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Computational Risk Assessment in Water Distribution Network

Yas Barzegar[1], Atrin Barzegar[2], *Stefano Marrone[2], Laura Verde[2], Francesco Bellini[1], and Patrizio Pisani[3]*

[1] Department of Management, Banking and Commodity Sciences, Sapienza University, Rome, 00161
{yas.barzegar,francesco.bellini}@uniroma1.it
[2] Universit. degli Studi della Campania "Luigi Vanvitelli", Mathematics and Physics Department, Viale Lincoln n°5, Caserta 81100, Italy
{atrin.barzegar,stefano.marrone,laura.verde}@unicampania.it
3 Unidata S.p.A., Viale A. G. Eiffel, 00148 Roma, Italy
patrizio.pisani@unidata.it

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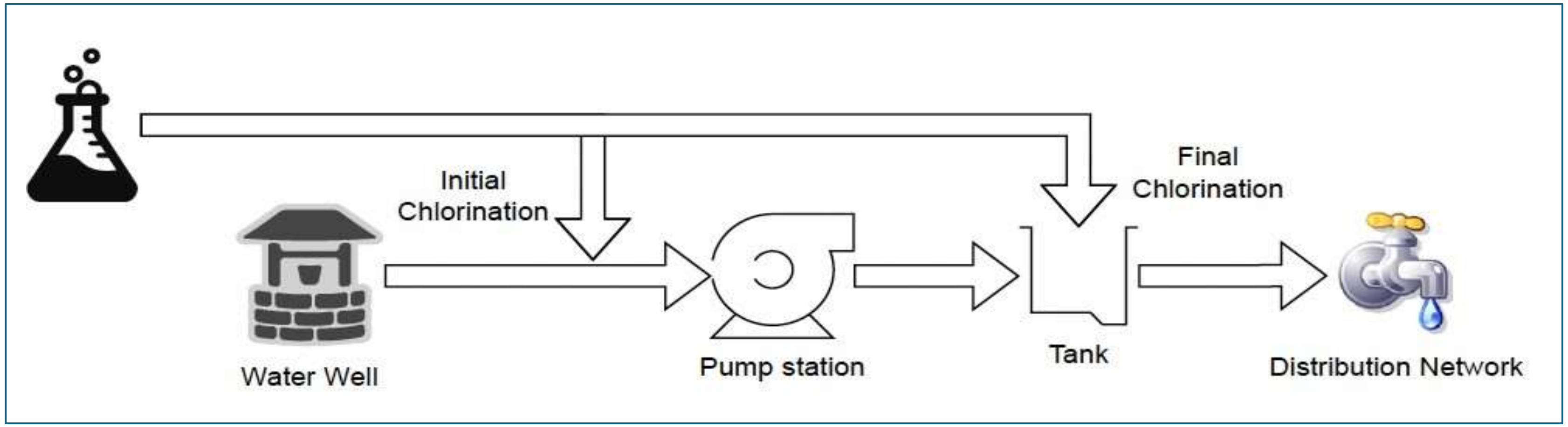
Abstract

- This study introduces a two-stage Mamdani Fuzzy Inference System (M-FIS) for assessing risks in Water Distribution Networks.
- It evaluates hazards across wells, tanks, and pump stations using fuzzy logic based on Occurrence, Severity, and Detectability.
- Monte Carlo Simulation enhances result robustness by accounting for uncertainty in risk factors.
- Tanks were identified as the highest-risk component when the model was applied to Hashtgerd, Iran.
- The approach supports informed decision-making through interpretable, data-light risk evaluation.
- Recommendations include zoning control, infrastructure upgrades, and real-time monitoring systems to reduce overall network risk.

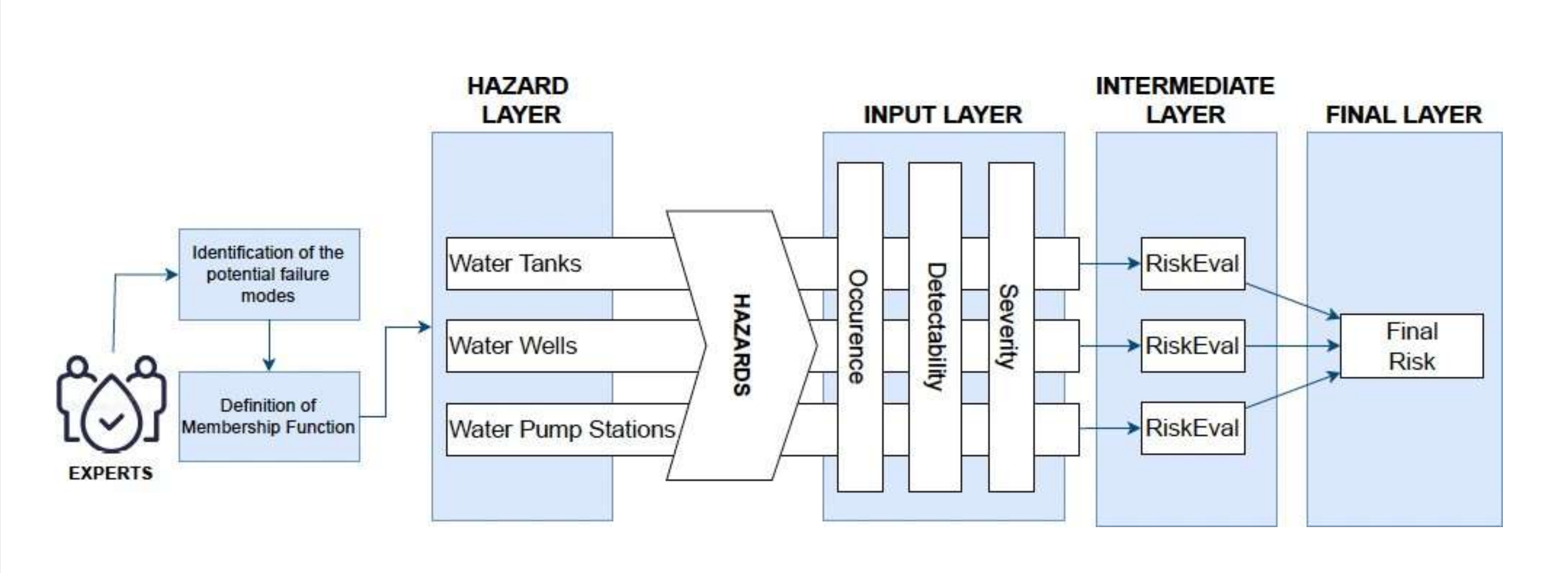
Introduction

- Water Distribution Networks (WDNs) are essential for delivering clean and safe water to urban populations.
- Aging infrastructure, environmental stress, and increasing demand pose significant risks to system reliability.
- Traditional risk assessment methods often struggle with uncertainty and incomplete data.
- This study adopts a fuzzy logic-based approach to enhance risk analysis under uncertain conditions.
- The goal is to support proactive maintenance and strategic decision-making in critical water systems.
- The methodology is tested on a real-world case study to demonstrate its effectiveness and adaptability.



Water Network Infrastructure

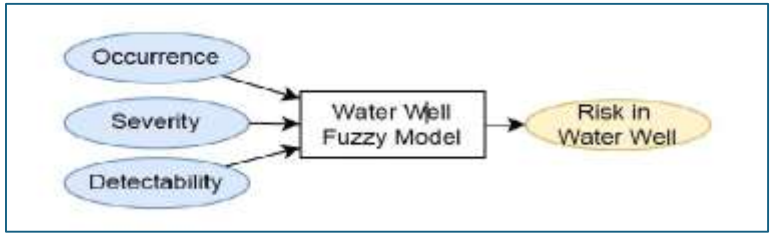
Structure of the Proposed Model



Methodology

Fuzzy Inference System Type: Two-stage Mamdani FIS

- Inputs: Occurrence, Severity, Detectability
- Output: Risk Level



Risk in Water Wells

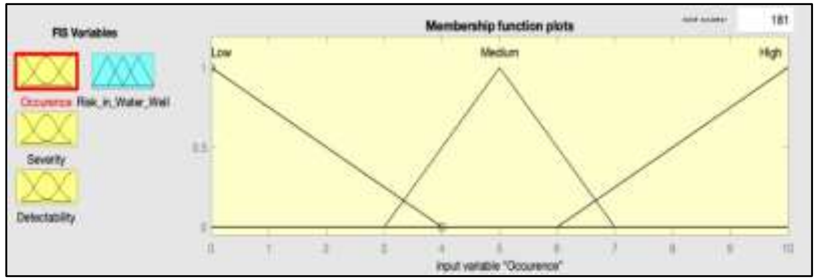
- Membership Functions:
  - Type: Triangular (for simplicity and computational efficiency)
  - Granularity: 3 levels per input (Low, Medium, High)

$$\mu_A(x) = \begin{cases} 0 & \text{if } x \le a \text{ or } x \ge c \\ (x - a)/(b - a) & \text{if } a < x \le b \\ (c - x)/(c - b) & \text{if } b < x < c \end{cases}$$

a : lower bound

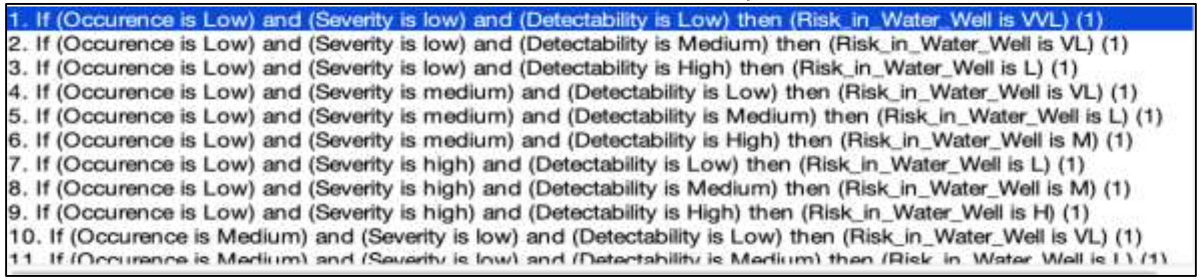
b : peak value

c : upper bound



Membership Functions

- Rule Base:
  - Expert-driven rule matrix consists of 27 Rules for each model
  - Combined in a hierarchical manner for subsystem evaluation



1. If (Occurence is Low) and (Severity is low) and (Detectability is Low) then (Risk_in_Water_Well is VVL) (1)
2. If (Occurence is Low) and (Severity is low) and (Detectability is Medium) then (Risk_in_Water_Well is VL) (1)
3. If (Occurence is Low) and (Severity is low) and (Detectability is High) then (Risk_in_Water_Well is L) (1)
4. If (Occurence is Low) and (Severity is medium) and (Detectability is Low) then (Risk_in_Water_Well is VL) (1)
5. If (Occurence is Low) and (Severity is medium) and (Detectability is Medium) then (Risk_in_Water_Well is L) (1)
6. If (Occurence is Low) and (Severity is medium) and (Detectability is High) then (Risk_in_Water_Well is M) (1)
7. If (Occurence is Low) and (Severity is high) and (Detectability is Low) then (Risk_in_Water_Well is L) (1)
8. If (Occurence is Low) and (Severity is high) and (Detectability is Medium) then (Risk_in_Water_Well is M) (1)
9. If (Occurence is Low) and (Severity is high) and (Detectability is High) then (Risk_in_Water_Well is H) (1)
10. If (Occurence is Medium) and (Severity is low) and (Detectability is Low) then (Risk_in_Water_Well is VL) (1)
11. If (Occurence is Medium) and (Severity is low) and (Detectability is Medium) then (Risk_in_Water_Well is L) (1)

Fuzzy Rules

- Defuzzification Method: Centroid (Center of Gravity)

$$R^* = \frac{\sigma_i \, \mu_i(x).xi}{\sigma_i \, \mu_i(x)}$$

R*: final risk value

- Why Mamdani: Prioritizes interpretability with linguistic rule-based design
- Integration: Coupled with Monte Carlo Simulation for uncertainty handling.

$$RPN = (1 / N) \times \Sigma_{i=1}^{n} (S_i \times O_i \times D_i)$$

Results

Risk Evaluation in Water Wells

Hazard	O	S	D	Risk	Critical Level
Wells near highways and busy routes	7	8	8	92.9	VVH
Soil conditions of the area	6	8	8	83.3	VH
Urban activities, pollution sources	7	6	8	83.3	VH
Contaminated aquifer(treated wastewater recharge-hardness/TDS)	5	7	8	83.3	VH
Intentional contamination of water through sabotage operations	4	8	8	83.3	VH
Contaminated aquifer (toxic minerals - wastewater recharge)	4	7	8	83.3	VH
Poor well maintenance, corrosion, casing issues	6	6	6	50	M
Lack of proper wellhead protection	4	7	7	83.3	VH
Insufficient perimeter and physical security	3	8	8	66.7	H
Physical attacks	6	6	5	50	M
Encroachment on buffer zone	3	5	8	50	M
Forestry and agricultural activities	3	5	8	50	M
Direct injection of well water into the network	2	5	6	33.3	L
Animal husbandry and livestock activities	1	6	7	50	M
Industrial and mining activities	1	4	7	50	M
Final Risk of Water Wells				**66.18**	**H**

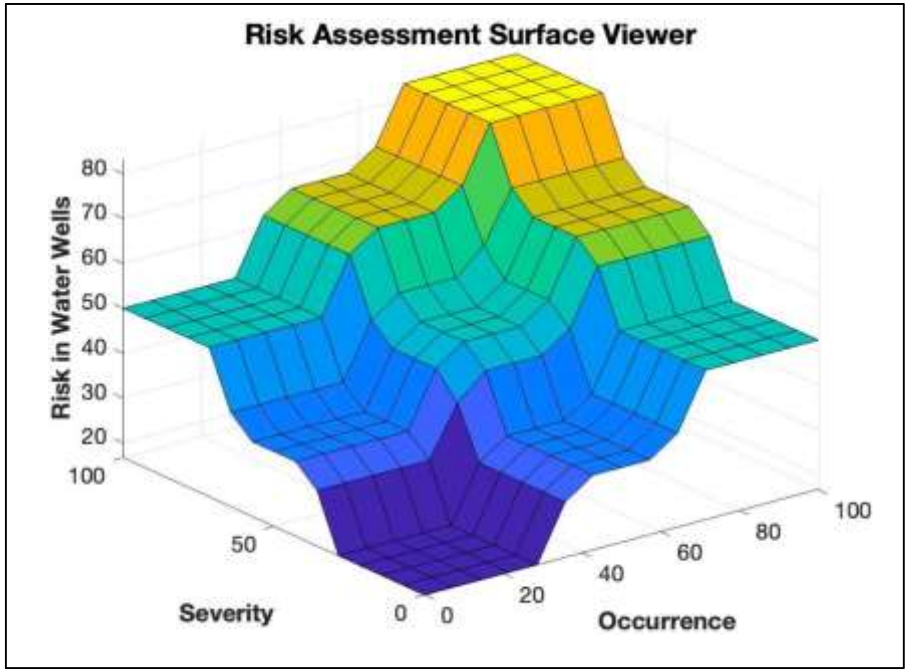
Risk Evaluation in Water Pump Station

Hazard	O	S	D	Risk	Critical Level
Long lifespan of the pumping station and transmission network	8	7	7	92.9	VVH
Chlorination near high-traffic areas	7	7	8	92.9	VVH
Water pressure and flow fluctuations	8	6	7	83.3	VH
Erosion and corrosion of infrastructure facilities	8	7	6	83.3	VH
Short distance of water pipes to sewage networks and wells	7	6	6	66.7	H
Deliberate contamination of water during sabotage operations	6	8	4	66.7	H
Inadequate perimeter and physical security	8	5	4	66.7	H
Deficiency and absence of warning and monitoring equipment	5	5	6	50	M
Lack of emergency power	4	6	6	50	M
Weak performance and deficiencies in the disinfection system	7	4	5	66.7	H
Improper storage of chemicals	4	4	4	50	M
Unprotected, open facilities with leaks	4	3	4	33.3	L
Average Risk of Water Pump Station				**66.87**	**H**

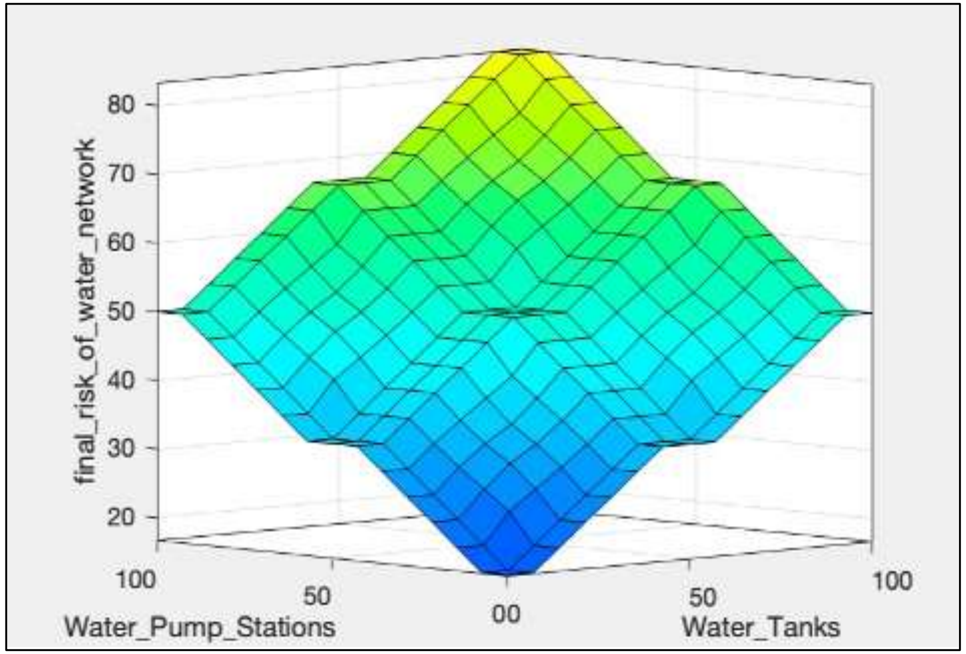
Risk Evaluation in Water Tank

Hazards	O	S	D	Risk	Critical Level
Physical attacks	8	8	9	93.8	VVH
Erosion and corrosion of infrastructure facilities	8	8	8	93.8	VVH
Chlorine storage near high-traffic areas	9	7	8	92.9	VVH
Pressure fluctuations and changes in flow	7	8	7	92.9	VVH
High lifespan of the distribution network	8	8	6	83.3	VH
Illegal and unauthorized connections	7	6	8	83.3	VH
Inadequate perimeter and physical protection	7	6	8	83.3	VH
Deliberate contamination of water during sabotage operations	5	7	8	83.3	VH
Very close distance of water pipes to sewage networks and wells	6	5	7	66.7	H
Lack of warning/monitoring equipment	7	5	5	66.7	H
Delayed cleaning of tanks	4	6	7	66.7	H
Improper storage of chemicals	5	3	5	33.3	L
Unprotected, open tanks with leaks	3	5	5	33.3	L
Weak performance and deficiencies in the disinfection system	3	6	4	33.3	L
Average Risk of water tank				**71.9**	**VH**

Results:Surface Viewer



Surface viewer of risk related to water wells hazard



The surface viewer of the final risk

Conclusion

- A fuzzy logic-based risk assessment model was employed for the Hashtgerd, Iran water distribution network.
- The model uses a two-stage Mamdani FIS to evaluate hazards in wells, tanks, and pump stations.
- Triangular membership functions and centroid defuzzification enabled accurate risk quantification.
- Water tanks have the highest average risk (71.9%), highlighting infrastructure vulnerabilities.
- The method supports prioritizing maintenance, security, and mitigation strategies.
- This flexible approach can be applied to other urban areas with diverse infrastructure profiles.
- Results emphasize the need for real-time monitoring, proactive zoning, and structural upgrades.

Future work:

- Integration with AI and IoT technologies could enhance future risk prediction and responsiveness. We can add other components of the water distribution network in order to have a more accurate model.