# Risk-Informed Asset Management Decision Support Model for Interdependent Water and Road Infrastructures

CASE SCHOOL OF ENGINEERING
CASE WESTERN RESERVE UNIVERSITY

UESI Pipelines 2021 Conference
A Virtual Experience | August 3–6, 2021

Ram K. Mazumder, PhD[1,2*]; Abdullah M. Salman, PhD[3]; Yue Li, PhD[1], Xiong Yu, PhD[1]

[1]Case Western Reserve University, Cleveland, OH-44106; [2] University of Kansas, Lawrence, KS 66045; [3]Alabama in Huntsville, Huntsville, AL 35899

Email: rxm562@case.edu

## Summary


- Failure of water pipelines often adversely impacted neighboring assets, especially road networks. This paper investigates interdependency between road and water networks, especially estimate the impact on road and water systems due to the failure of water pipelines beneath the road.
- The probability of water pipeline failures is determined based on a physical probabilistic approach whereas the consequence is estimated by evaluating 14 factors associated with water and road network. A fuzzy-based hierarchical model is developed to integrate the consequence of failure.
- The risk of each integrated road and water segment is determined by utilizing a risk equation. The impact of road and network due to water pipe failure is determined based on the topological shortest-path based network efficiency measure.
- The proposed approach is illustrated for water and road networks of the Rancho Solano, Fairfield, California. This study's outcome reveals that a critical segment's failure may result in significant system efficiency losses for both networks. A critical segment failure resulted in 7.5% and 9.6% system efficiency losses in water and road networks, respectively.


## Methodology

The proposed framework consists of three modules:

(1) **Risk assessment:** the riskiest segments of the water and road networks are identified utilizing a risk equation and a risk matrix. The failure probability of individual pipeline is estimated using a physical probabilistic pipe failure method. 14 factors are used for determining the consequence of the failure of integrated water and road segments.

(2) **Interdependency analysis:** geospatial interdependency is evaluated in GIS to recognize water and road segments that share the same corridor.

(3) **Decision making:** criticality of a components in a network is identified using shortest path based network efficiency. The Networkx python tool is used to determine the network efficiency of a network. The output of the risk analysis and topological analysis are combined to generate decision alternatives for prioritizing maintenance tasks.

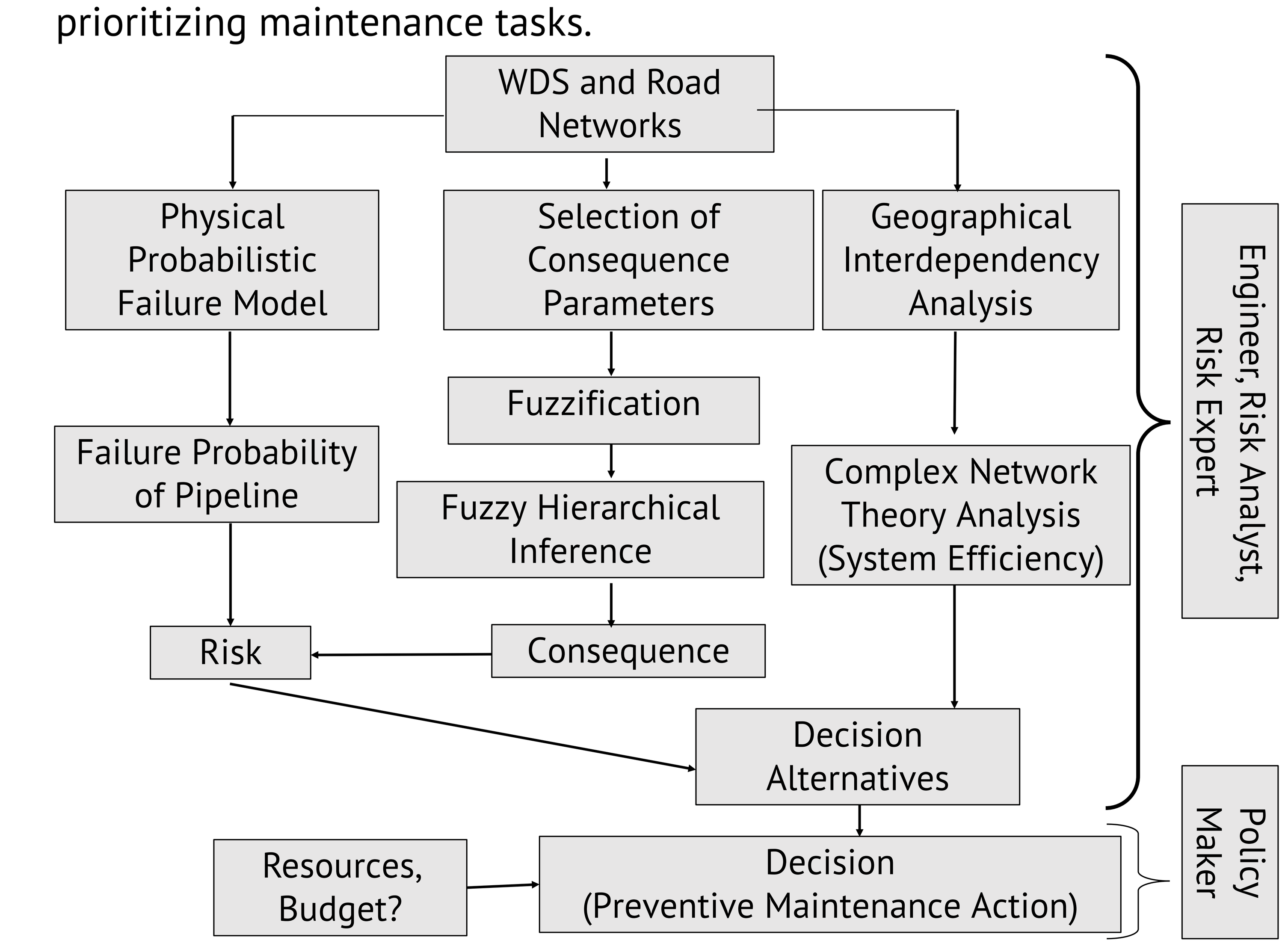
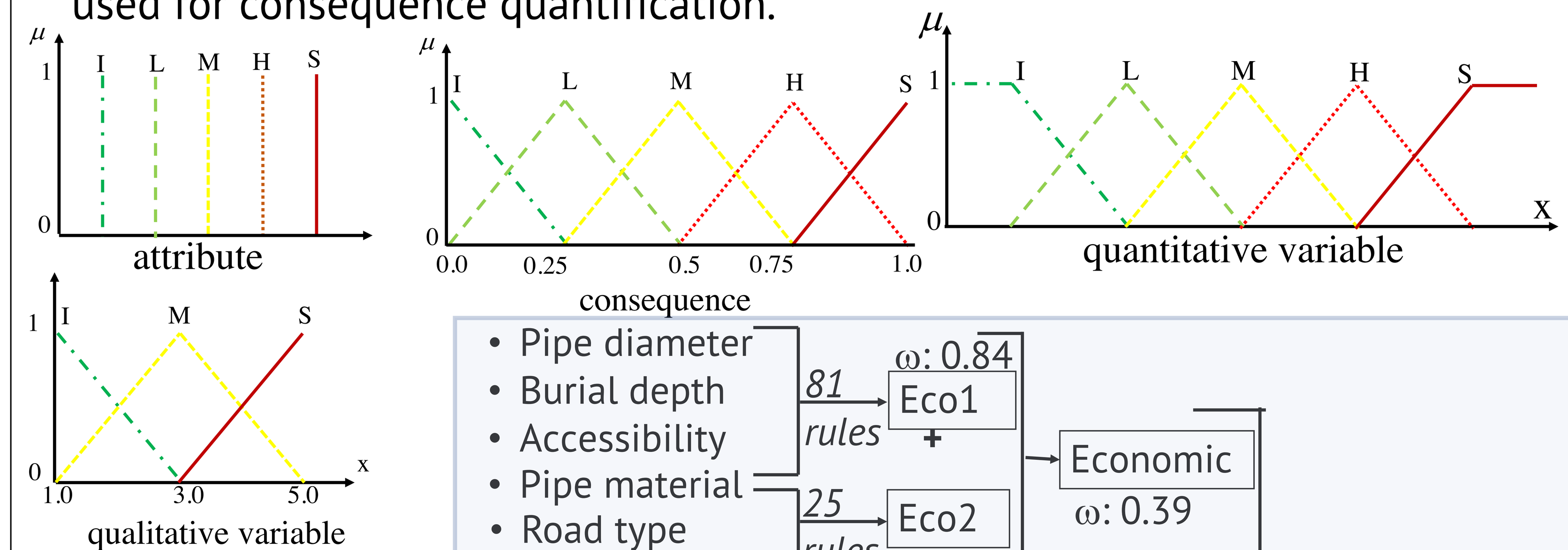



Figure 1: Flowchart of proposed framework

## Fuzzy Model

- **14 consequence factors** are mapped into **fuzzy membership functions**, and Mamdani type input-output rule-based **fuzzy hierarchical inference system** is used for consequence quantification.




$$C_f = \frac{\sum_{i=1}^{n} \bar{A}_i \times c_i}{\sum_{i=1}^{n} \bar{A}_i}$$

**Consequence Quantification using centroid area method**

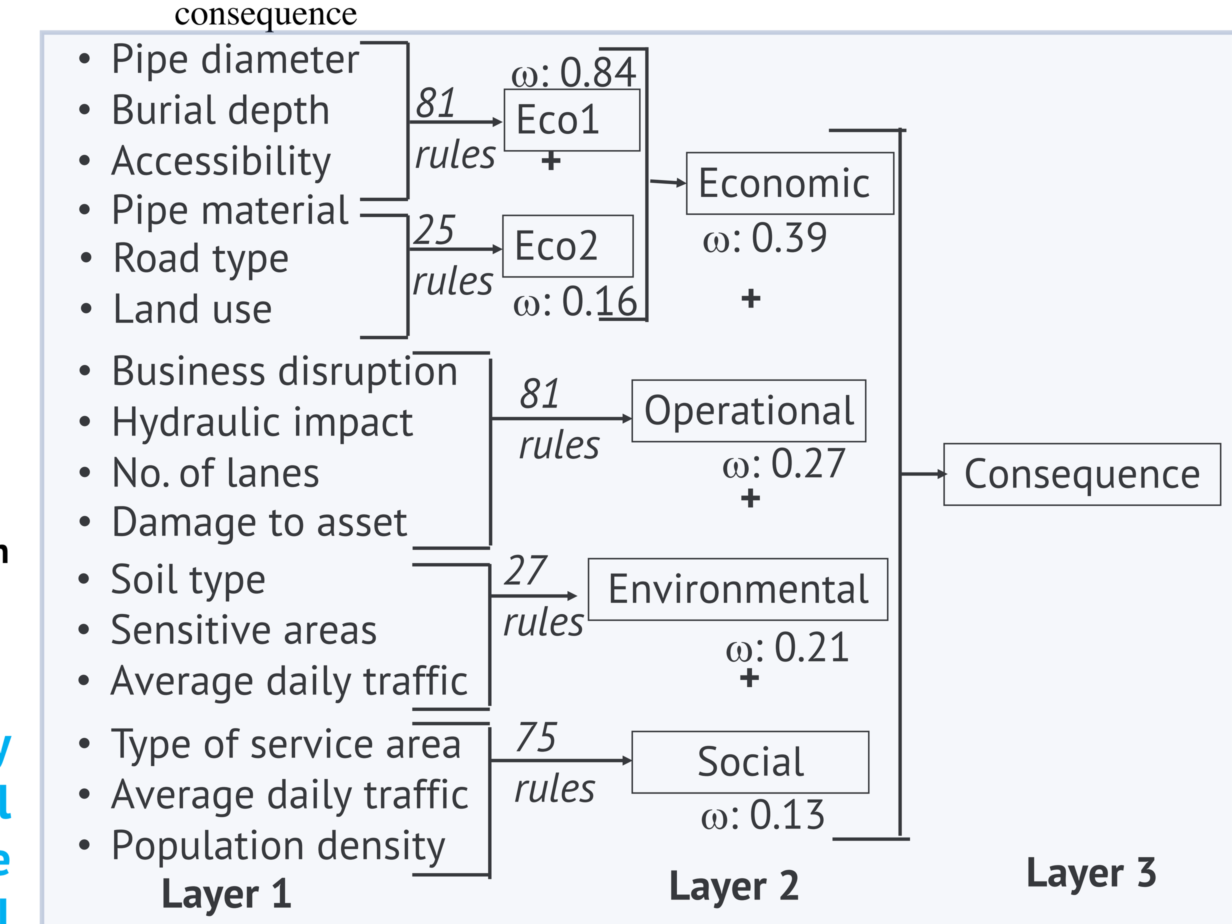



Figure 2: Fuzzy Hierarchical Inference Model

## Risk Analysis

- Infrastructure assets are categorized into five risk groups, based on their performances

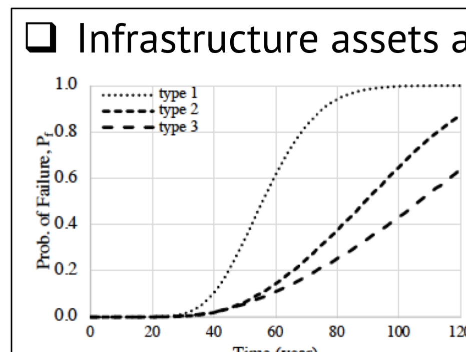



Figure 3: Prob. of Failure

| Likelihood of failure | Grade | Description |
|---|---|---|
| Severe | S | Severe impact on the performance and consequence |
| High | H | Highly influence the performance and at risk |
| Moderate | M | Moderately affect the component |
| Low | L | Minor impact on the performance |
| Insignificant | I | No or very little influence on the performance |

| $P_f$ \ Consequence | 0.0-0.2 | 0.2-0.4 | 0.4-0.6 | 0.6-0.8 | 0.8-1.0 |
|---|---|---|---|---|---|
| 0.0-0.2 | I | I | L | M | M |
| 0.2-0.4 | I | L | L | M | H |
| 0.4-0.6 | L | L | M | H | H |
| 0.6-0.8 | M | M | H | H | S |
| 0.8-1.0 | M | H | H | S | S |

Figure 4: Risk Matrix

## Interdependency Analysis

- The **geospatial interdependency** is evaluated in GIS to recognize water and road segments that share the same corridor in an overlapping buffered layer.
- The **impact on WDS and road network** due to water pipe failure is analyzed using shortest path based network efficiency metric, using the OSMnx tool.

$$\eta(G) = \frac{1}{n(n-1)} \sum_{i=1}^{n} \sum_{\substack{j=1 \\ i \neq 1}}^{n} \frac{1}{d_{ij}}$$

$$I_\eta(l) = \frac{\eta(G) - \eta(\bar{G})}{\eta(G)}$$

$$DI = \text{Weight of Risk} \times \text{Normalized Risk} + \text{Weight of } I_\eta \times \text{Normalized } I_\eta$$

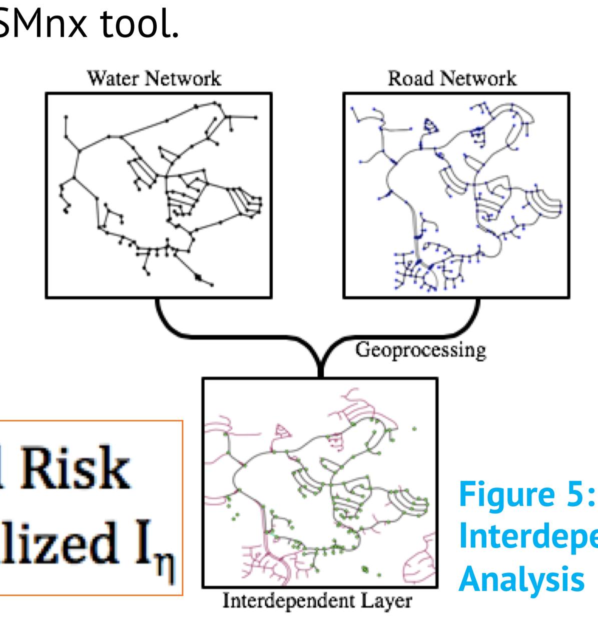
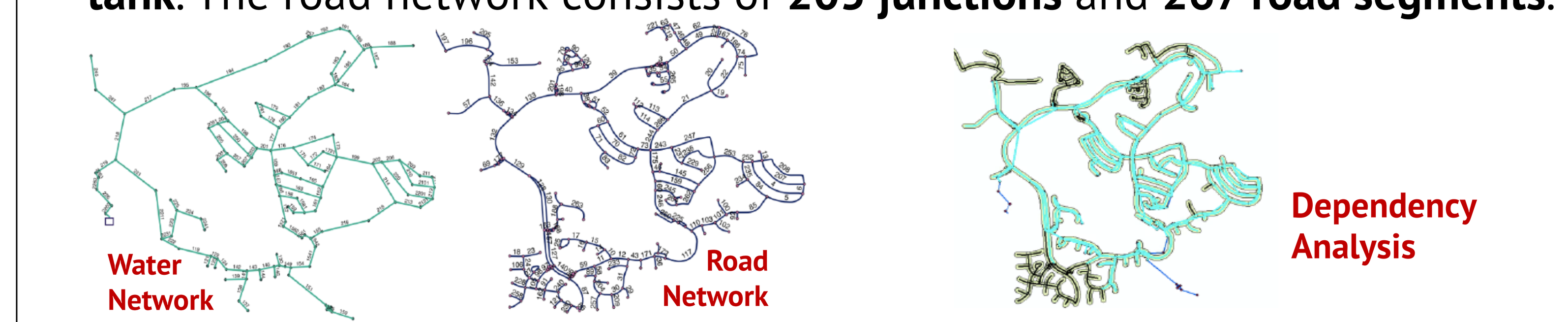



Figure 5: Interdependency Analysis

## Case Study

- The water and road networks of **Rancho Solano, Fairfield, California**, are used. The water network is composed of **111 nodes, 126 pipes, and 1 water tank**. The road network consists of **205 junctions** and **267 road segments**.



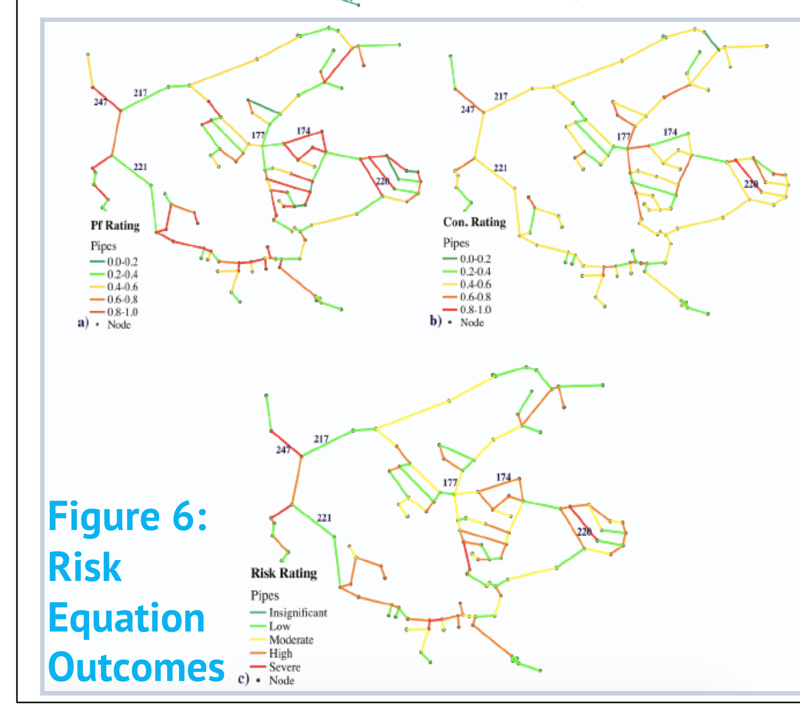



Figure 6: Risk Equation Outcomes

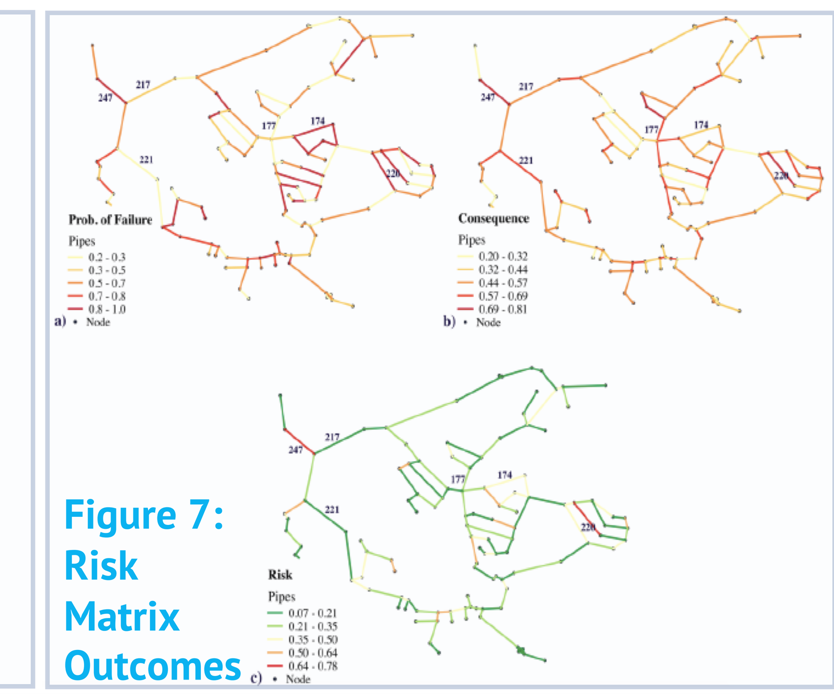


Figure 7: Risk Matrix Outcomes

## Decision Analysis and Impact Assessment

Figure 8: Normalized network impact index

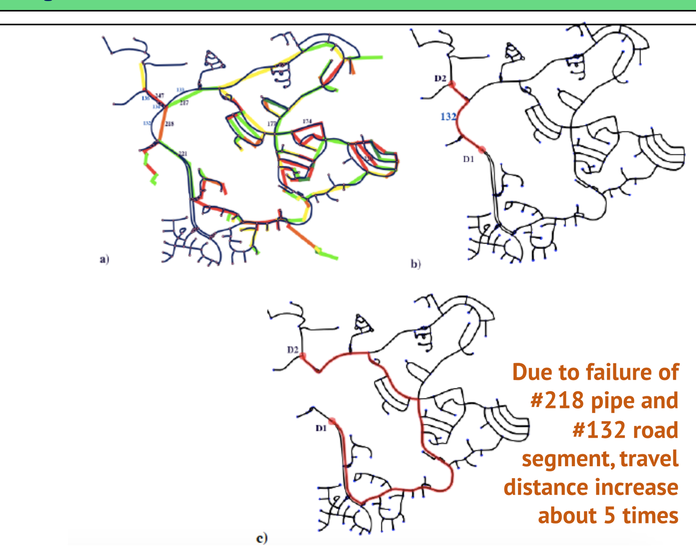



Figure 10: Impact Analysis

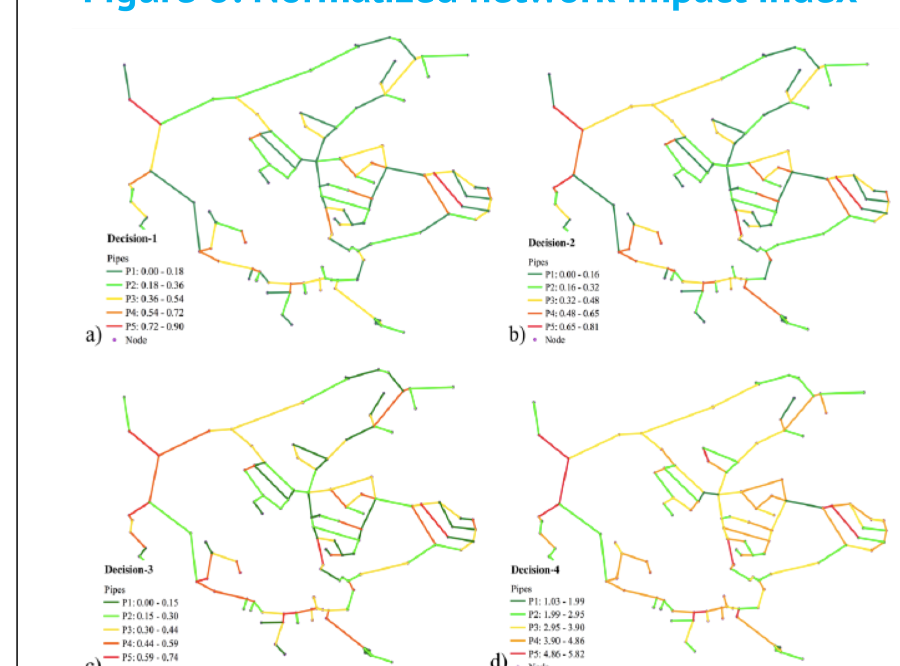


Figure 9: Decision Alternatives

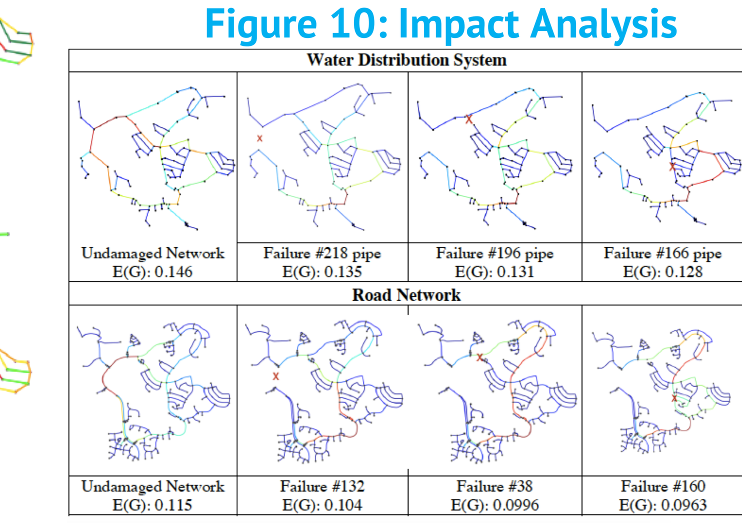



Figure 11: Network Efficiency Outcomes

## Conclusions

- **Four decision scenarios are developed** in this study, combining outputs from the risk analysis and the network criticality analysis.
- The case study showed that the identification of **critical components provides useful information about the post-failure consequence** at the system level.
- It was observed that due to the failure of a single segment (one of the riskiest pipelines and dependent road links) in the critical part, **the network efficiencies of WDS and road network might drop by 7.5% and 9.6%, respectively.**

**Further detail of this study can be found here:**

Mazumder, R. K., Salman, A. M., Li, Y., & Yu, X. (2021). Asset Management Decision Support Model for Water Distribution Systems: Impact of Water Pipe Failure on Road and Water Networks. Journal of Water Resources Planning and Management, 147(5), 04021022.

**Acknowledgement:**

The research described in this paper was supported, in part, by the National Science Foundation (NSF) Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) under Grant No. NSF– 1638320.