructure for the service area in downtown Miami, Florida. The impacts on traffic flow were evaluated by segmentation based on the node-based connections and visualized using ArcGIS. Based on the analyses, about 3.15 square miles in the case study area (17.76 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.

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. Failure in one infrastructure network can result in service disruptions or increase in demand in other infrastructure networks. For example, when a water transmission fails as a result of pipe breakage, the water needs of a community may be met through 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 closure).

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 Eq. (1) (Masse et al., 2007):

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

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

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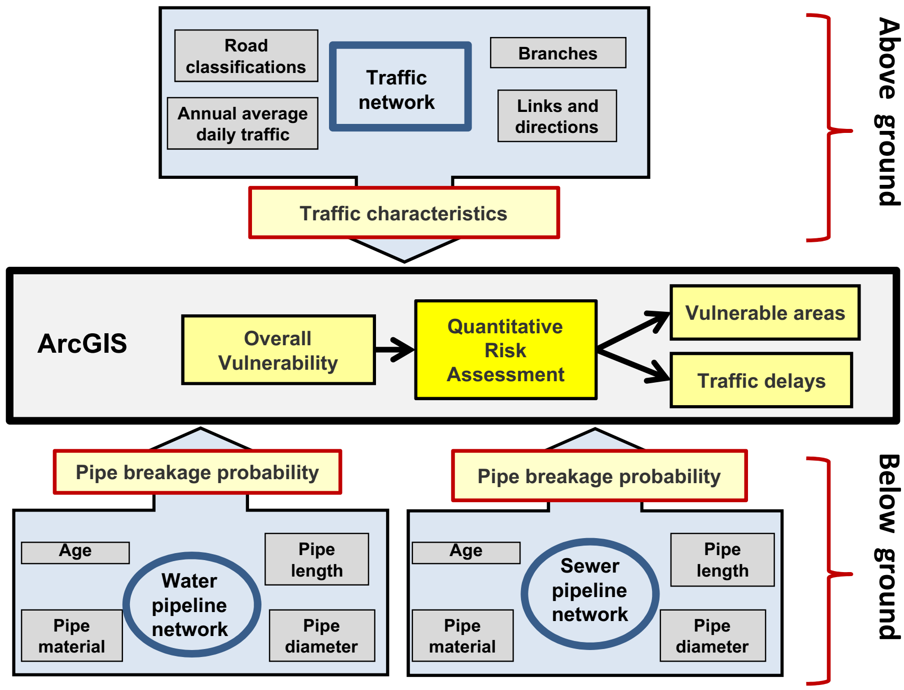

Fig. 1. Framework for the interactive vulnerability assessment of transportation and pipeline networks.

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.

Table 2
Assigned vulnerability factors for the transportation network components.

Transportation network component	Vulnerability	Assigned vulnerability factor
Highway	High	0.5
Collector	Medium	0.3
Other	Low	0.2

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 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). Nobre et al. (2007) assessed groundwater vulnerability and risk mapping based on an index methodology. They used a fuzzy hierarchy methodology to evaluate the indices; employing GIS. In another study, a semi-quantitative model and fuzzy analytic hierarchy approach were employed to assess flood risk in China. Kleiner et al. (2004) applied a fuzzy based Markovian approach to model failure of buried pipelines. 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; Michaud and Apostolakis, 2006; Halfawy et al., 2008; Koonce et al., 2008; Johansson and Hassel, 2010; Seyedshohadaie et al., 2010; 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-Barqawi 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