Norwegian University of Life Sciences

UNIVERSITAS GALATIENSIS

Risk assessment of urban water infrastructure (Part I: *Concepts & methods*)

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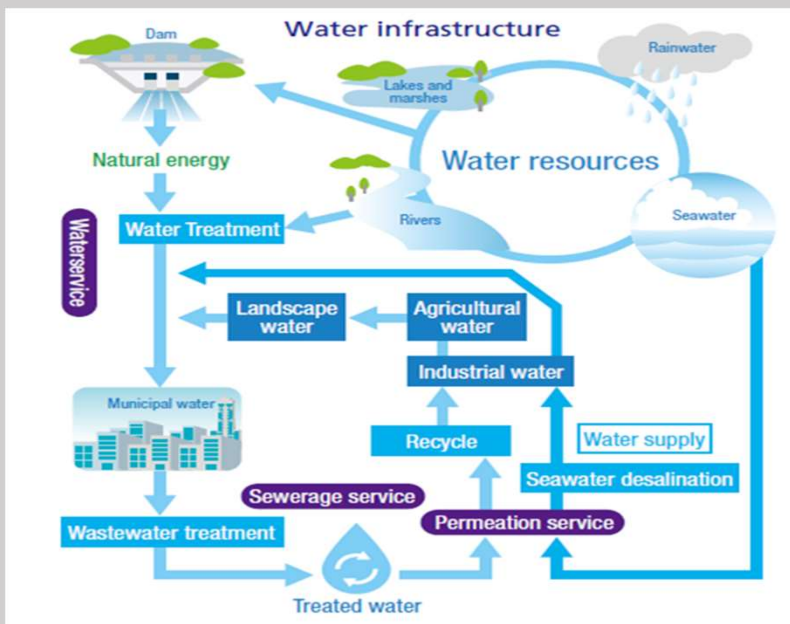
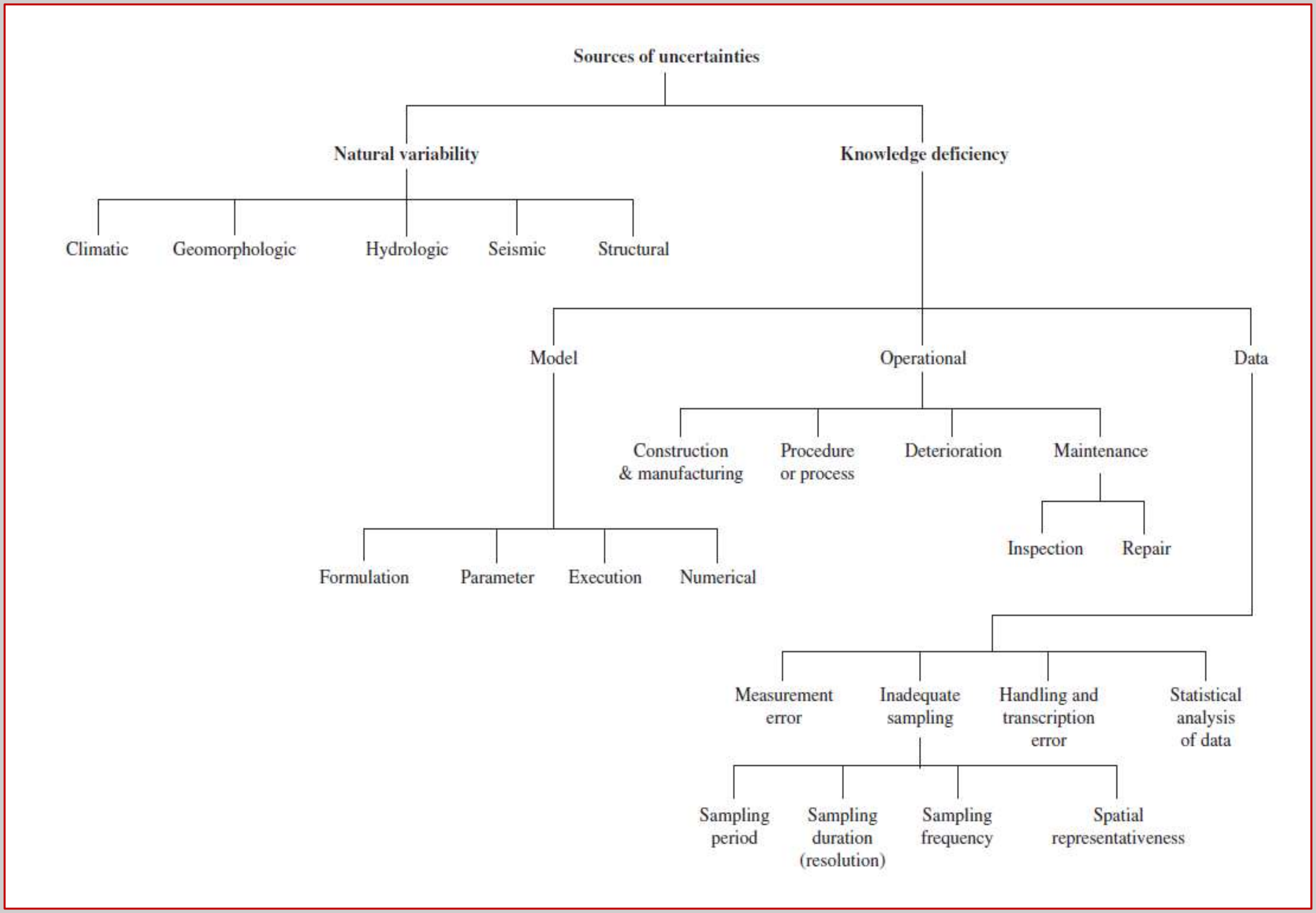
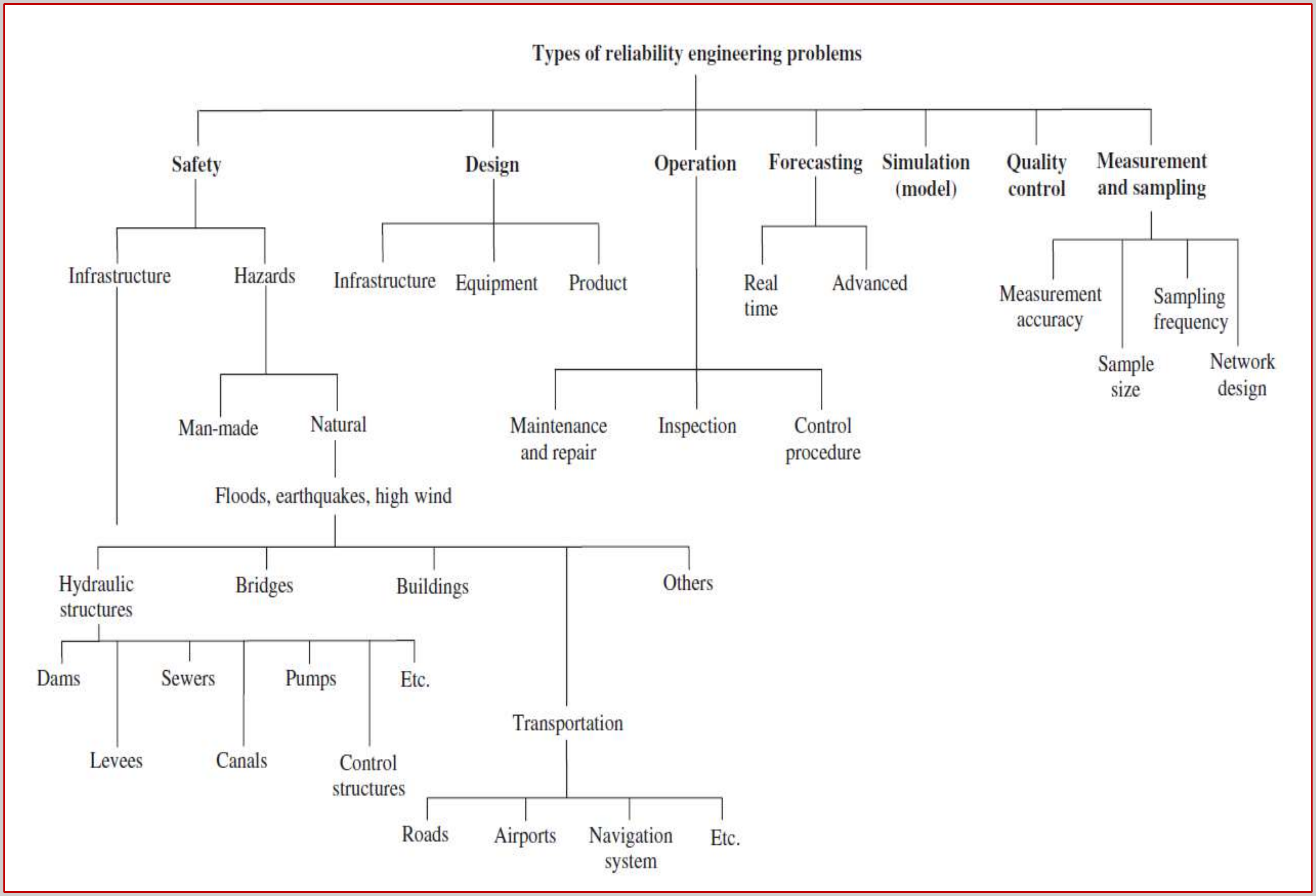


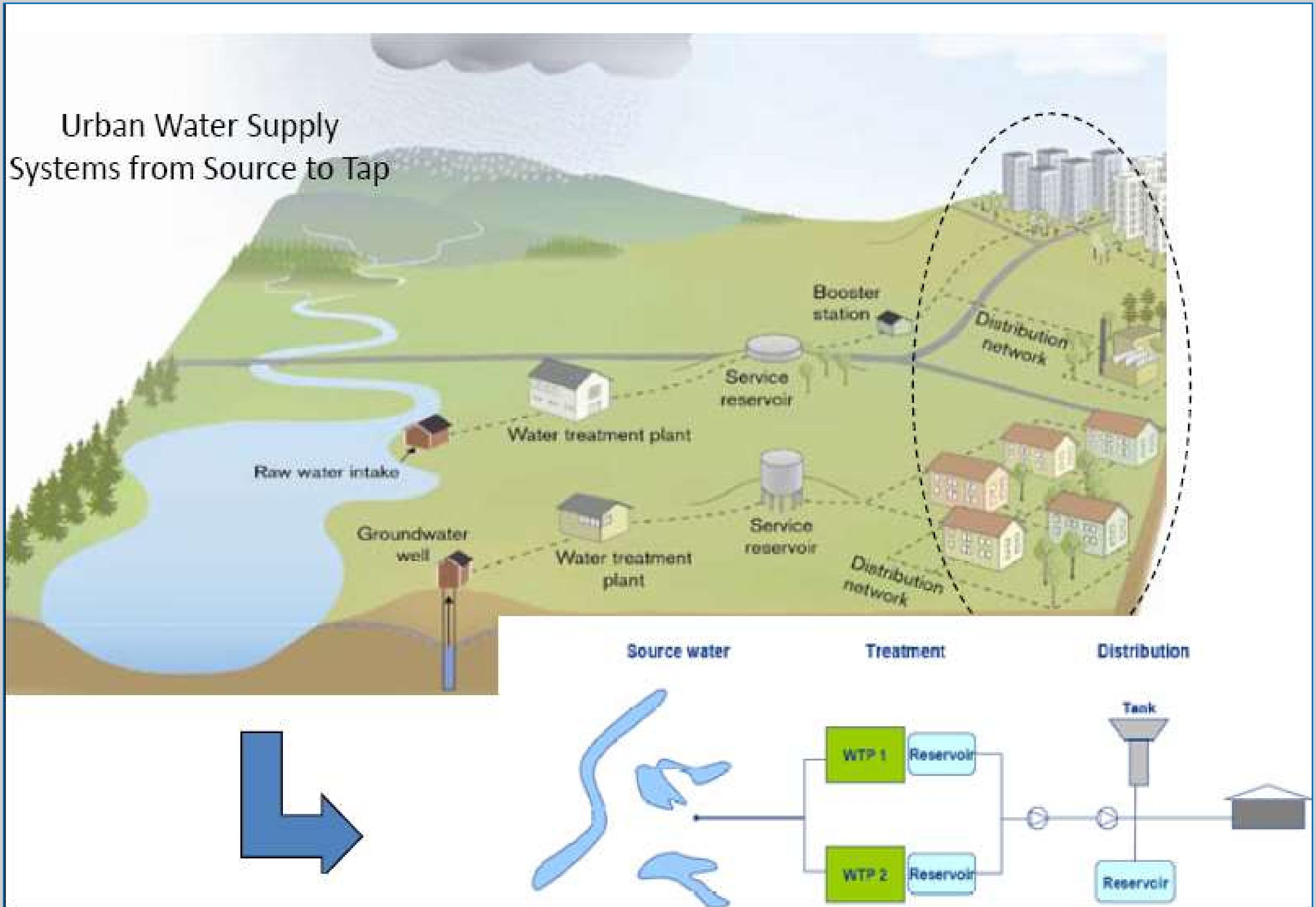
University of Galati, June 2023

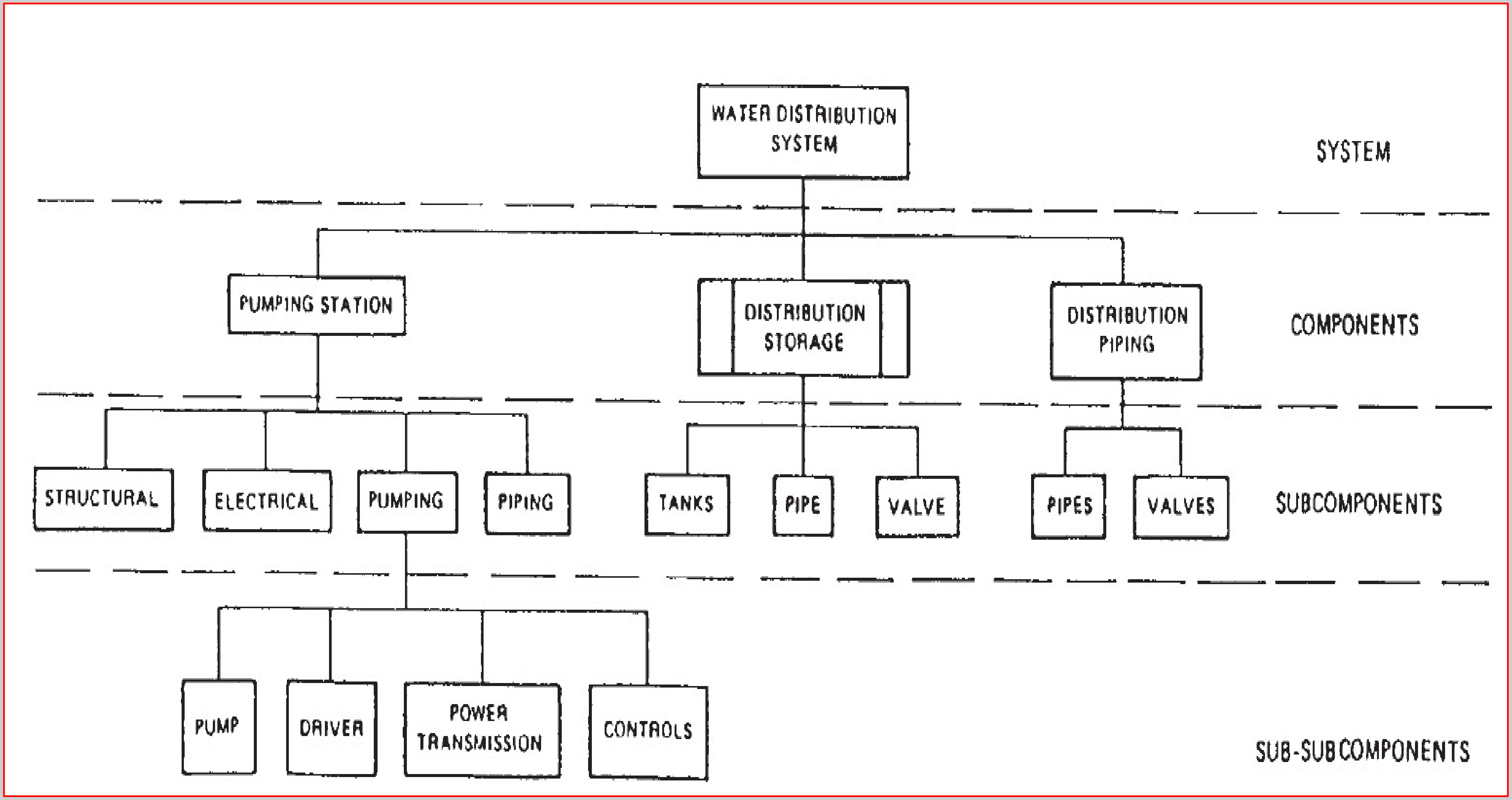
The performance of a hydrosystem infrastructure or function of an engineering project, involve a number of contributing components, and most of them are subject to various types of *uncertainty!* Reliability and risk, generally are associated with the system as a whole. Thus, methods to account for the component uncertainties and to combine them are required to yield the system reliability.



The basic idea of ***reliability and risk engineering*** is to determine the failure probability of an engineering system, from which the safety of the system can be assessed, or a rational decision can be made on the design, operation, or forecasting of the system




Urban Water Supply
Systems from Source to Tap
Booster station
Service reservoir
Distribution network
Water treatment plant
Raw water intake
Groundwater well
Water treatment plant
Service reservoir
Distribution network
Source water
Treatment
Distribution
Tank
WTP 1
Reservoir
WTP 2
Reservoir
Reservoir



Hierarchical relationships for a water distribution system

Natural hazards and human related threats to a water supply system

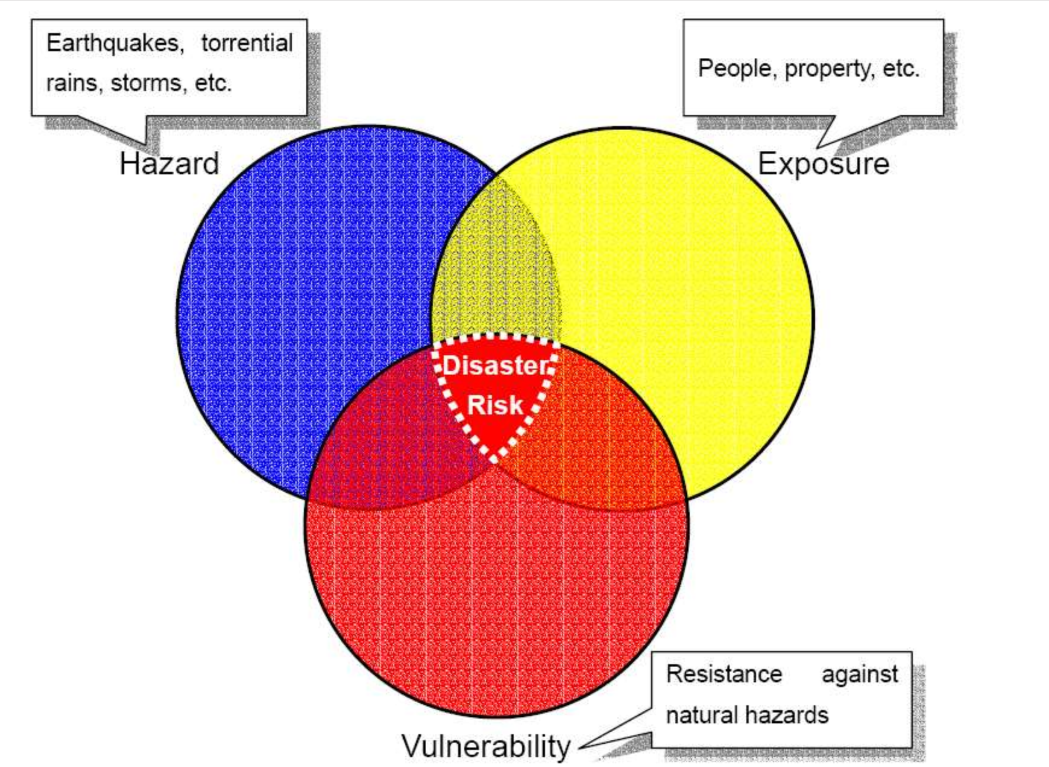
Threats and hazards		Consequences
Natural hazards	Earthquake	• Pipe breaks • Loss of power • Structure collapse
	Flooding	• Loss of treatment plant • Contamination of distribution system
	Drought	• Water shortages • Water quality problem
	Wind	• Flood-induced problems • Structure damage • Loss of power
	Water born diseases	• Sickness • Death • Loss of public confidence
	Severe weather	• Frozen pipes, • Outages and leaks • High water use
Human-related threats	Cyber threats	• Physical disruption of SCADA (supervisory control and data acquisition) network • Attacks on central control system to create simultaneous failures • Electronic attacks using worms and viruses • Network flooding • Jamming • Disguising data to neutralize chlorine or add no disinfectant, allowing addition of microbes
	Physical threats	• Physical destruction of system's assets or disruption of water supply is more likely than contamination • Loss of water pressure compromising firefighting capabilities and could lead to possible bacterial build-up in the system • Potential for creating a water hammer effect by opening and closing major control valves and turning pumps on and off too quickly, which could result in simultaneous main breaks.
	Chemical/Biological threats	• Heath problems, or death of customers • Panic • Loss of public confidence

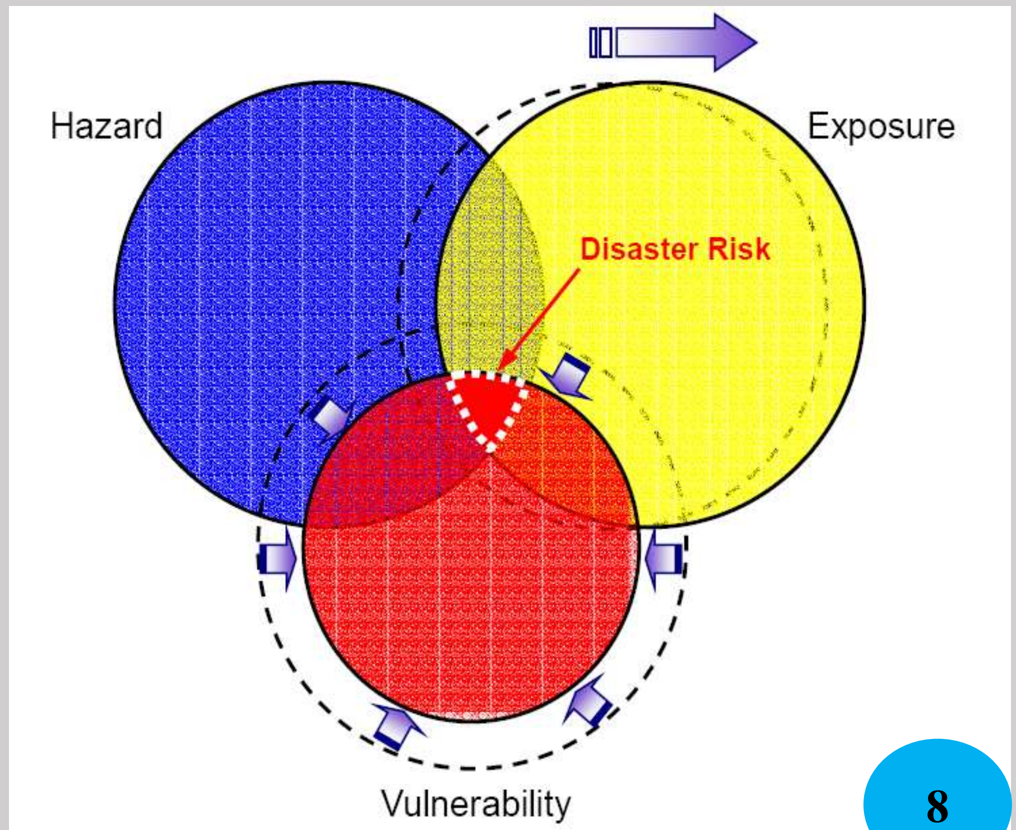
*Source: Grigg (2003) and Mays (2004)

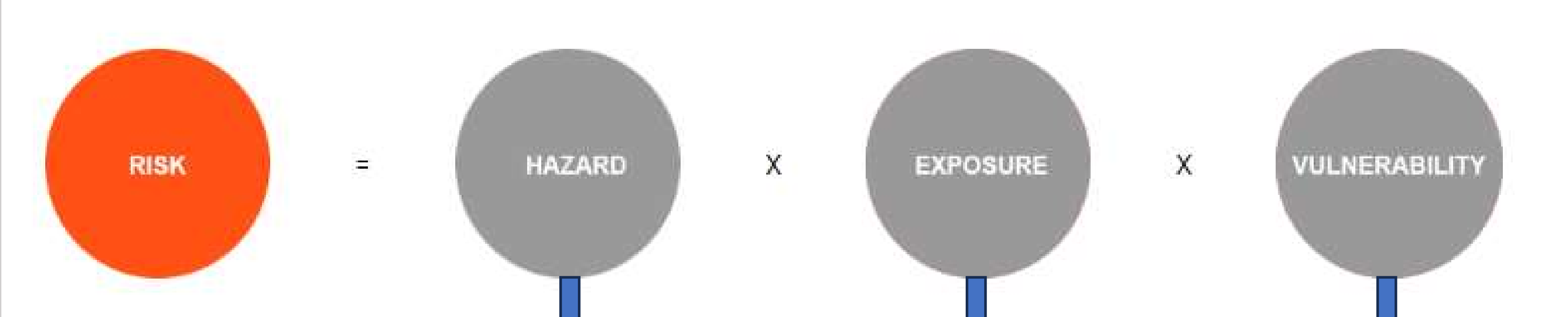
Hazards or threats associated with basic components in a water supply system (WHO, 2004)

Basic components	Failure states	Hazards/Threats	Relative risk
Water source	Natural hazards failure	Drought	Reduced water quantity
	Natural hazards failure	Flood Underground minerals	Water contamination
	Human-caused threat	Sewage discharge Industrial discharge Livestock Chemical/biological	Water contamination
	Interdependence failure	Spills Contaminated site	Water contamination
Water treatment plant	Natural hazards failure	Earthquake Flood	Reduced water quantity and water contamination
	Human-caused threat	Chemical/biological	Water contamination
	Operational failure	Process control Equipment failure Alarm and monitoring Inadequate backup Inappropriate treatment	Reduced water quantity and water contamination
	Interdependence failure	Power failure	Reduced water quantity and water contamination
	Interdependence failure	Contaminated material	Water contamination
Pipe	Natural hazards failure	Earth movement	Reduced water quantity
		Flood	Reduced water quantity and water contamination
	Operational failure	External load Temperature Internal pressure Natural deterioration	Reduced water quantity
	Operational failure	Regrowth of organism Leaching of chemicals	Water contamination
	Interdependence failure	Contaminated water Contaminated soil	Contamination
Pump	Natural hazards failure	Earthquake Flood	Reduced water quantity
	Human-caused threat	Bombing	Reduced water quantity
	Operational failure	Control failure Equipment failure Alarm and monitoring Inadequate backup Age	Reduced water quantity
	Interdependence failure	Power failure	Reduced water quantity
Storage	Natural hazards failure	Animal Rainfall	Water contamination
	Human-caused threat	Disruption of structure	Reduced water quantity
	Human-caused threat	Chemical/biological Contaminated water	Water contamination

Risk is the probability of a loss that depends on three aspects: hazard, vulnerability, and exposure.





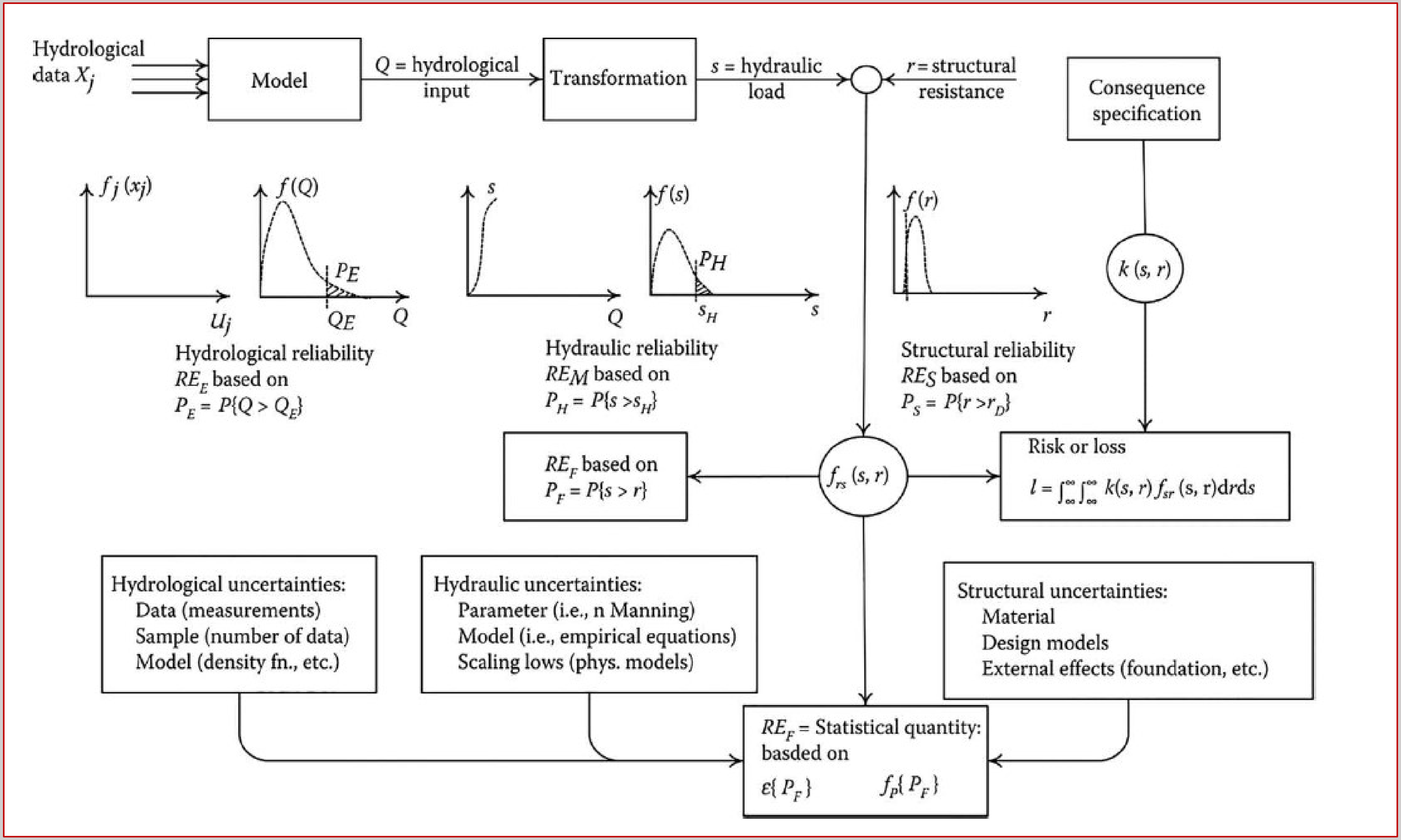


A hazard is a process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation. Hazards may be natural, human-made or socio-natural in origin.

The situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas.

The characteristics determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards.

https://www.youtube.com/watch?v=MeCw010x8H8



Generalized concept of risk and reliability analysis for water systems

In another view, risk of an attack can be measured as the product of consequence, threat, and vulnerability:

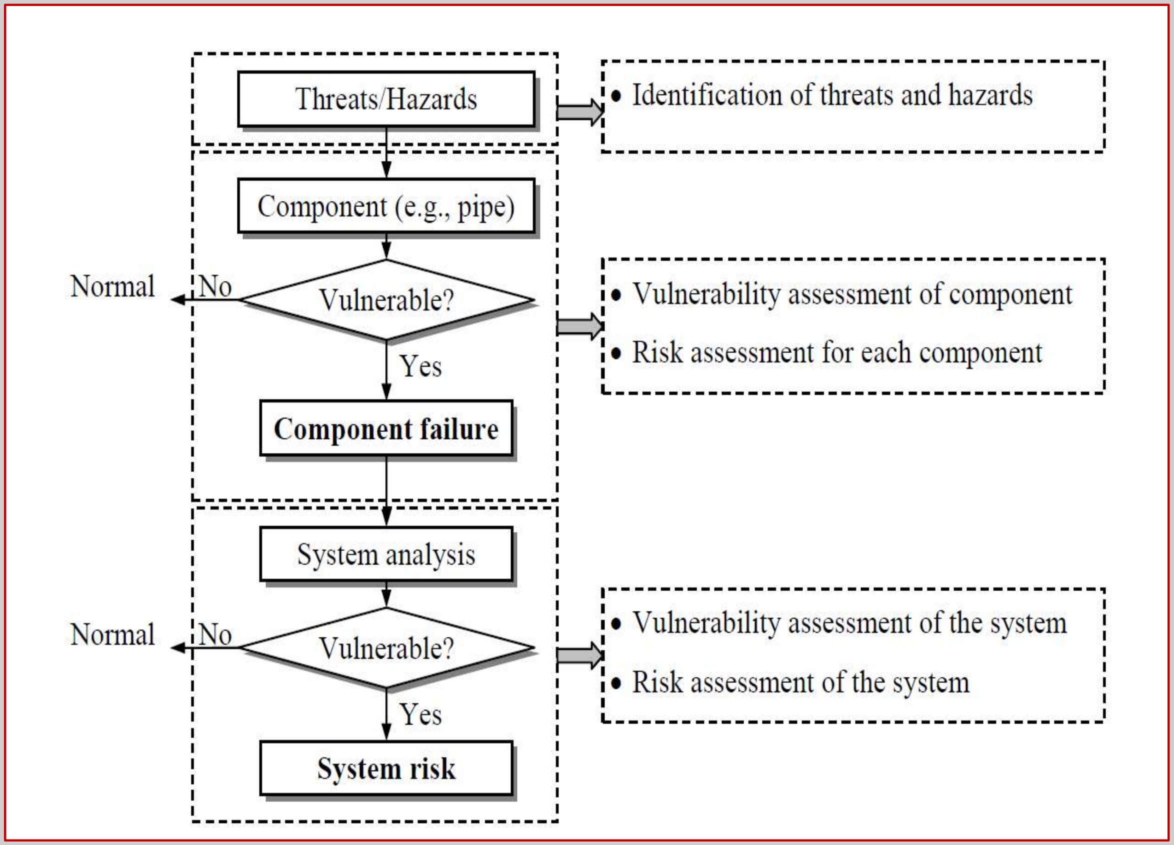
Risk= f(C, T, V)

where R is the overall risk, C are the consequences measured by loss of life, economic impact, loss of public confidence, or other metrics, T are the threats characterized by their likelihood of occurrence, and V is the vulnerability which is defined as a property associated with a component of the system to reduce the possibility of being influenced by hazards with given likelihood and consequence. The third axiom is that system vulnerability is a function of component access and exposure!

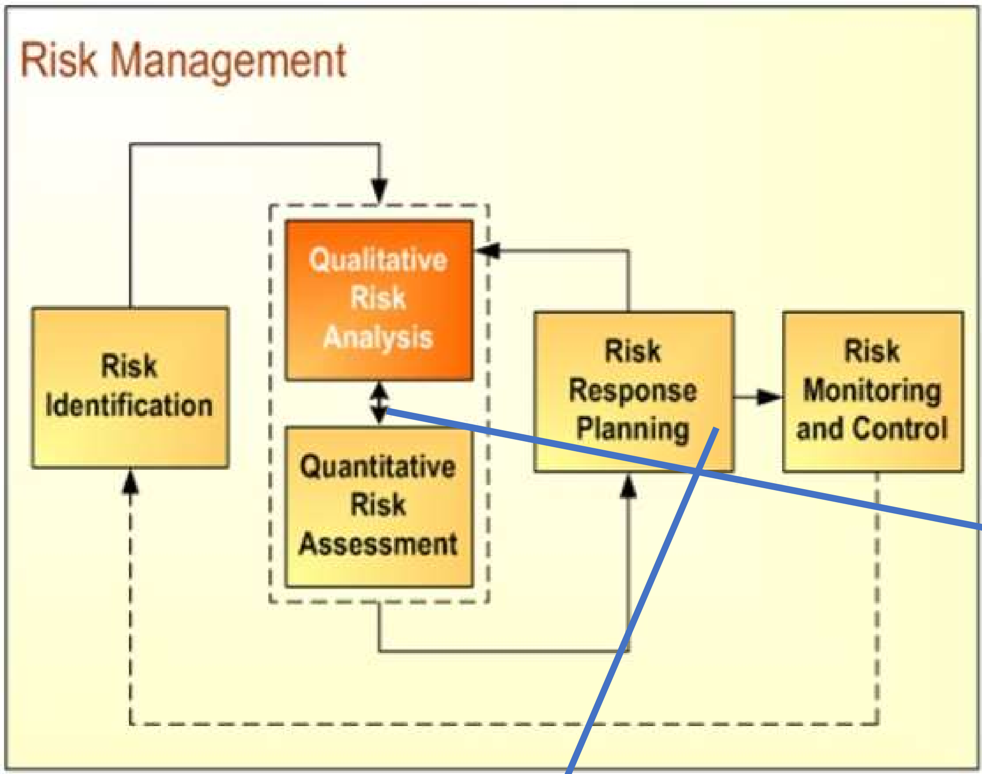
Risk= Likelihood × consequence × Vulnerability

Risk assessment of a water supply system is usually expressed as a process of identifying threats/hazards, analyzing vulnerabilities of components and system, and evaluating risks of components and system (Li and Vairavamoorthy, 2004).

- A comprehensive approach in assessing the performance of each component and reducing their vulnerability can lead to cost reduction of inappropriate performance in critical situations and also a focus on the most important vulnerable parts to increase their reliability.
- There are several reliability and risk assessment models for urban water systems varies from simple qualitative analysis to complicated quantitative analysis.



General procedure of risk assessment in a water supply system



- Probability-impact Matrix
- Risk Register
- HAZOP
- Expert Judgments
- …

- Fault Tree Analysis (FTA)
- Bayesian Networks
- Event Tree Analysis
- Fuzzy Techniques
- Monte Carlo Simulation
- Decision Tree Analysis
- …

- MCDM
- LCA
- Optimization Models
- Risk-based design
- Digital Tools
- Digital Twins

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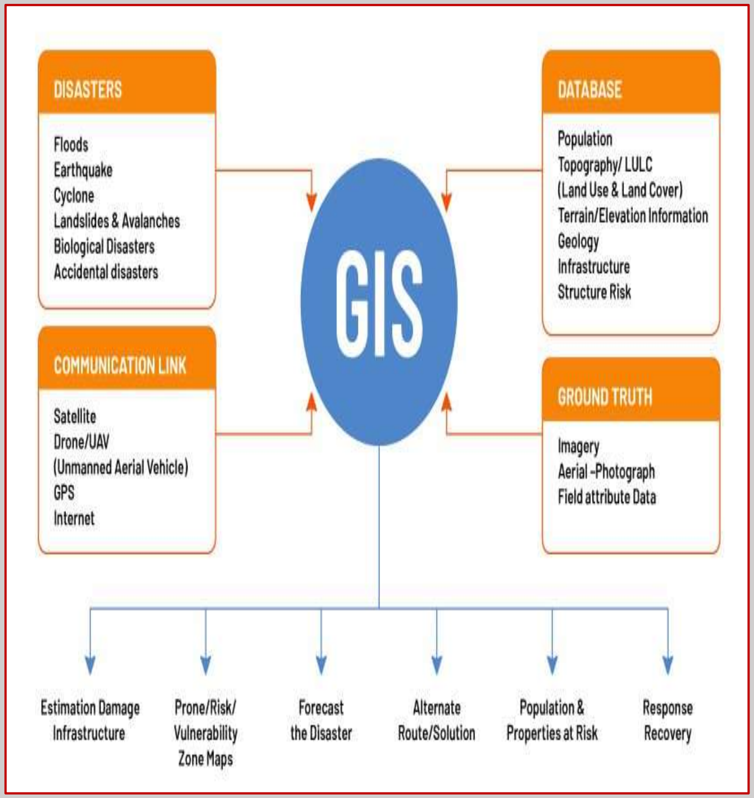
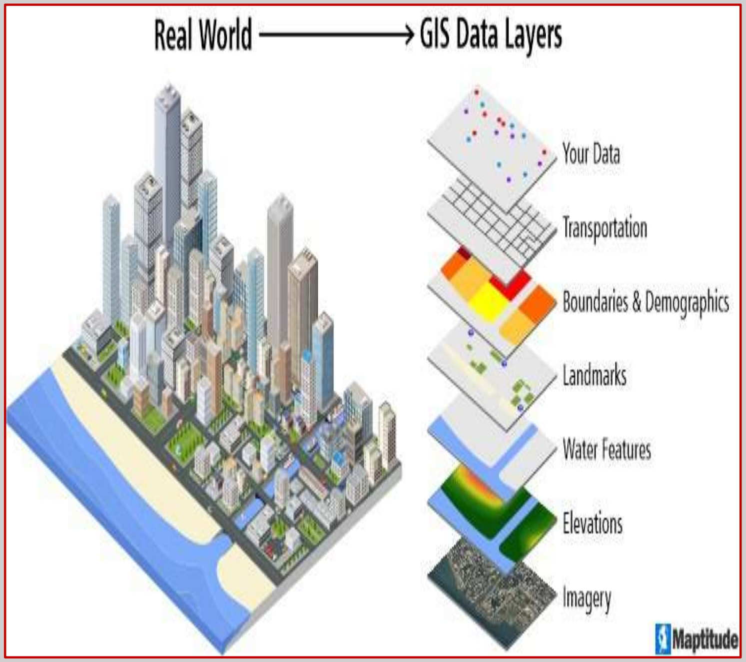
Different types of data for risk assessment

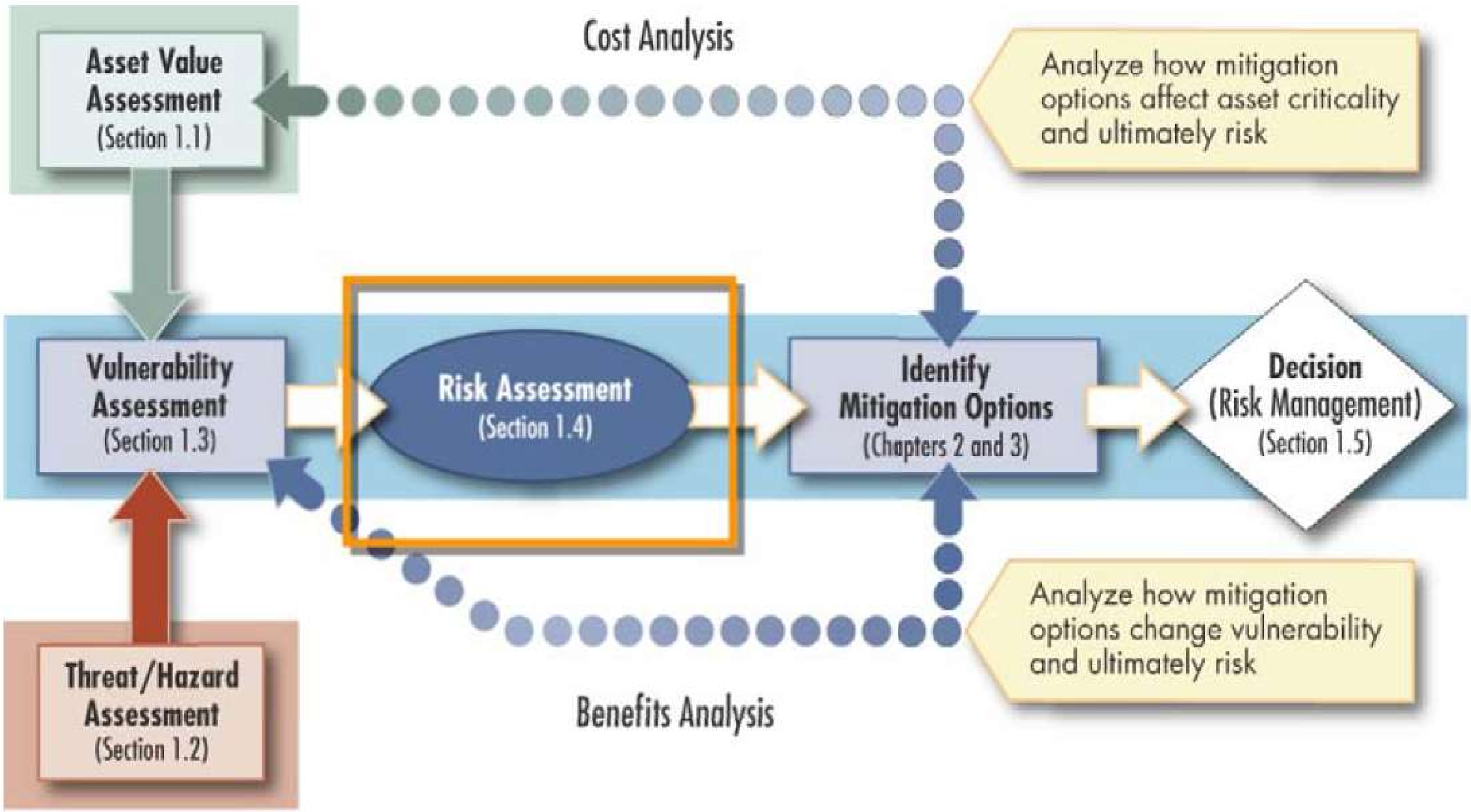




Type of data	Use	Data sources
Generic data		
• Data on health effects of various doses of various pollutants on humans; cf. dose-response (QMRA) • Effectiveness of treatment systems for various types of contamination • Weights to be used in DALY calculations	• Efficiency of treatment systems (i.e. level of contamination in source being unacceptable) • Calculations of risk in terms of DALY	• Microrisk website (www.microrisk.com) • WHO website • Databases available on USEPA websites provide additional information (e.g. for health risk assessment) in comparison to the WHO or Microrisk websites.
System data		

• Geographical data
• Layout of the catchment area and source
• Possible hazards in the catchment area, water source and the distribution system
• GIS data on hazards
• Environmental data
• Treatment systems
• Water distribution network
• Number and types of consumers connected to water utility
• Volume of water consumed per consumer (per day)
	System description is used throughout risk analysis to assess e.g.
	• Hazards
	• Hazardous events
	• Treatment system reliability
	• Exposure and consequences to water quality and human health
		• Maps
		• Water utility/plant data:
		  o Technical drawings
		  o Layout drawings
		  o Asset databases
		  o Maintenance systems
		• Municipality, water utility (GIS maps, water distribution networks etc)
		• Local knowledge
		• On-site inspection

Event Data		
• Failure data for various subsystems, (treatment systems / barriers) • Data on erroneous operation (human errors) • Events that have resulted in contaminated water • Preventive and corrective maintenance data	• Reliability and failure rate of equipment and systems • Type and frequency of hazardous events	• Failure data base of water utility • Maintenance system • Generic failure data bases • Vendor information (e.g. on failures) • Reporting system for hazardous/undesired events • Local knowled[...] maintenance personnel)


Cost Analysis
Asset Value Assessment (Section 1.1)
Analyze how mitigation options affect asset criticality and ultimately risk
Vulnerability Assessment (Section 1.3)
Risk Assessment (Section 1.4)
Identify Mitigation Options (Chapters 2 and 3)
Decision (Risk Management) (Section 1.5)
Analyze how mitigation options change vulnerability and ultimately risk
Threat/Hazard Assessment (Section 1.2)
Benefits Analysis

FEMA

Definition of Risk

Risk is a combination of:

- The probability that an event will occur, and
- The consequences of its occurrence

	Low Risk	Medium Risk	High Risk
Risk Factors Total	1-60	61-175	≥ 176

Risk = Asset Value x Threat Rating x Vulnerability Rating

FEMA

An Approach to Quantifying Risk

Risk = Asset Value x Threat Rating x Vulnerability Rating

Table 1-18: Risk Factors Definitions

Very High	10
High	8-9
Medium High	7
Medium	5-6
Medium Low	4
Low	2-3
Very Low	1

Table 1-19: Total Risk Color Code

	Low Risk	Medium Risk	High Risk
Risk Factors Total	1-60	61-175	[illegible]

FEMA

Risk Assessment Results

Function	Cyber Attack	Armed Attack (single gunman)	Vehicle Bomb	CBR Attack
Administration	280	140	135	90
Asset Value	5	5	5	5
Threat Rating	8	4	3	2
Vulnerability Rating	7	7	9	9
Engineering	128	128	192	144
Asset Value	8	8	8	8
Threat Rating	8	4	3	2
Vulnerability Rating	2	4	8	9
Warehousing	96	36	81	54
Asset Value	3	3	3	3
Threat Rating	8	4	3	2
Vulnerability Rating	4	3	9	9
Data Center	360	128	216	144
Asset Value	8	8	8	8
Threat Rating	9	4	3	2
Vulnerability Rating	5	4	9	9
Food Service	2	32	48	36
Asset Value	2	2	2	2
Threat Rating	1	4	3	2
Vulnerability Rating	1	4	8	9
Security	280	140	168	126
Asset Value	7	7	7	7
Threat Rating	8	4	3	2
Vulnerability Rating	5	5	8	9
Housekeeping	16	64	48	36
Asset Value	2	2	2	2
Threat Rating	8	4	3	2
Vulnerability Rating	1	8	8	9
Day Care	54	324	243	162
Asset Value	9	9	9	9
Threat Rating	3	4	3	2
Vulnerability Rating	2	9	9	9

FEMA

Measures to Reduce Risk

THREATS

Deter

Detect

Deny

Devalue

Affect the threat posed by the adversary

ASSETS

Relocate

Reduce assets

Plan for recovery

Insure

Reduce the impact on the assets

VULNERABILITIES

Conceal

Reduce

Eliminate

Affect the degree of vulnerability

Risk Matrix Method

Likelihood \ Consequences	Insignificant	Minor	Moderate	Major	Critical
Almost certain	**Medium**	**Medium**	**High**	**Extreme**	**Extreme**
Likely	**Low**	**Medium**	**High**	**High**	**Extreme**
Possible	**Low**	**Medium**	**High**	**High**	**High**
Unlikely	**Low**	**Low**	**Medium**	**Medium**	**High**
Rare	**Low**	**Low**	**Low**	**Low**	**Medium**

Guidelines for Drinking-water Quality

THIRD EDITION
INCORPORATING THE FIRST AND SECOND ADDENDA
Volume 1
Recommendations

World Health Organization

Geneva
2008

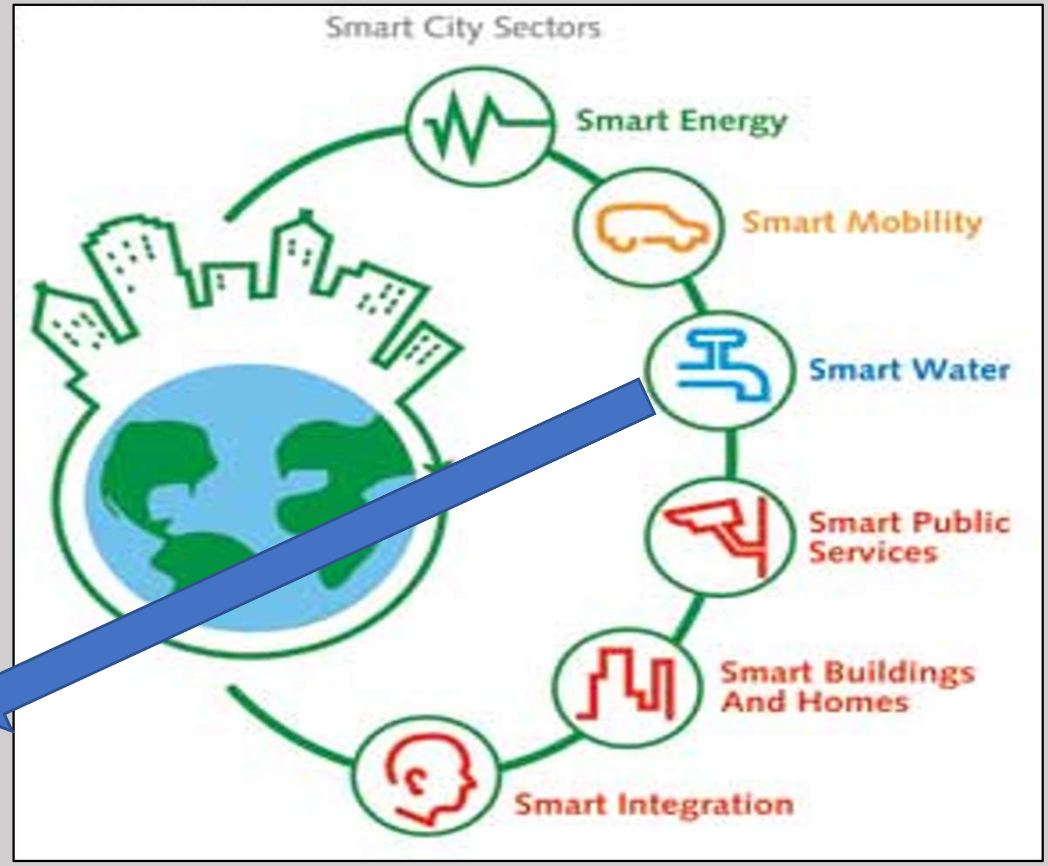
Table 4.2 Example of a simple risk scoring matrix for ranking risks

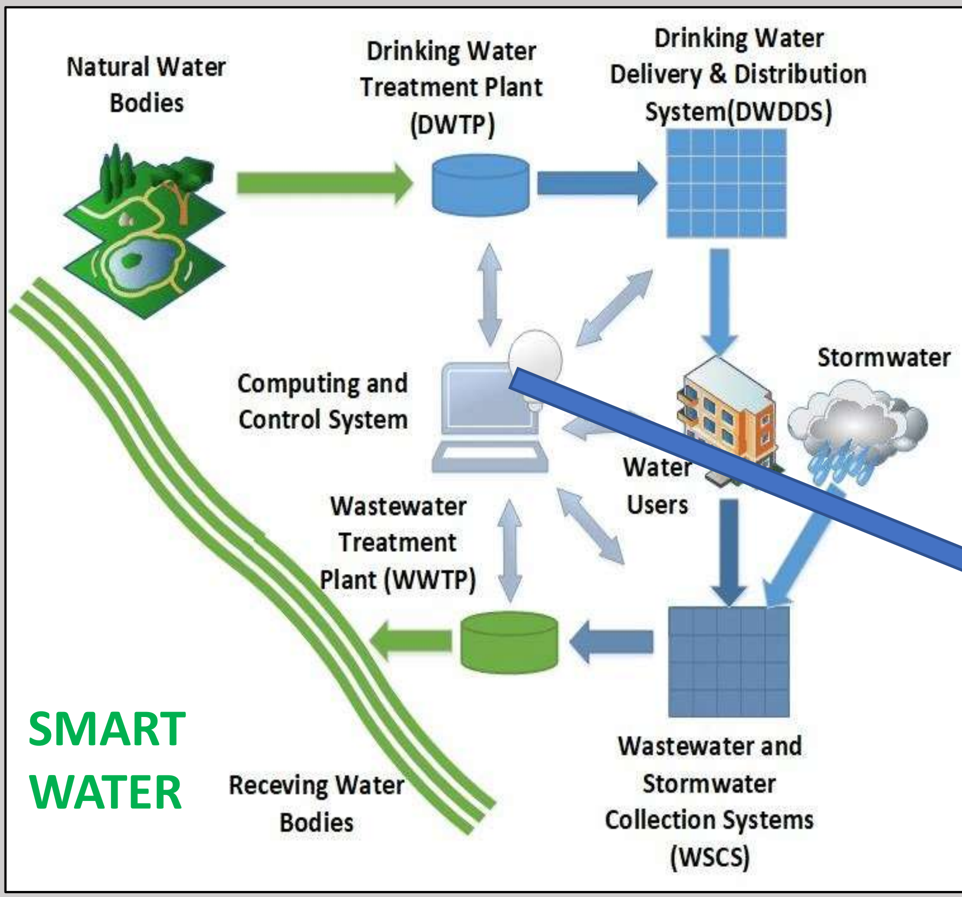
	Severity of consequences				
Likelihood	**Insignificant**	**Minor**	**Moderate**	**Major**	**Catastrophic**
Almost certain					
Likely					
Moderately likely					
Unlikely					
Rare					

Table 4.3 Examples of definitions of likelihood and severity categories that can be used in risk scoring

Item	**Definition**
Likelihood categories	
Almost certain	Once per day
Likely	Once per week
Moderately likely	Once per month
Unlikely	Once per year
Rare	Once every 5 years
Severity categories	
Catastrophic	Potentially lethal to large population
Major	Potentially lethal to small population
Moderate	Potentially harmful to large population
Minor	Potentially harmful to small population
Insignificant	No impact or not detectable

"**Smart Water**" system is designed to gather meaningful and actionable data about a city's water and wastewater and effectively use them in simulation and optimization of water and wastewater systems.

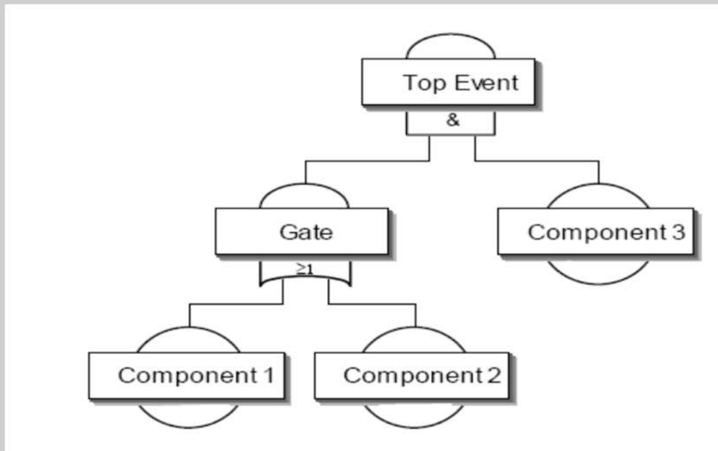




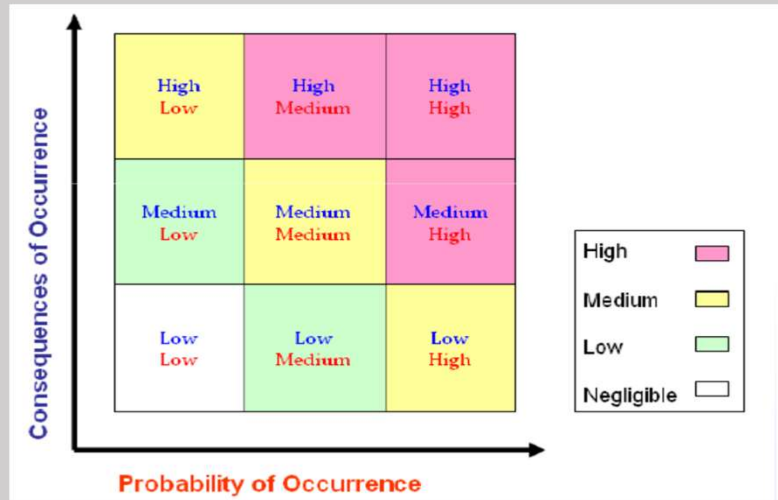
Statistical and machine learning methods for risk assessment

Most Popular methods

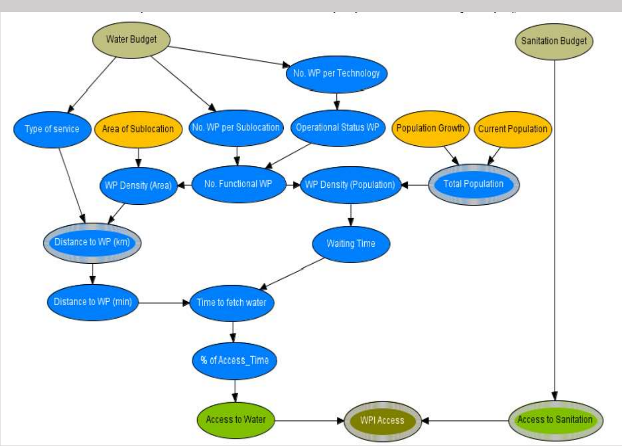
Fault Tree Analysis



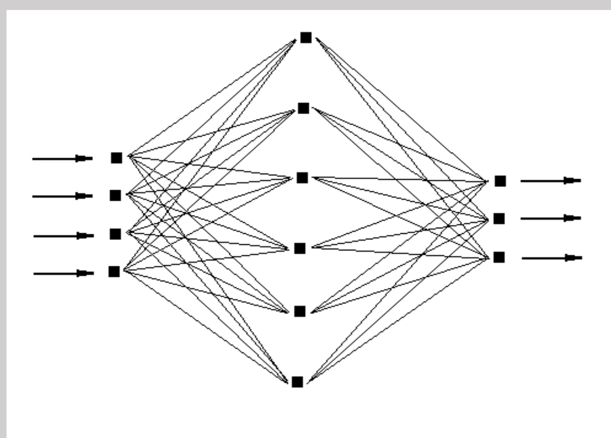
Qualitative Analysis



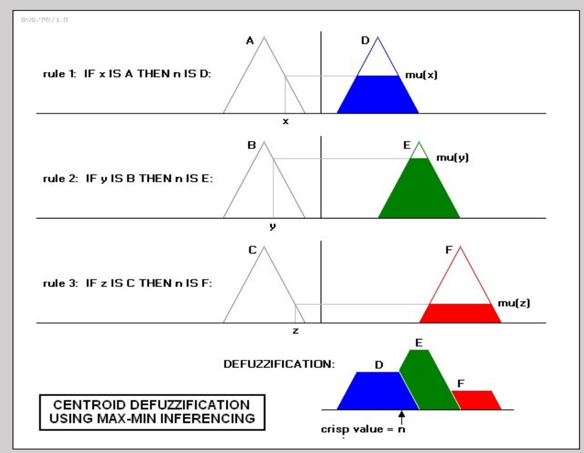
Bayesian Networks



Neural Networks



Fuzzy Logic



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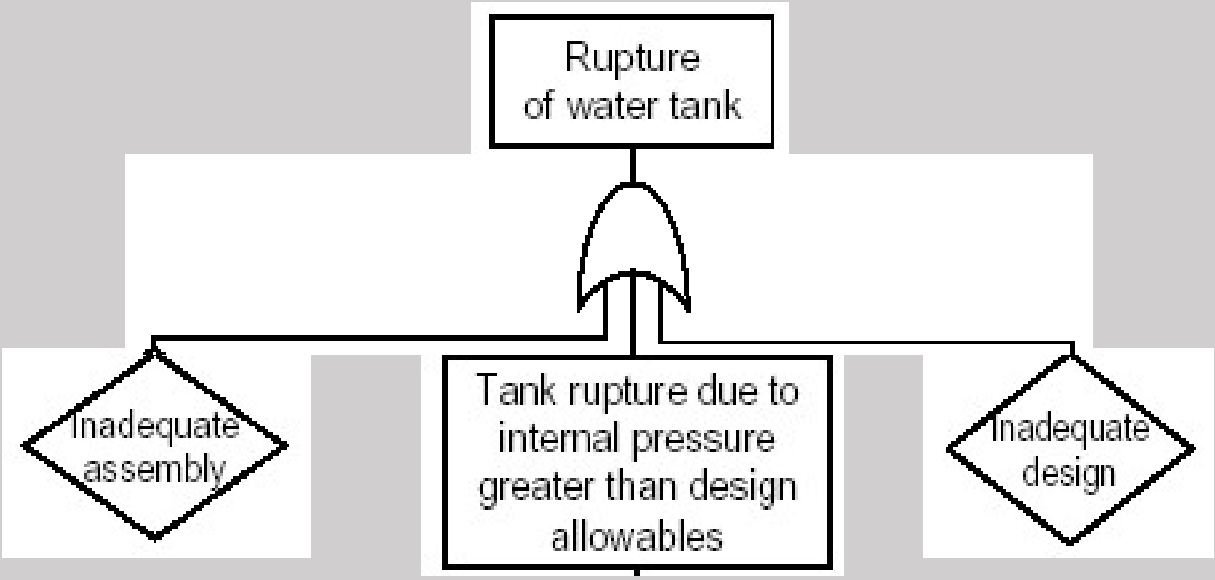
Fault Tree Analysis Method

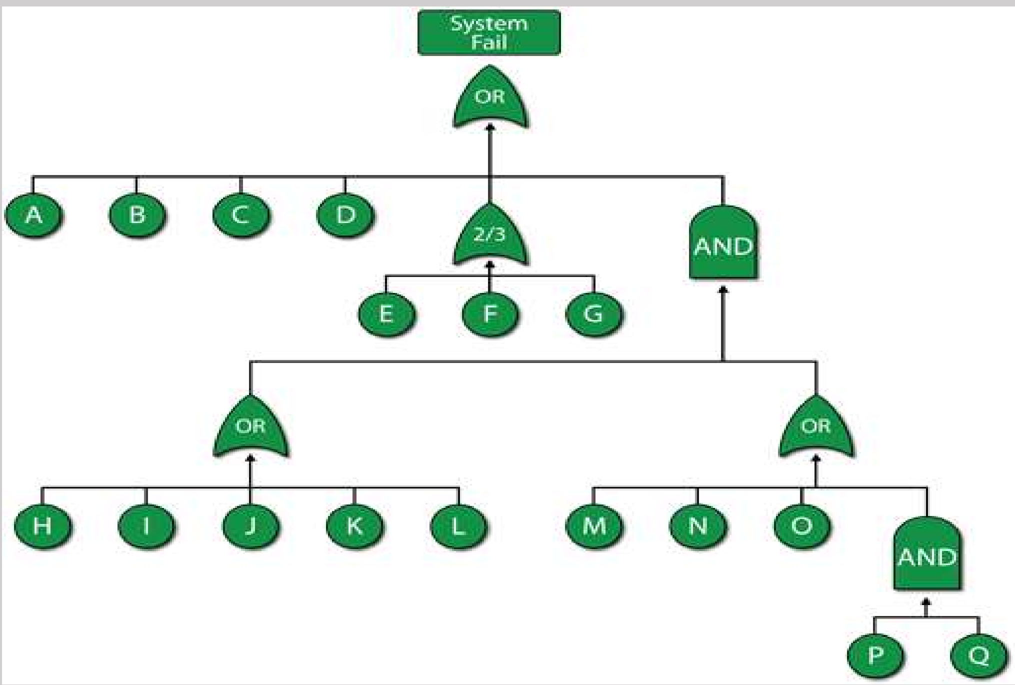
- FTA is a deductive top-down approach based on system failure and begins with an unfavorable event (the top event), and then the causes are determined using a systematic reverse process.
- FTA, based on a logical diagram, by introducing the relationships between the basic events and the top event and providing a quantitative analysis of the system, shows the failure probability and calculates the degree of system reliability.

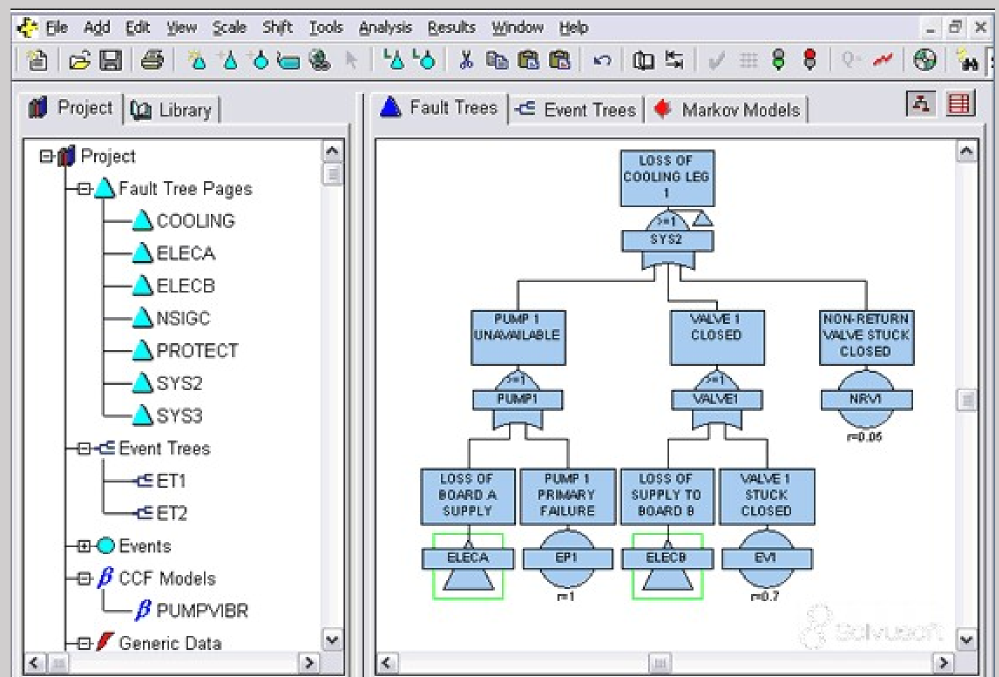


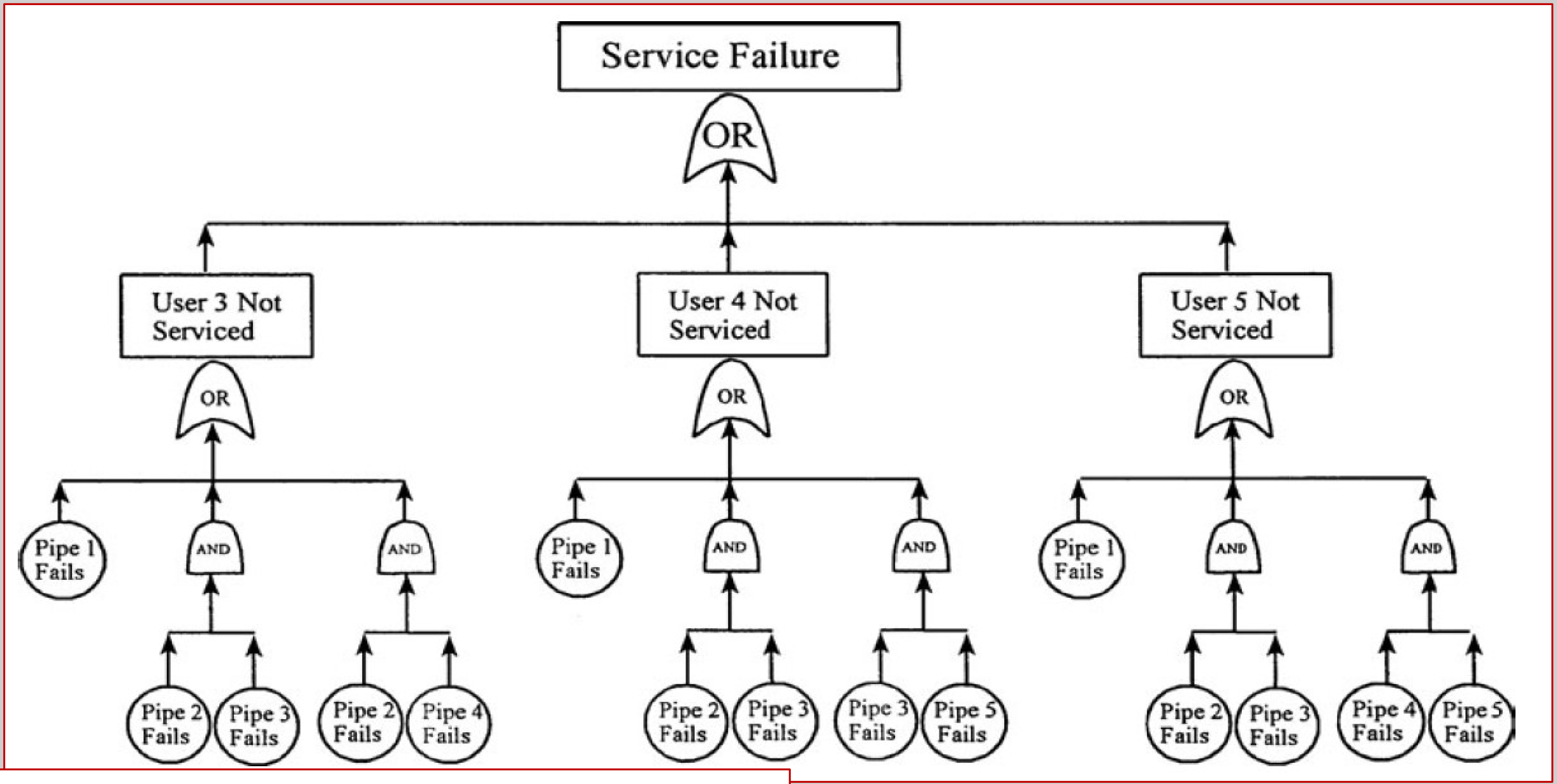
S.No	Gate Symbol	Description
1	AND Gate	The output event occurs when all the input events occur
2	OR Gate	The output event occurs when at least one of the input events occur
3	Priority AND Gate	The output event occurs when all the input events occur in the order from left to right
4	Exclusive OR gate	The output event occurs if either of the two input events occur but not both
5	Inhibit gate	The output event occurs when the input event occurs and the attached condition is satisfied

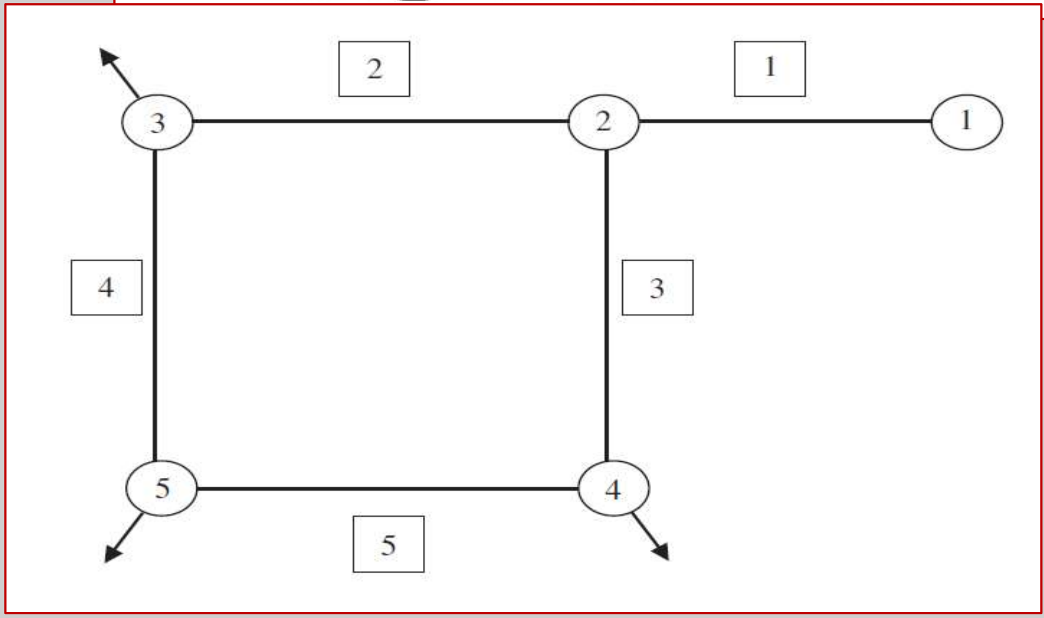
$$P_F = \prod_{i=1}^{n} P_i$$

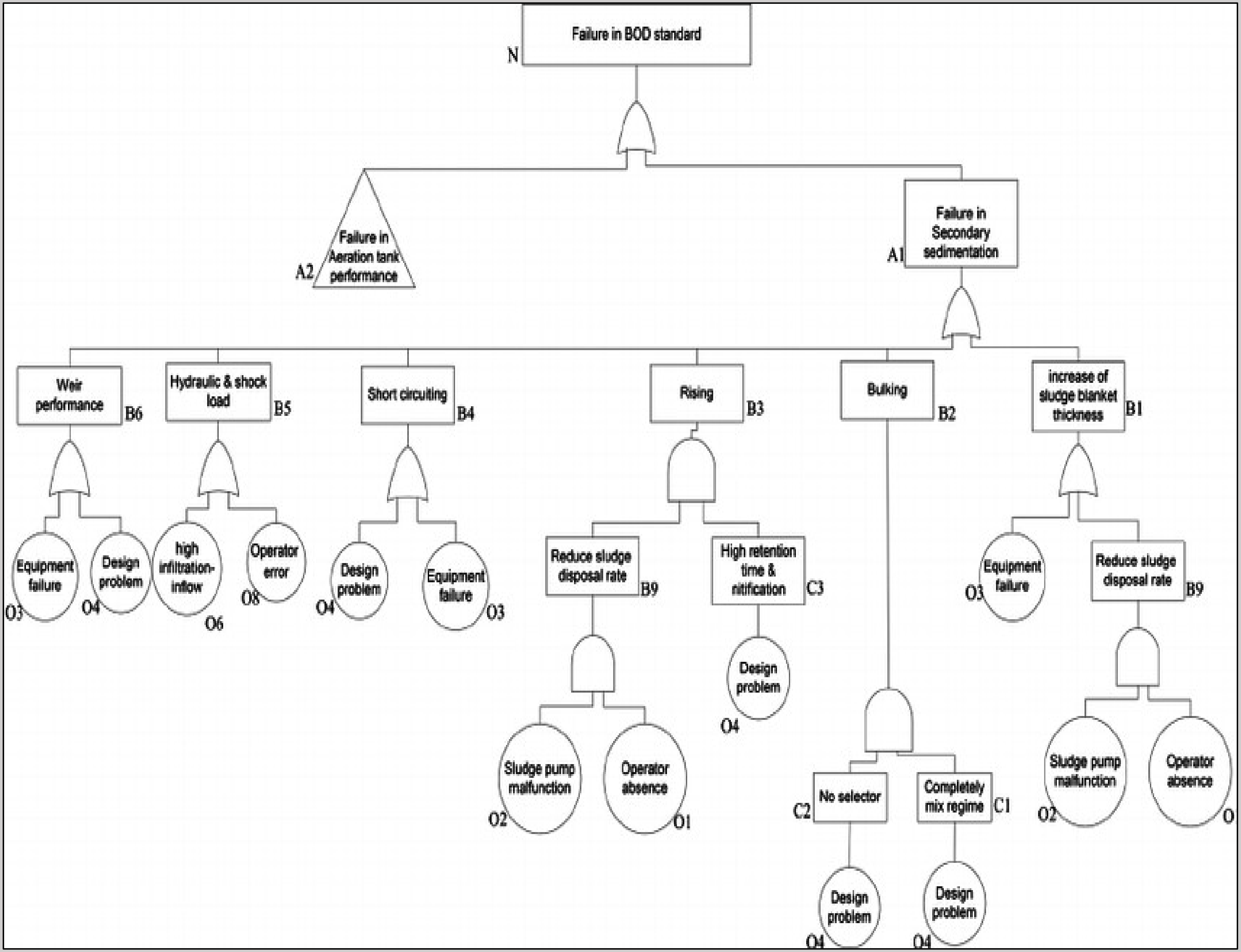
$$P_F = 1 - \prod_{i=1}^{n} (1 - P_i)$$






Service Failure
OR
User 3 Not Serviced
User 4 Not Serviced
User 5 Not Serviced
OR
OR
OR
Pipe 1 Fails
AND
AND
Pipe 1 Fails
AND
AND
Pipe 1 Fails
AND
AND
Pipe 2 Fails
Pipe 3 Fails
Pipe 2 Fails
Pipe 4 Fails
Pipe 2 Fails
Pipe 3 Fails
Pipe 3 Fails
Pipe 5 Fails
Pipe 2 Fails
Pipe 3 Fails
Pipe 4 Fails
Pipe 5 Fails


2
1
3
2
1
4
3
5
4
5



Failure in BOD standard
N
Failure in Aeration tank performance
A2
Failure in Secondary sedimentation
A1
Weir performance
B6
Hydraulic & shock load
B5
Short circuiting
B4
Rising
B3
Bulking
B2
increase of sludge blanket thickness
B1
Equipment failure
O3
Design problem
O4
high infiltration-inflow
O6
Operator error
O8
Design problem
O4
Equipment failure
O3
Reduce sludge disposal rate
B9
High retention time & nitification
C3
Equipment failure
O3
Reduce sludge disposal rate
B9
Design problem
O4
Sludge pump malfunction
O2
Operator absence
O1
No selector
C2
Completely mix regime
C1
Sludge pump malfunction
O2
Operator absence
O
Design problem
O4
Design problem
O4

Machine Learning is a technique which develops complex algorithms for processing large data. It uses complex programs which can learn through experience and make predictions.

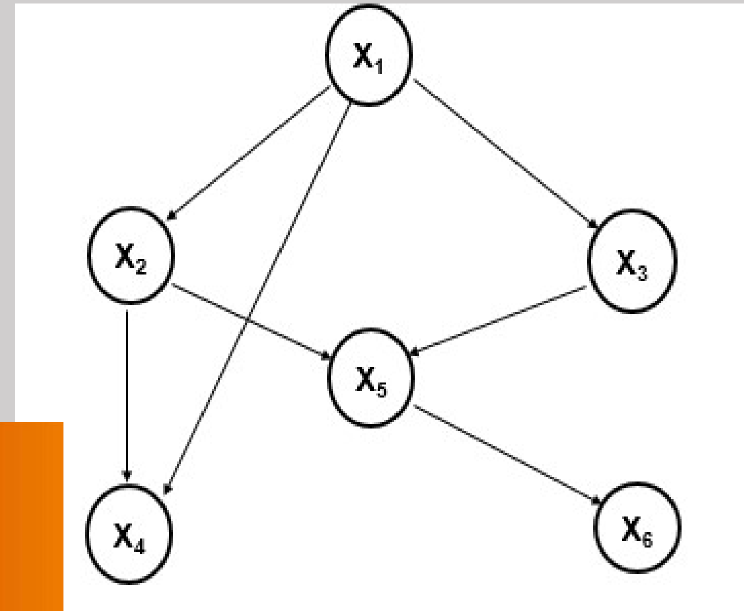
- Bayesian Network
- Decision Tree Learning
- Artificial Neural Networks (ANNs)
- Bayesian Neural Networks (BNNs)
- Genetic Algorithms
- Reinforcement Learning
- Support Vector Machine
- Markov Model

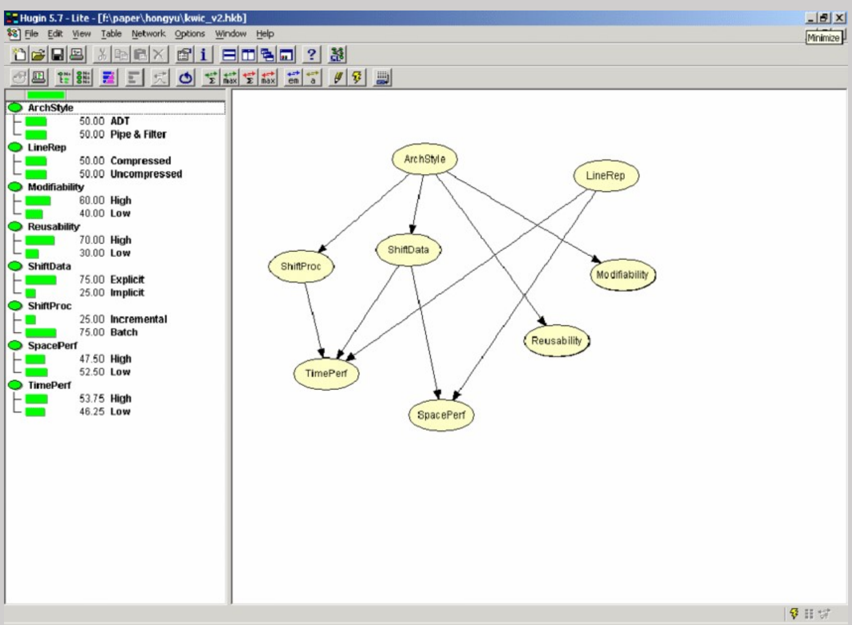
…

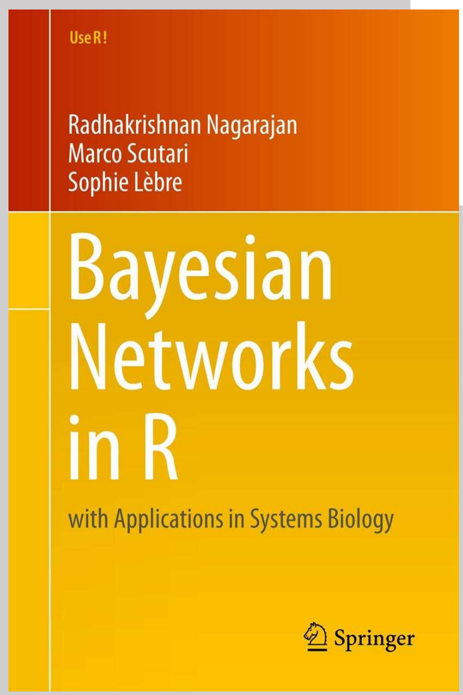
✓ **A Bayesian network is a graphical model for probabilistic relationships among a set of variables**

What do Bayesian Networks and Bayesian Methods have to offer ?

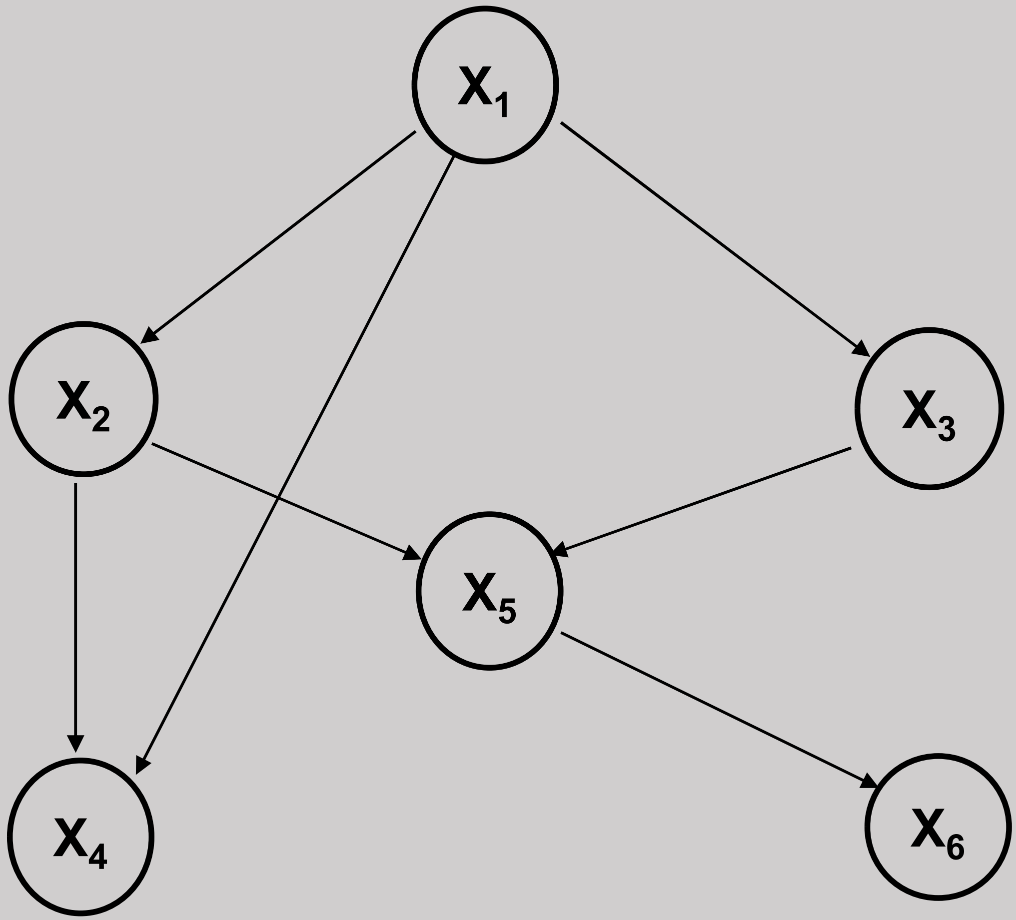
- Handling of Incomplete Data Sets
- Learning about Causal Networks
- Facilitating the combination of domain knowledge and data





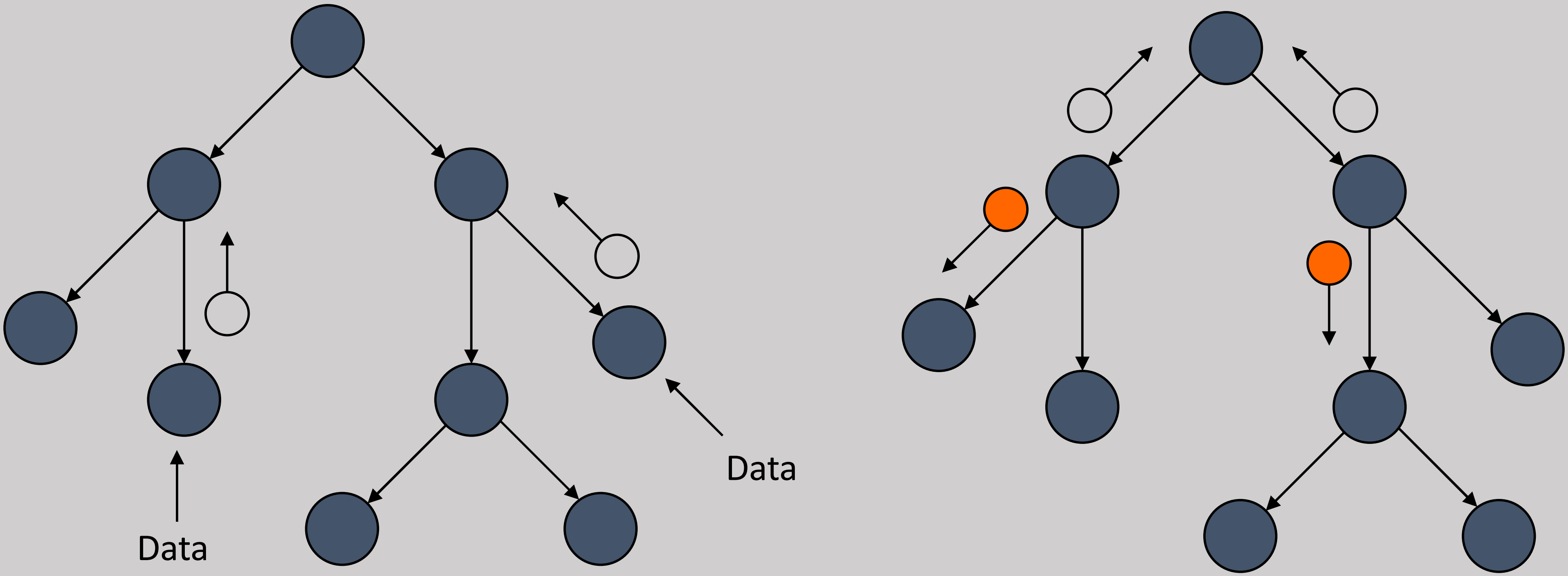


Sample Factored Joint Distribution



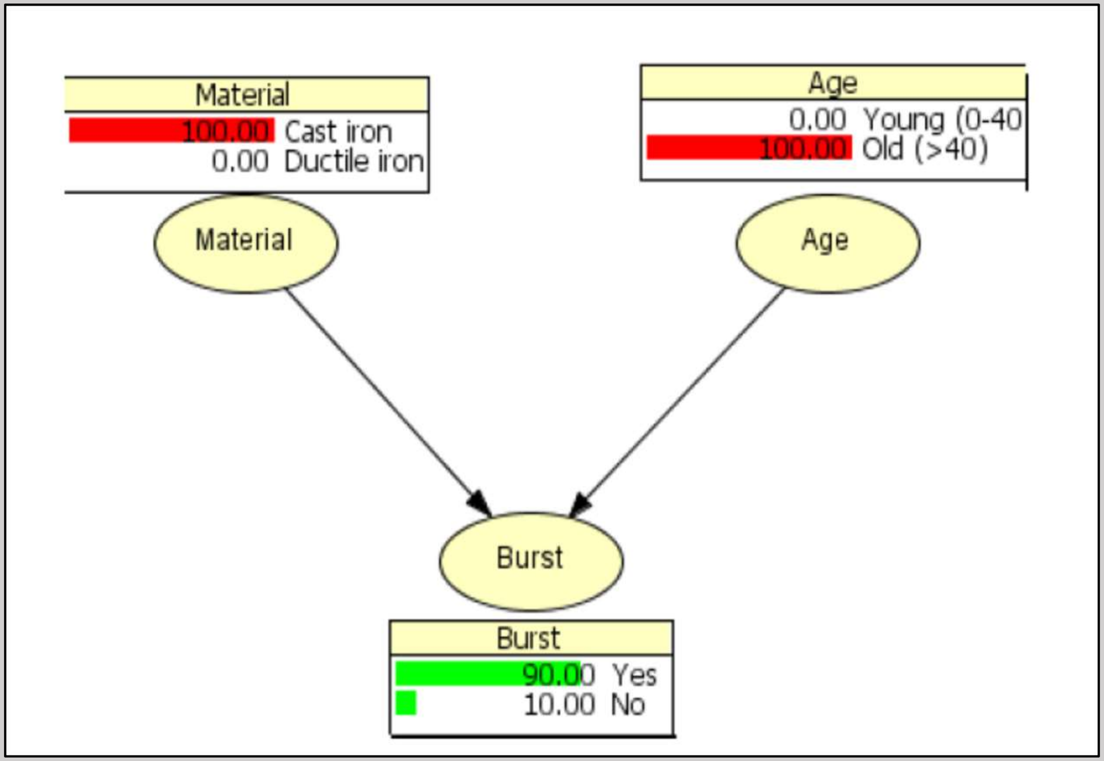
$$p(x_1, x_2, x_3, x_4, x_5, x_6) = p(x_6 \mid x_5)\, p(x_5 \mid x_3, x_2)\, p(x_4 \mid x_2, x_1)\, p(x_3 \mid x_1)\, p(x_2 \mid x_1)\, p(x_1)$$

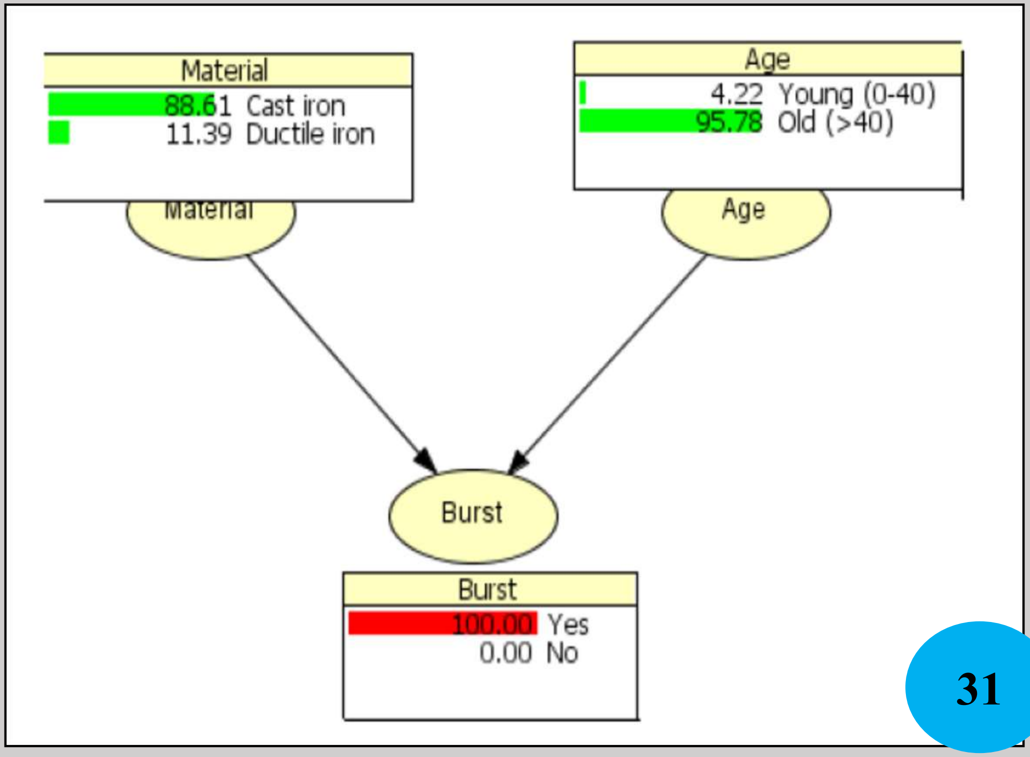
Propagation Algorithm Objective



- The algorithm's purpose is "… fusing and propagating the impact of new evidence and beliefs through Bayesian networks so that each proposition eventually will be assigned a certainty measure consistent with the axioms of probability theory." (Pearl, 1988, p 143)

Simple Example

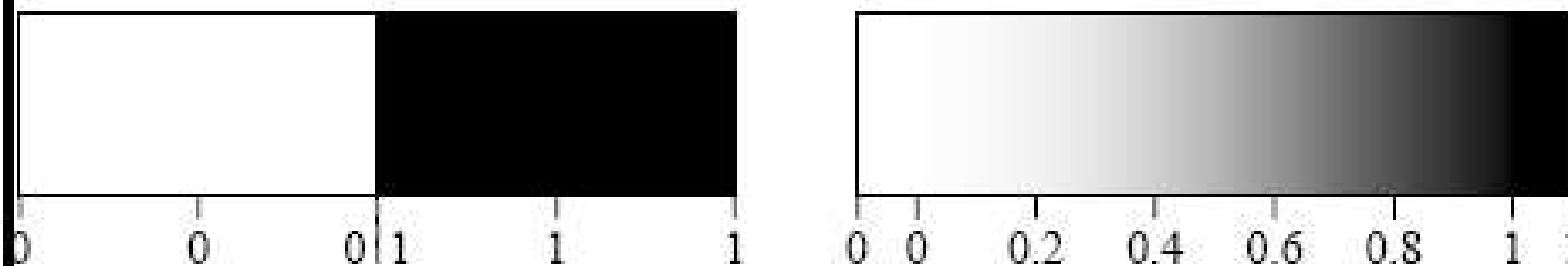




Fuzzy Sets

"The theory of fuzzy sets is a theory of graded concepts, a theory in which everything is a matter of degree." Lotfi Zadeh, 1973

Unlike two-valued Boolean logic, fuzzy logic is based on **degrees of membership**. It deals with **degrees of truth.**



(*a*) Boolean Logic. (*b*) Multi-valued Logic.

Why use Fuzzy Logic?

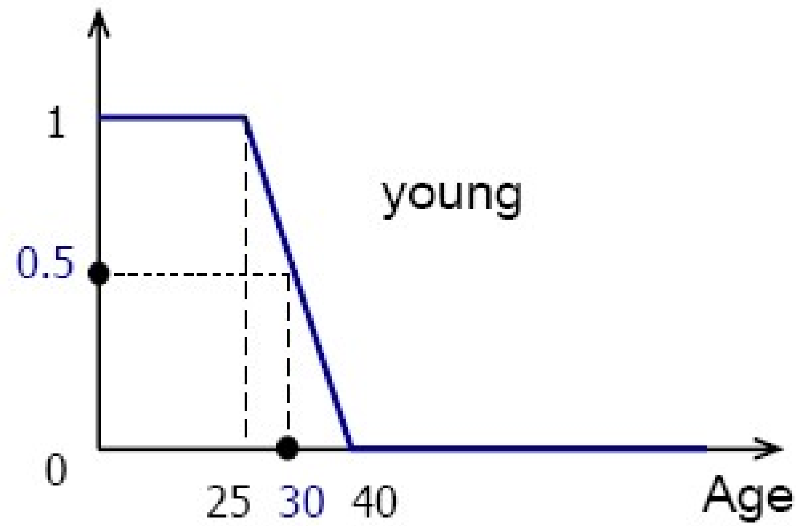
- Easy to understand
- Flexible
- Don’t need precise data
- Can model nonlinear functions
- Based on natural language

Fuzzy Set Definition

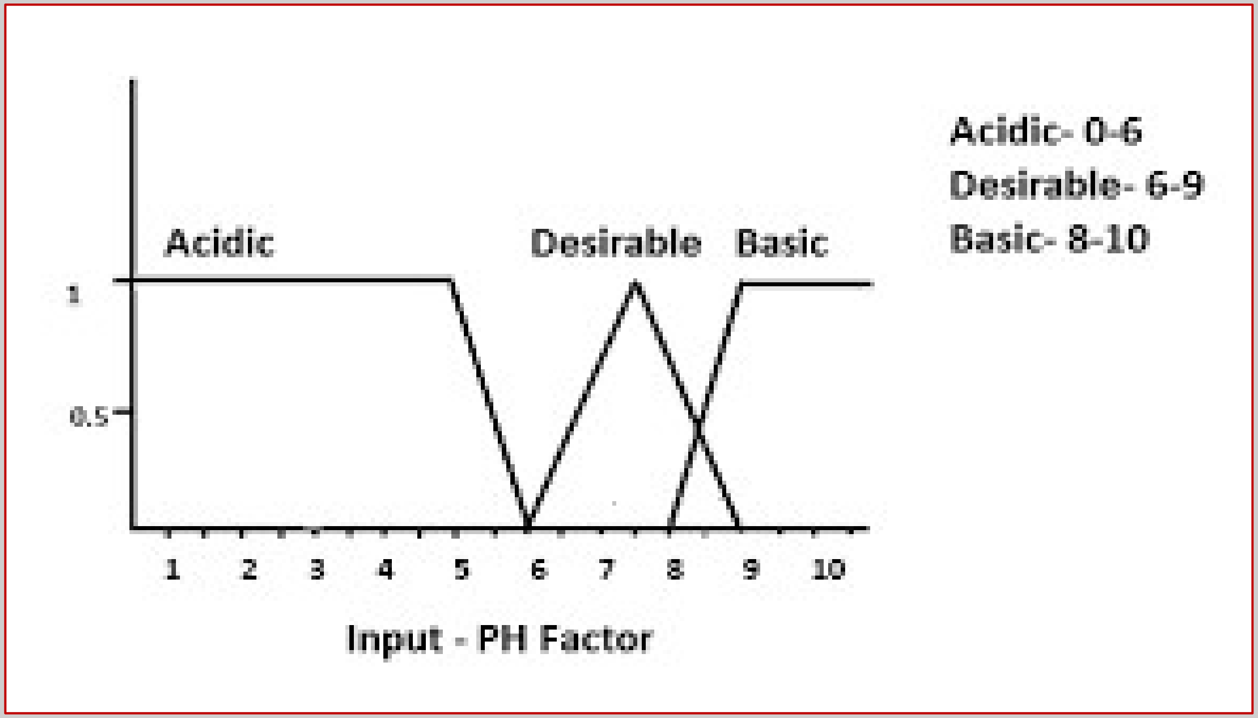
A fuzzy set is defined by a membership function that maps elements of a given domain (a crisp set) into values in [0, 1].

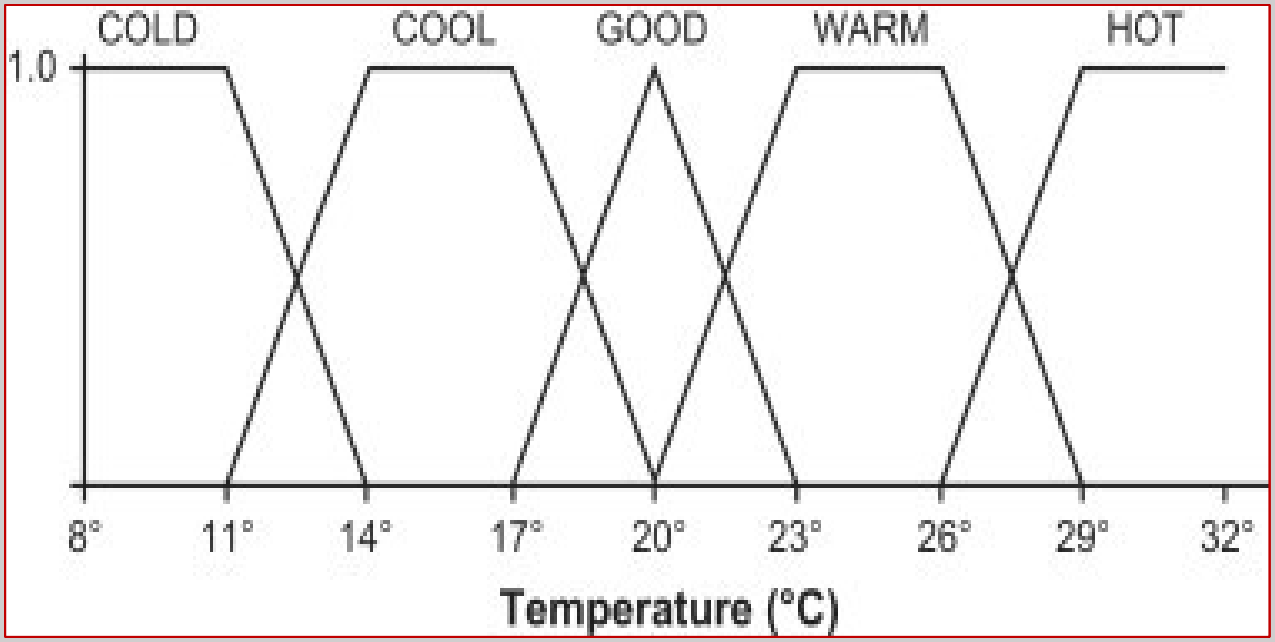
$\mu_A : U \rightarrow [0, 1]$

$\mu_A \leftrightarrow A$

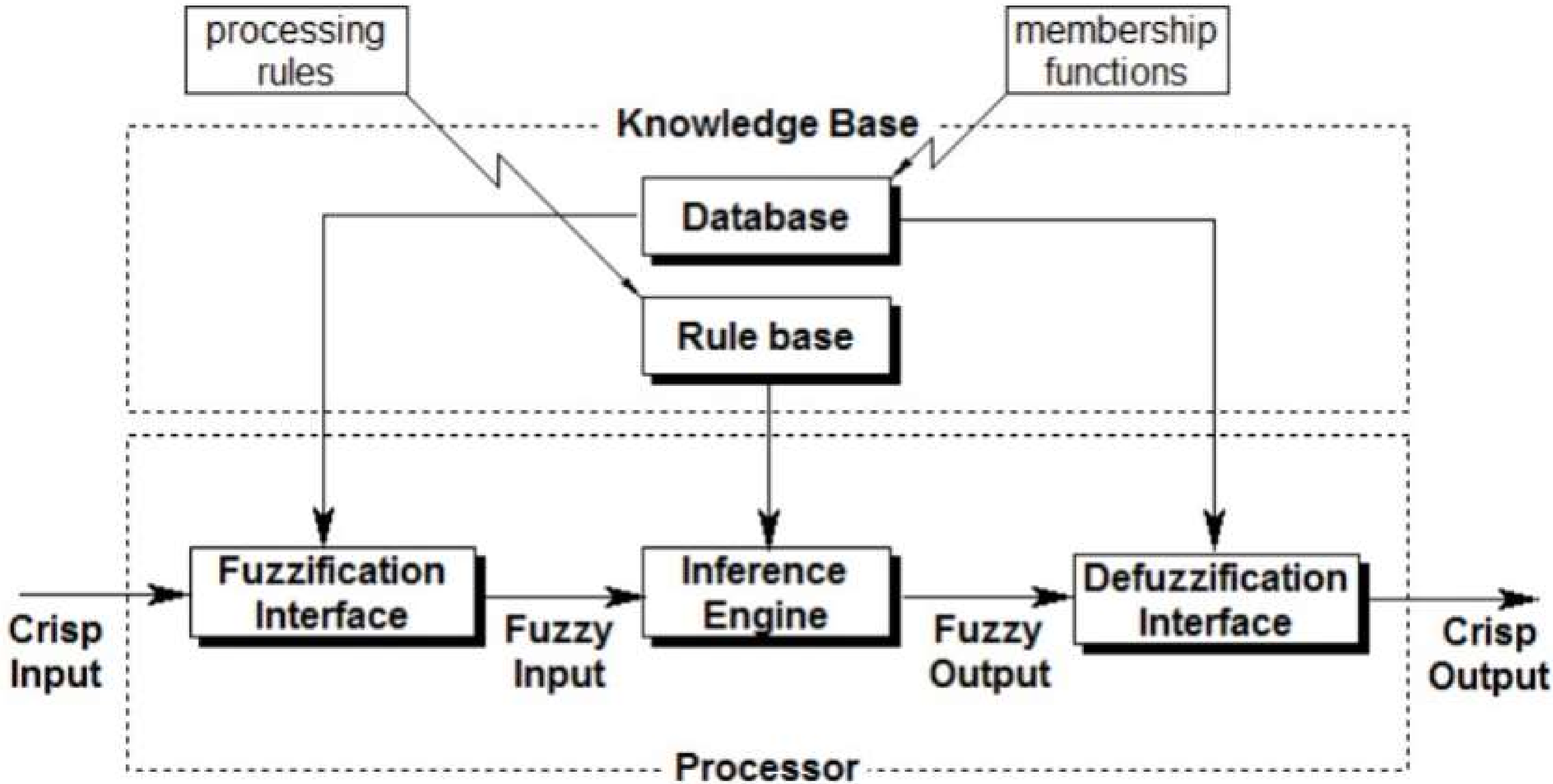


3


Acidic
Desirable
Basic
1
0.5
1 2 3 4 5 6 7 8 9 10
Input - PH Factor
Acidic- 0-6
Desirable- 6-9
Basic- 8-10


COLD
COOL
GOOD
WARM
HOT
1.0
8° 11° 14° 17° 20° 23° 26° 29° 32°
Temperature (°C)

Fuzzy Inference System



(Crisp) Rule 8

IF Likelihood is "Low" AND Severity is "Moderate"
THEN the risk is "medium"

Severity
3. moderate

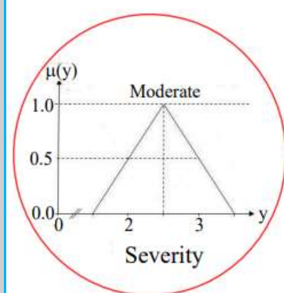
Severity	1	2	3	4	5
5	MH 5	MH	MH	H	H 25
4	M	M	MH	MH	H
3	M	M 8	M 13	MH	MH
2	L	L 7	L 12	M	MH
1	L 1	L	L	M	MH

Likelihood
2. low

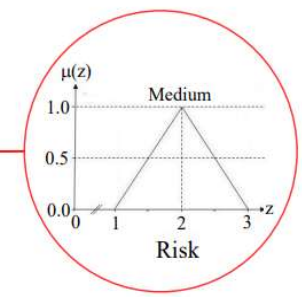
Risk Categories
M: medium

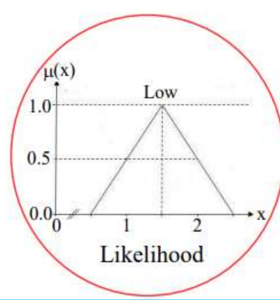
(Fuzzy) Rule 8

IF Likelihood is "Low" AND Severity is "Moderate"
THEN the risk is "Medium"



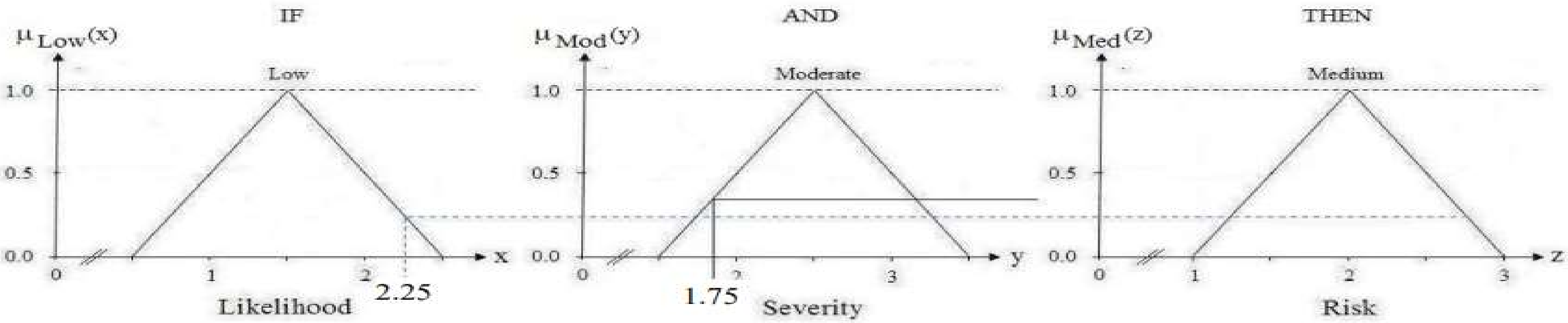
Severity	1	2	3	4	5
5	MH 5	MH	MH	H	H 25
4	M	M	MH	MH	H
3	M	M 8	M 13	MH	MH
2	L	L 7	L 12	M	MH
1	L 1	L	L	M	MH

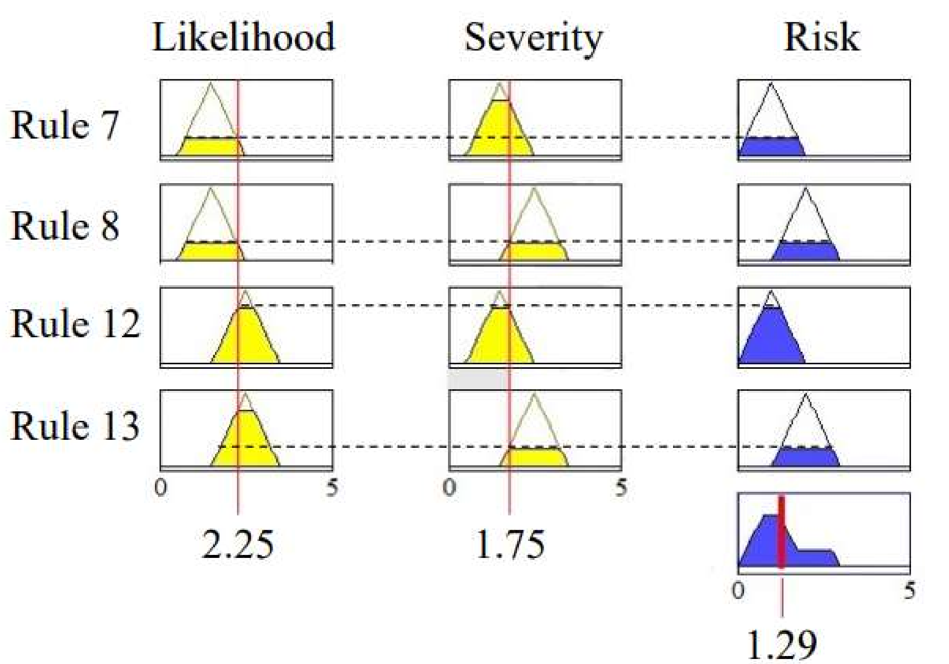


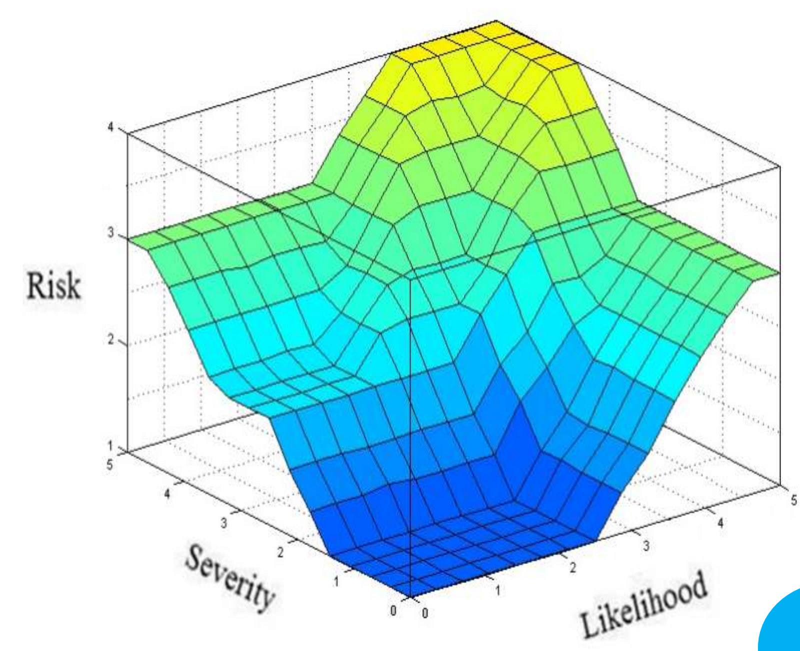


Fuzzy Rule 8

IF Likelihood is "Low" AND Severity is "Moderate"
THEN the risk is "medium"







Overview of risk analysis methods

Life cycle phase	Decision / Purpose of analysis	Method: Name	Method: Analysis Complexity	Comments / Examples
Design and development	Select type of water treatment	HAZOP/Hazid	M/L	Hazards to water source/catchment area
		FMECA	L	Reliability of treatment systems
		Removal efficiency	H	Specification of treatment system
	Select/design distribution system, (capacity, redundancy)	Network model	H	For distribution only
	Identification of control points	CRA (HACCP)	M	Establish monitoring system. Primarily for source & treatment
	Hazard identification	Hazid/HAZOP	L/M	Identify need for risk reduction options
	Plan for risk reduction/avoidance	FMECA	L	Technical failures; (primarily for treatment?)
		FTA	H	E.g. to investigate redundant systems
		RBD	M	E.g. to investigate redundant systems
		HRA	H	Analyse potential for human errors causing maloperation
		QMRA/QCRA	H	Analyse (effects of) microbial/chemical contaminations
	Develop emergency plans	Could be based on CRA	M	Plans for warning consumers, obtain substitute of delivery, recovery, ….
Production and/or construction	Avoid construction work to pollute water source	CRA	L	Analyse hazardous events of construct.
		HAZOP	M	Identify hazards / hazardous events for water source
Operation	Protect against undesired events	CRA (HACCP)	L/M	Prioritise risk reduction options
	Extend risk analyses to cope with specific problems	HRA	H	Improve procedures
		FTA	H	Identify causes of failure events
		ETA	M	Consequences of undesired events
		Bayes Network	H	Effect of risk influencing factors
		GIS	H	More complete picture of hazards/vunerabilitie
	Changes in network capacity or reliability	Network model	H	Optimise water availability for consumers
		FTA	H	Causes of network failures
	New (type of) users to be connected	HAZOP/hazid	M/L	E.g. food industry, hospital, ….
	Unreliable equipment observed	Markov	H	Maintenance optimisation
	Security problems; new threats;	HAZOP/hazid	M/L	Identify threats and vulnerable points
	Changes in environm. of source	Hazid	L	New buildings, roads, animals, etc.
	Modifications / Life extension	Hazid/HAZOP	L/M	New hazards appear?
		FTA	H	Identify "new" failure causes
		RBD	M	

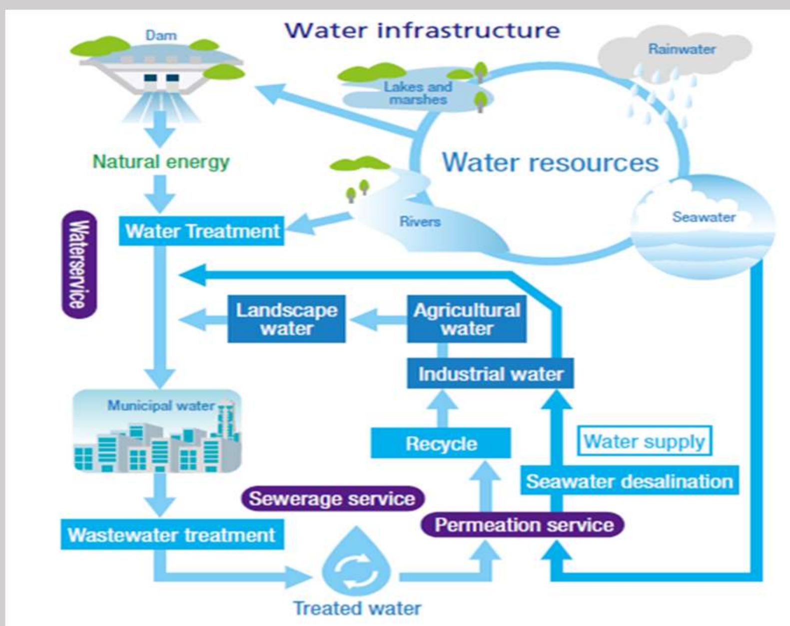
abbas.roozbahani@nmbu.no

Norwegian University of Life Sciences

Risk assessment of urban water infrastructure (Part II: *Applications*)

Abbas Roozbahani

Associate Professor, Faculty of Science and Technology



University of Galati, June 2023

Case Study 1: Risk assessment of pipeline failure in water distribution networks

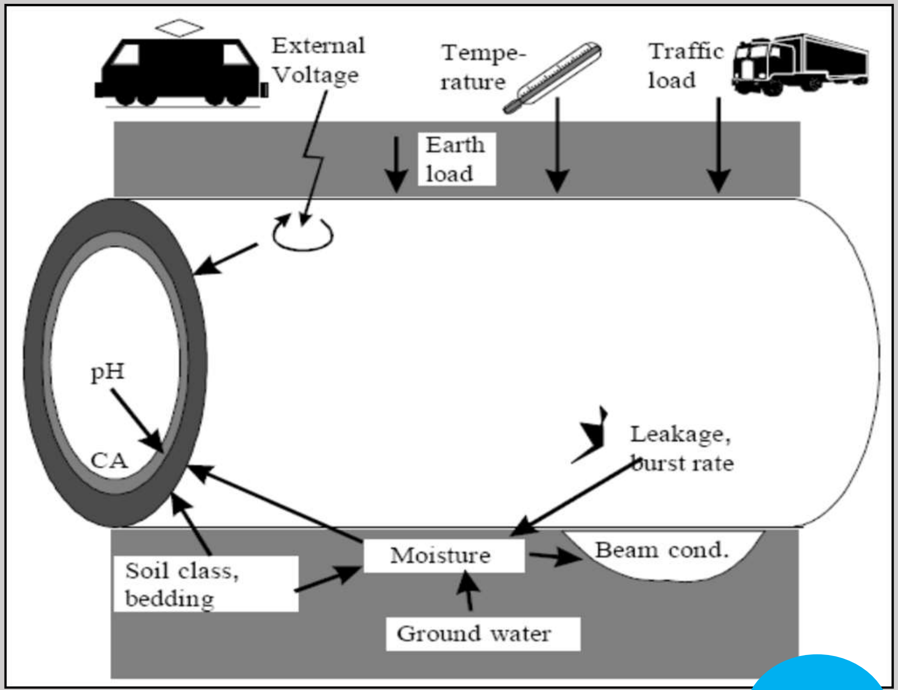
- **Chinatown Area-Singapore**
- **San Marcos-USA**

2011-2015

✓ **Pipe failure is a kind of Physical losses in water distribution networks**

- Why we should assess the pipes' failure risk?
  - Minimize non-revenue water
  - Preventive maintenance
  - Exploit fully the useful life of a pipe
  - Optimal rehabilitation of the water supply network

- How?
  - A priori prediction of failure – Burst (sudden) or small leaks (incipient)
  - Exploit static and dynamic characteristics of pipe network in conjunction with a systematic statistical analysis scheme e.g., Bayesian framework.

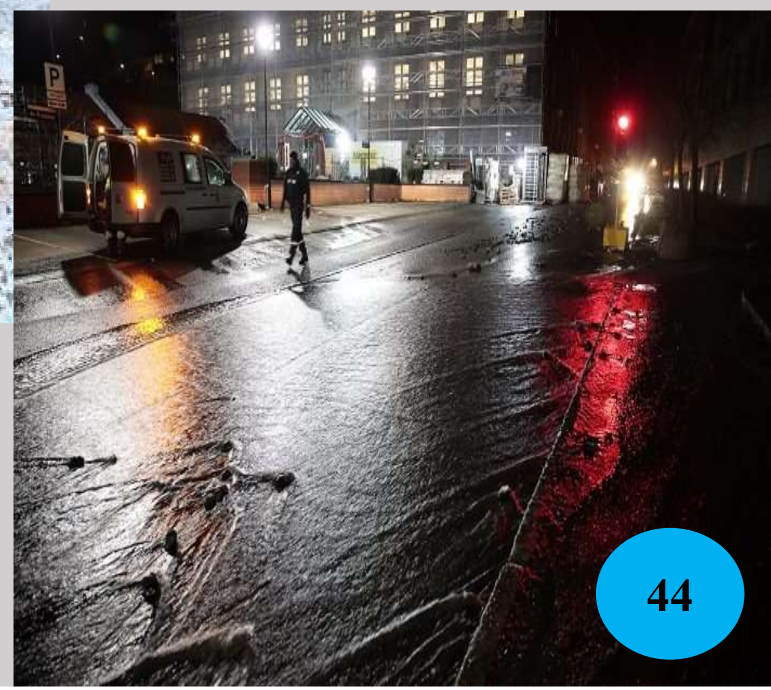


Pipe failure in Water Distribution Network

New York City

Ledbury, UK

Oslo, Norway



Risk Management (WDS Rehabilitation)

Pipe bursts forecasting results

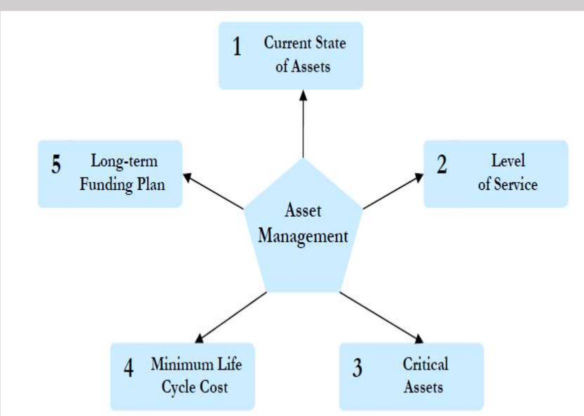
Benefit/Cost Function & Constraints

WDN hydraulic Modeling

Water Quality Constraints

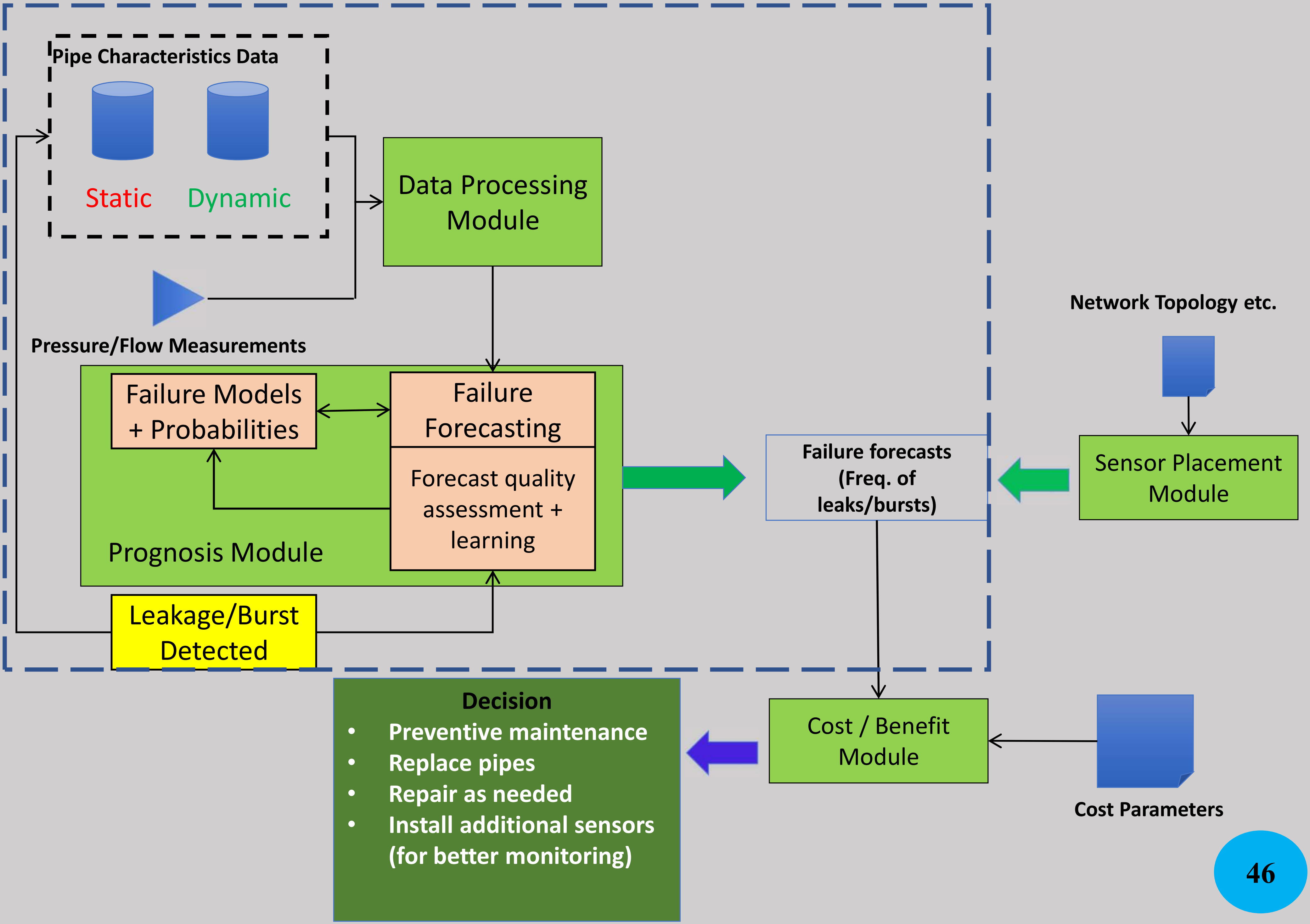
Multi Objective Optimization Model

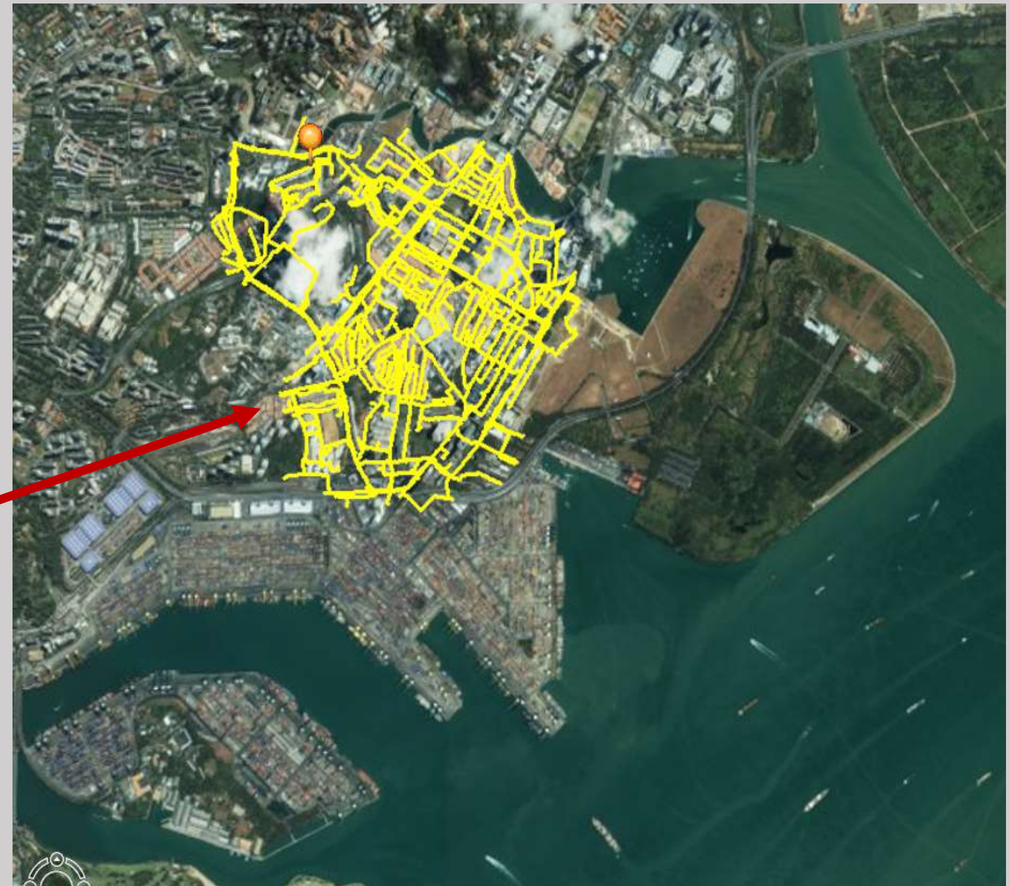
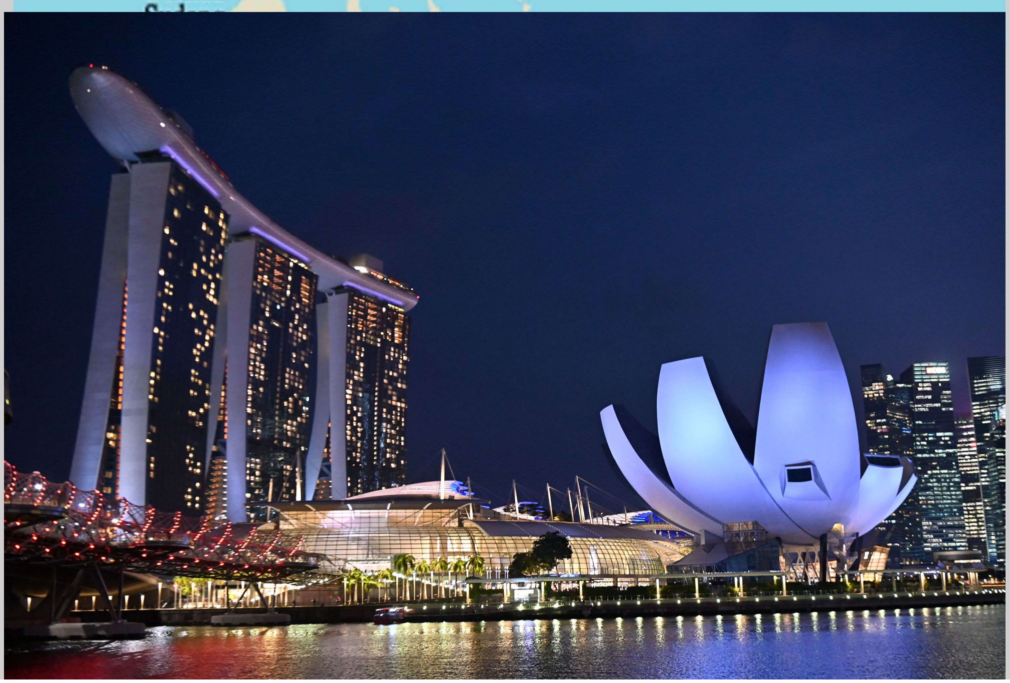
Hydraulic Function & Constraints



Long & short-term rehabilitation plans & guidelines

Data Based Decision Support Framework




SINGAPORE
Johor Bahru
MALAYSIA
Sembawang
Straits of Johor
Woodlands
Yishun
Kranji
Pulau Ubin
Singapore Zoological Gardens
Nee Soon
Seletar Airport
Punggol
Straits of Johor
Changi Village
Choa Chu Kang
SINGAPORE
Ang Mo Kio
Hougang
Loyang
Nanyang Technological University
Bukit Timah Nature Reserve
Paya Lebar
Tampines
Changi International Airport
Toa Payoh
Clementi
Bedok
Tuas
Orchard Road
Little India
Katong
Arab St
Colonial District
Straits of Jurong
Chinatown
Jurong
Straits of Singapore
Sentosa Island
Straits of Singapore
SOUTHERN ISLANDS
Pulau



珠
坊
Forever
Spa
SPA
MASSAGE
AHEAD

General information

▪**Two databases are available:**
✓AIMS: including pipes characteristics
✓CINDY: including pipe bursts hysterical data for 2002-2011

▪**Number of pipes:** 3975 (>=100 mm)
▪**Range of diameter:** 100-1400 mm
▪**Available pipe characteristics:** Diameter, Length, Material, Age, lining, trench depth, pipes burst and leakage data

▪**Number of failure cases:** 269

▪**Number of real failure cases which can be used in model:** 27 (only Major Leaks)

▪**failure rate:** ~8%

▪**Applied tools:** **Hugin, MATLAB, Water Gems, ArcGIS, Excel, AutoCAD**.

Parameters classifications for modeling

Pipe diameter (D):
100<=D<=150 (L)
150<D<=300 (M)
300<D (H)

Pipe Length (L):
L<=3 (L)
3<L<=13 (M)
13<L (H)

Previous breaks (PB):
0<= PB <1 (L)
1< = PB <2 (M)
2< = PB (H)

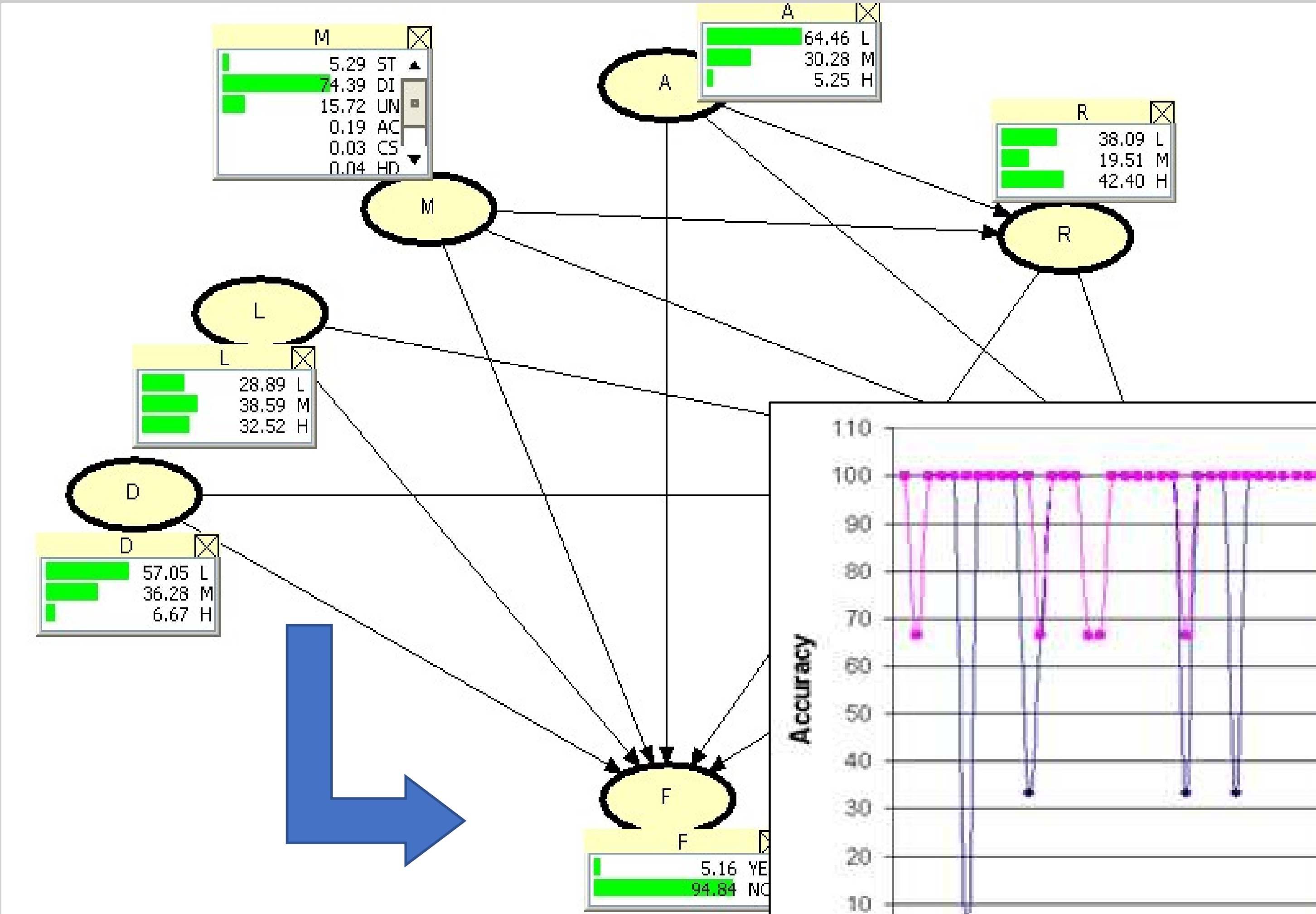
Age (A):
A<=10 (L)
10<A<=20 (M)
20< A (H)

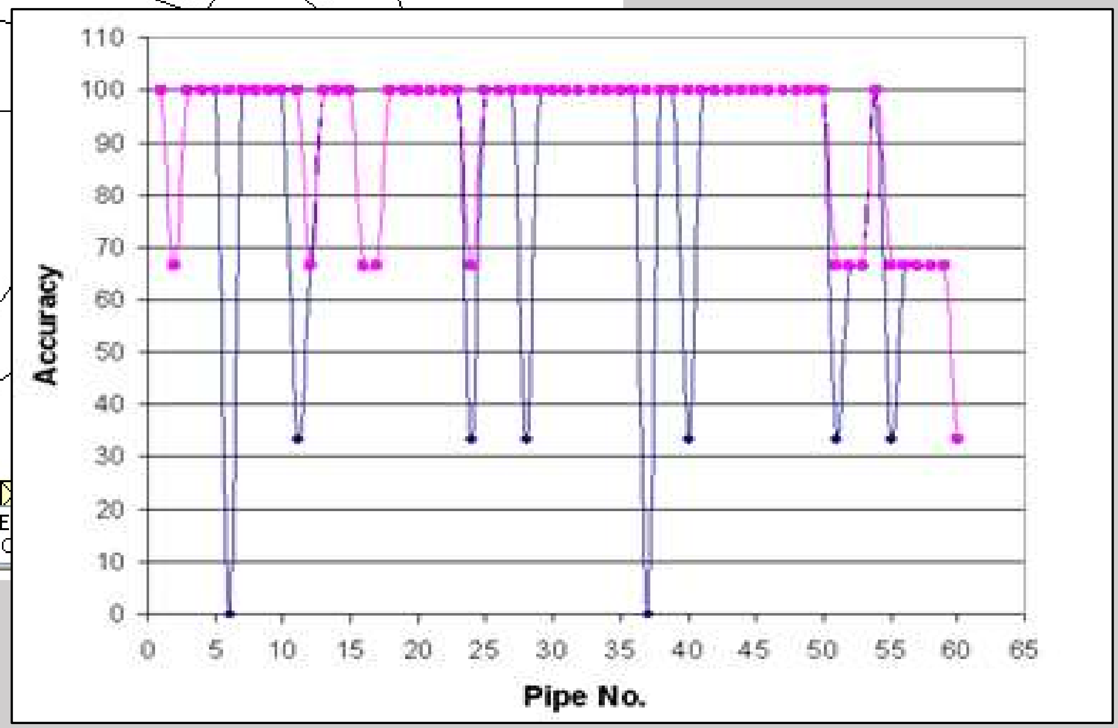
Material (M):
ABESTOS CEMENT (AC)
CAST IRON (CI)
CAST STEEL (CS)
DUCTILE IRON (DI)
HDPE (HD)
STEEL (ST)
UNKNOWN material (UN)

Roughness (R):
R<=120 (L)
120<A<=131 (M)
131< A (H)

Pipe failure (F)
Leak or burst-failure (YES)
No Leak or burst-no failure (NO)

Model validation for pipes failure or leakage prediction



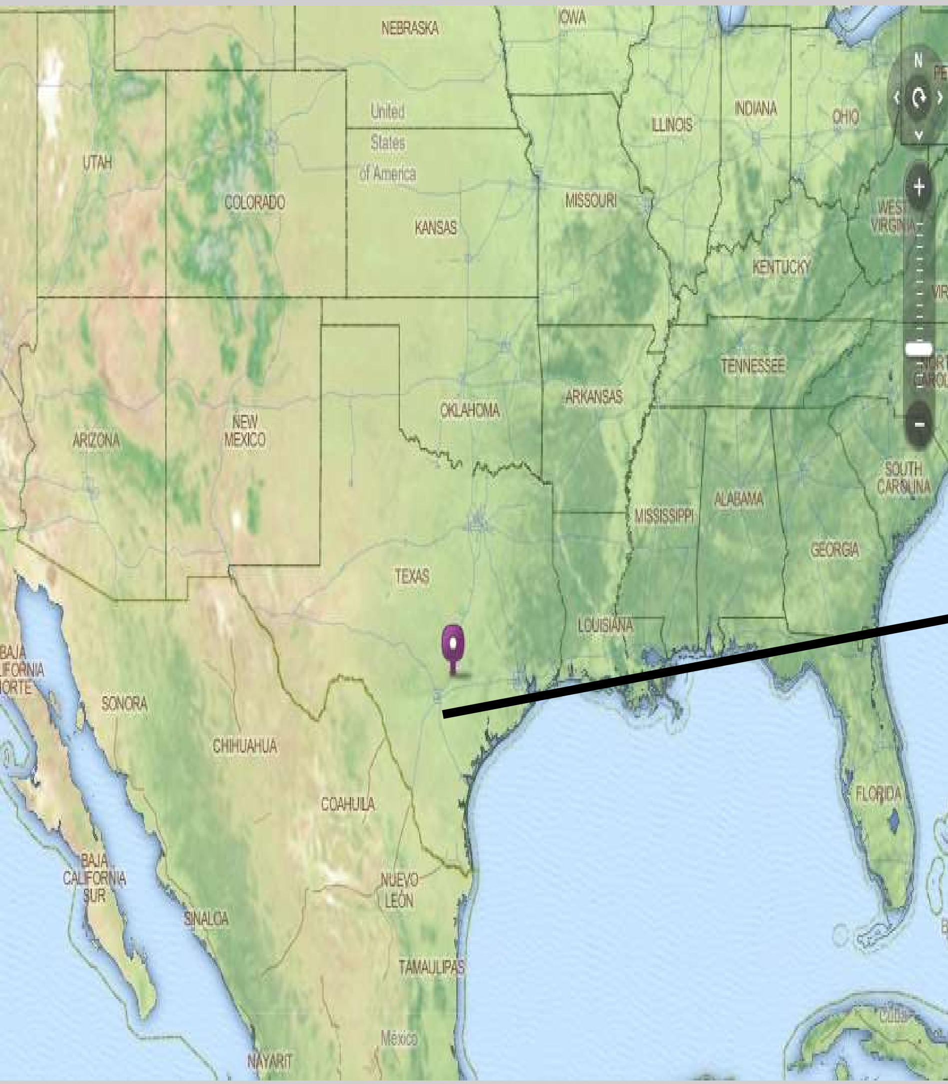


Maintenance Strategy (Risk management)

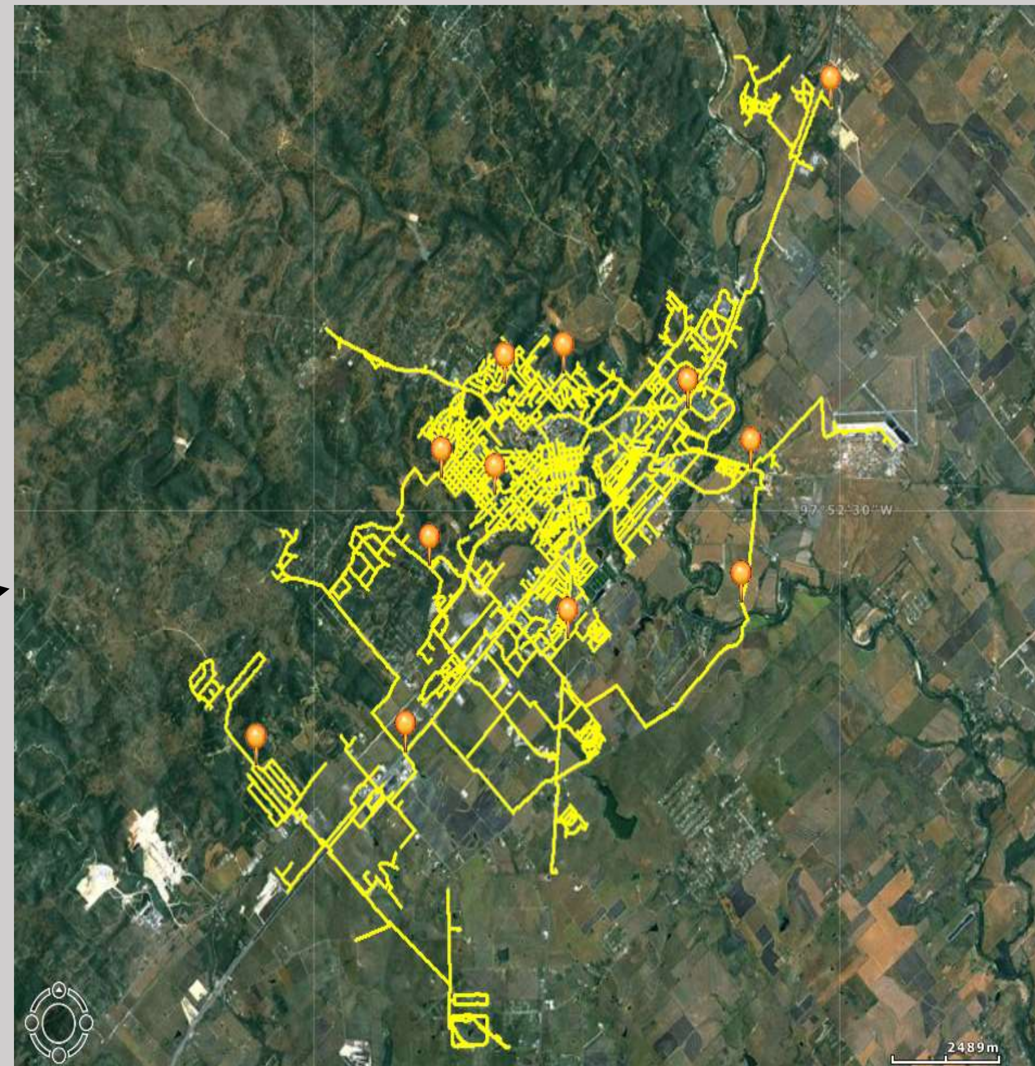
No need to any action	Monitoring	Low Priority rehabilitation	Medium Priority rehabilitation	High Priority rehabilitation
12.50%	19%	26%	32.50%	10%

San Marcos Water Distribution Network

Geographical location

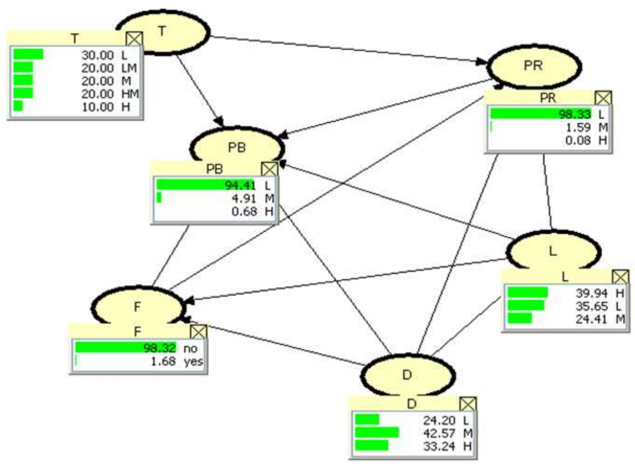


Water utility

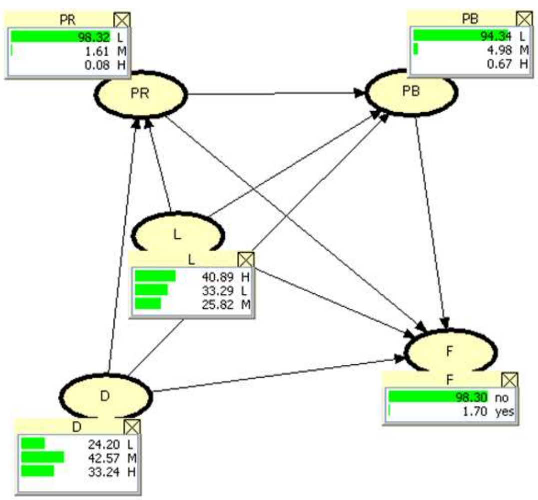


Number of failure cases: 1199 (2000-2013)

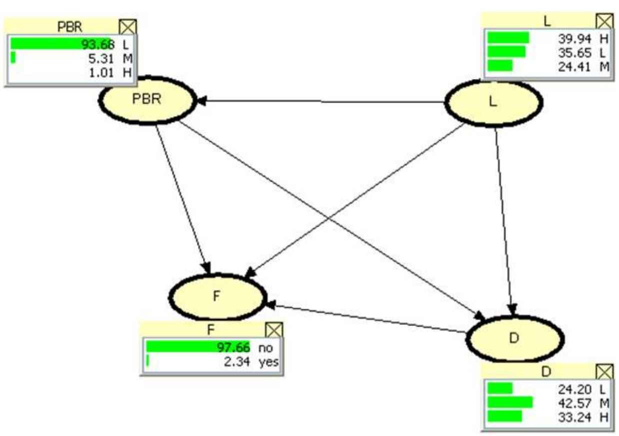
Model 1:



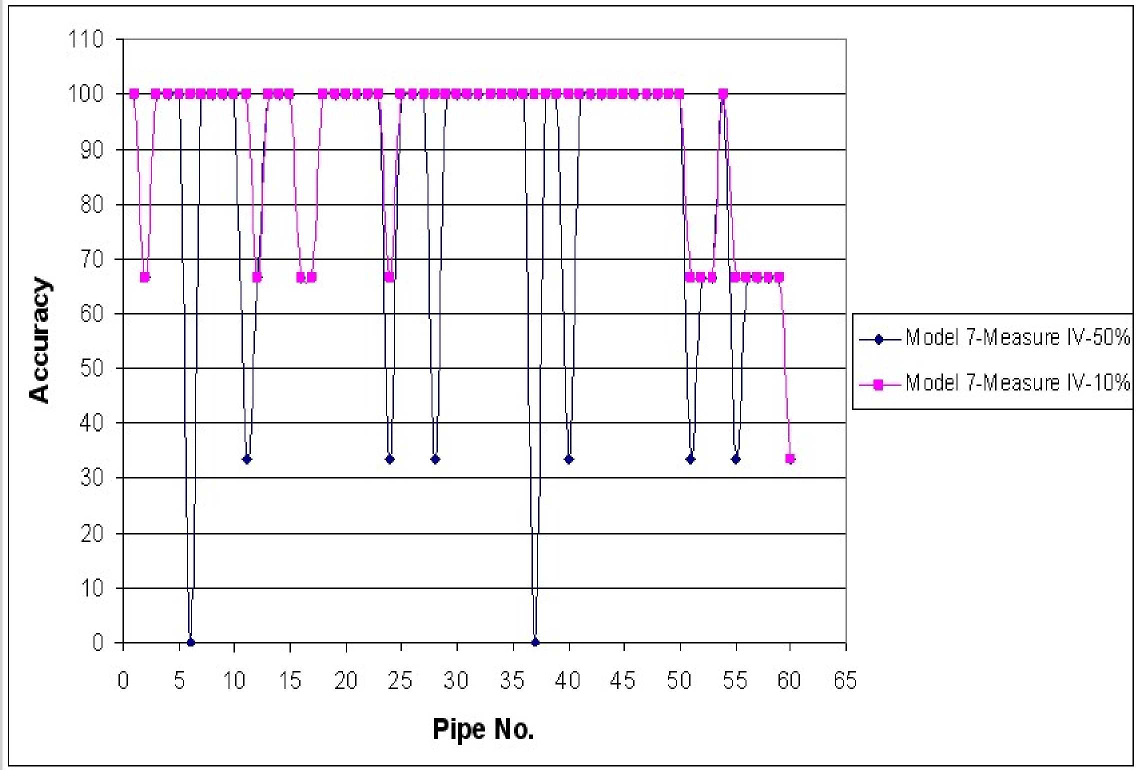
Model 7:



Model 8:



Failure prediction accuracy for each pipe-Model 7

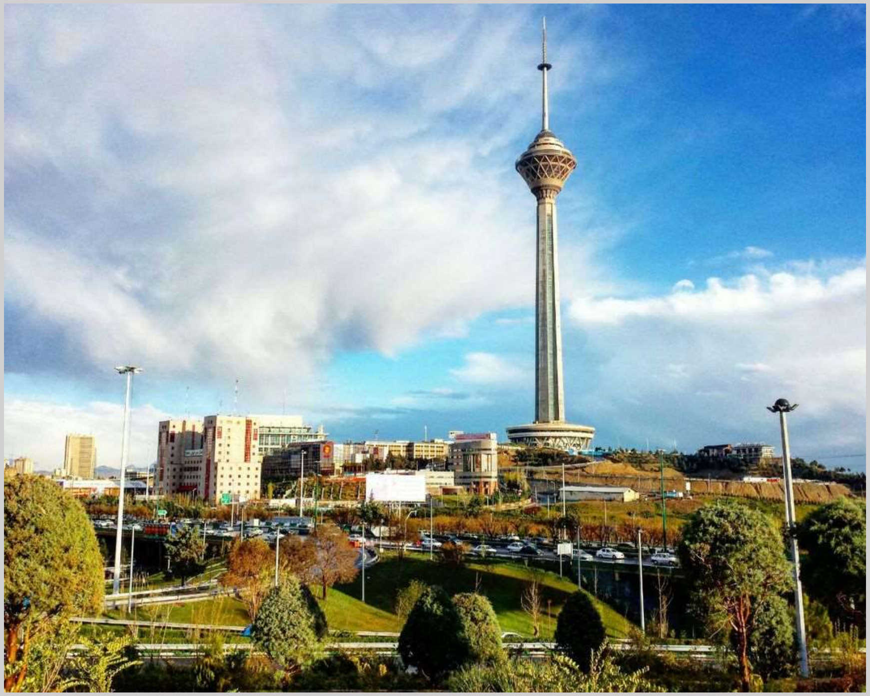


✓Models 7 has been found to yield better results as compared to the other models (Averagely 70-80% accuracy)

Case Study 2: Risk assessment of pipeline failure in wastewater collection networks

- **Tehran-Iran**

Roozbahani et al. (2015)

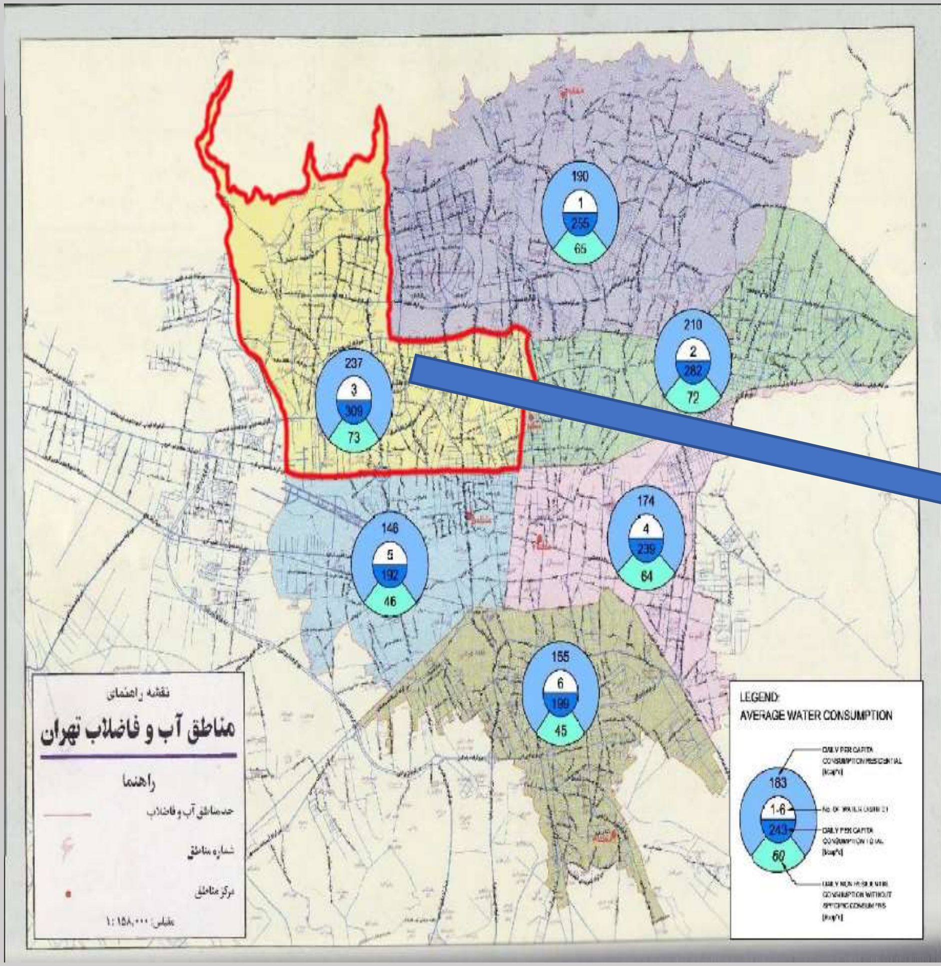


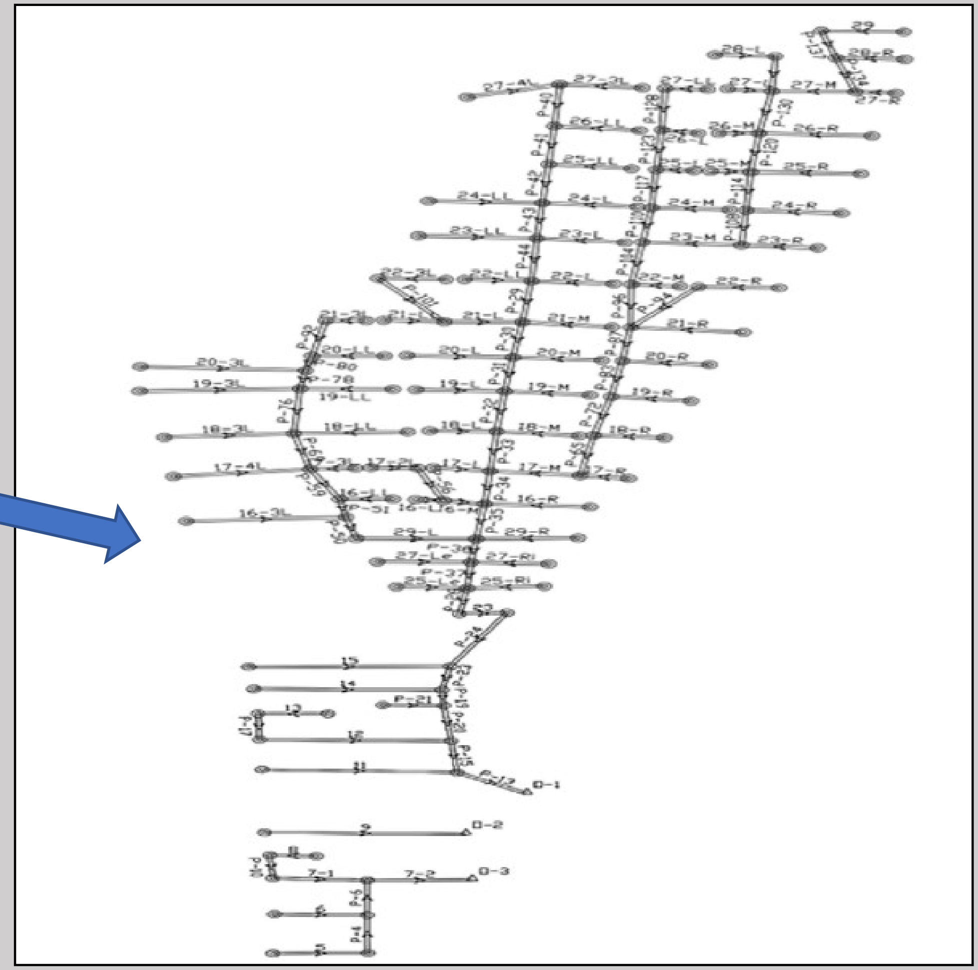
Tehran Province Water and Wastewater Co.

- Wastewater collection networks are critical in the preservation of a society public health, environment and economy.

- Structural and hydraulic failures occurrence in networks can lead to pollution of groundwater, waterways and wetlands, damage to roads and buildings, and disruption of vital services.

- The development of data mining models which can prioritize sewer pipes inspection based on their criticality and risk level is essential.

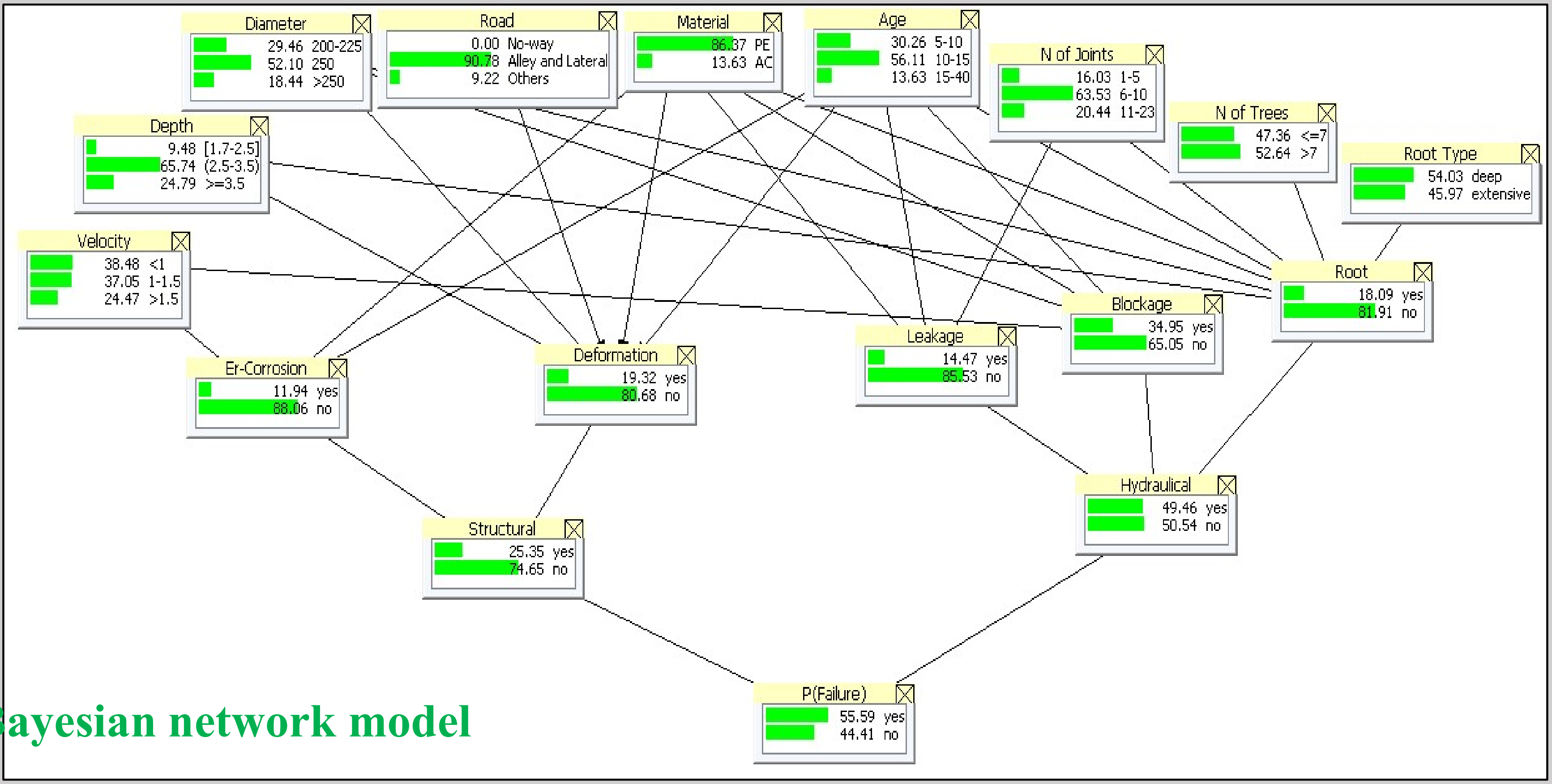




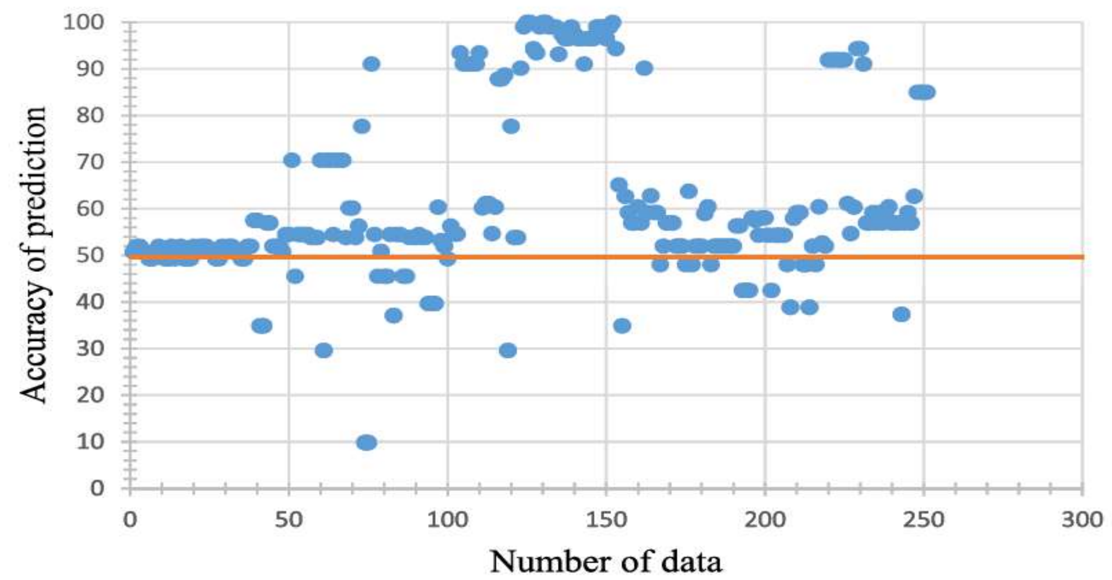
Sewer collection network in Gisha Area, Tehran City, Iran

Impact factors in the calculation of the probability of failure

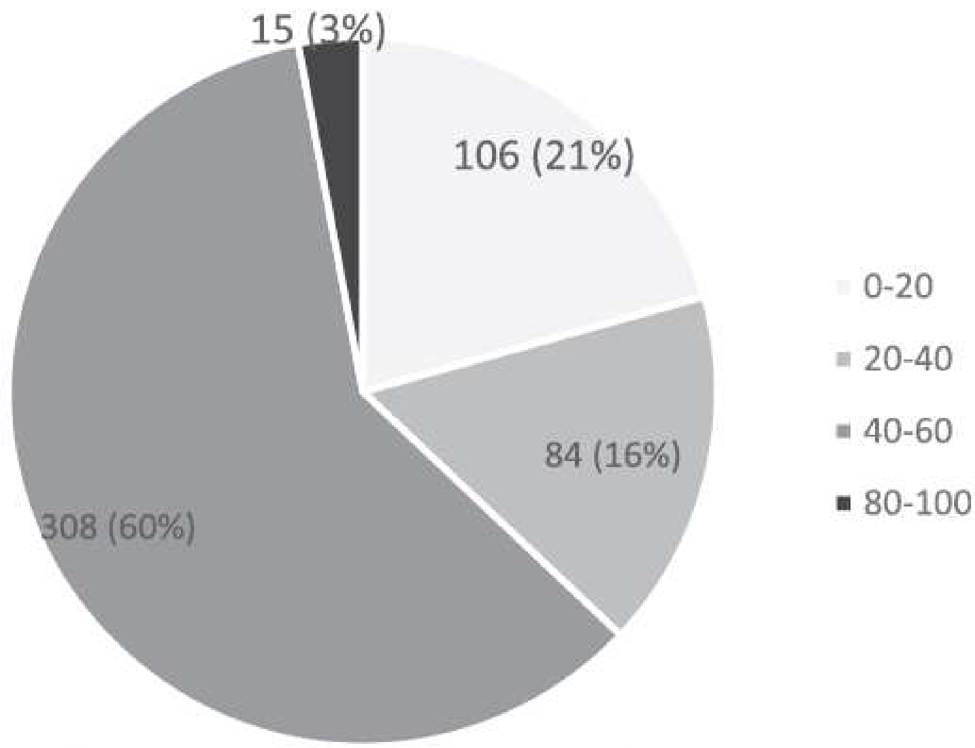
Type of failure	Damage	Impact factors
Structural failure	Erosion and corrosion	Age, material, cover and coating of the sewer, wastewater flow velocity, cathodic protection (in the case of iron and steel pipes)
	Deformation	Age, material, diameter and depth of the sewer, traffic volume (roadway type)
	Cracking, pipe fracturing or collapse	Age, diameter, size and depth of the sewer, groundwater level and traffic rate
Hydraulic failure	Leakage	Age and material of the sewer, number of connections and groundwater level
	Blockage due to sediments	Age, material and diameter of the sewer, wastewater flow velocity, sewer system (separate/combine)
	Blockage due to root	Number of trees around the pipe, type of trees (deep or shallow roots), age, material, depth and diameter of the sewer, number of connections



Bayesian network model



Model prediction accuracy for validation datasets.

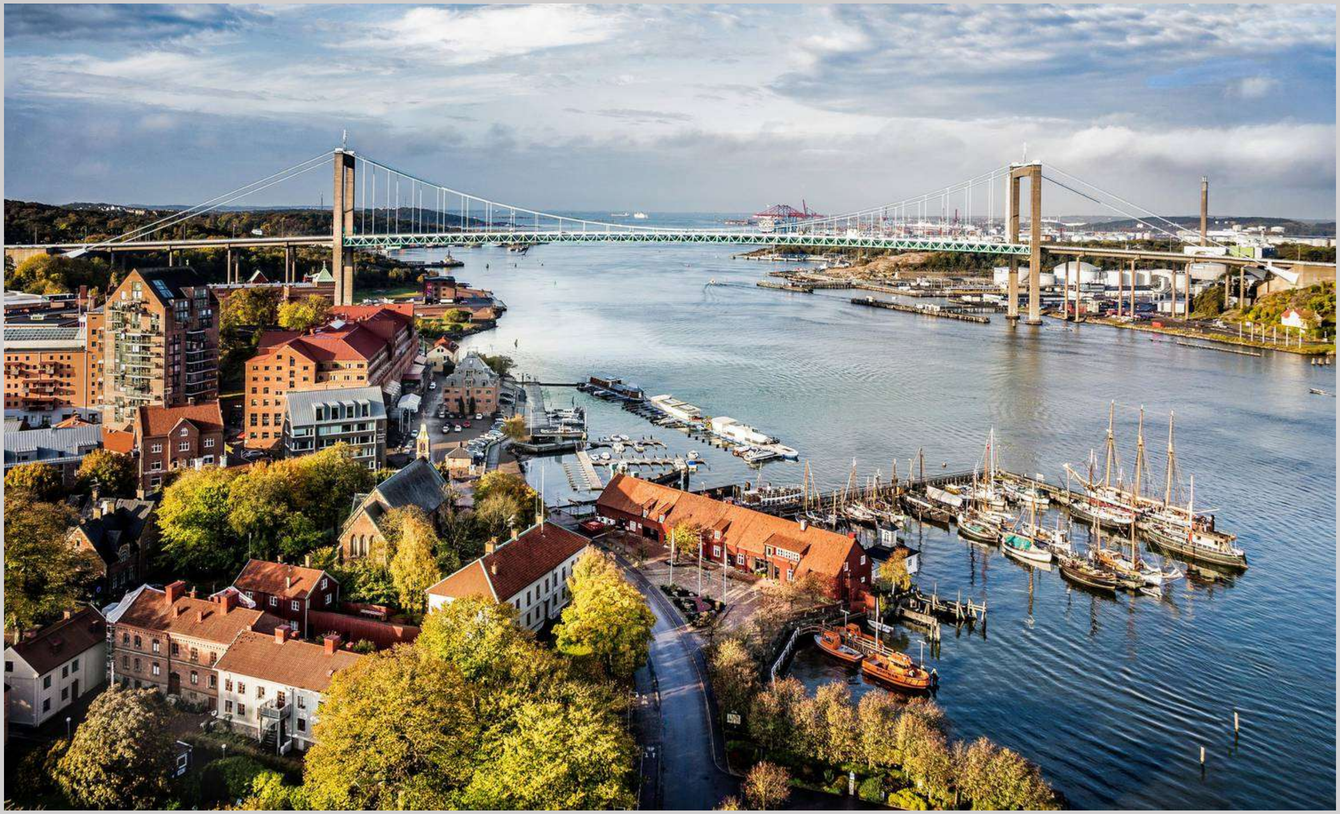


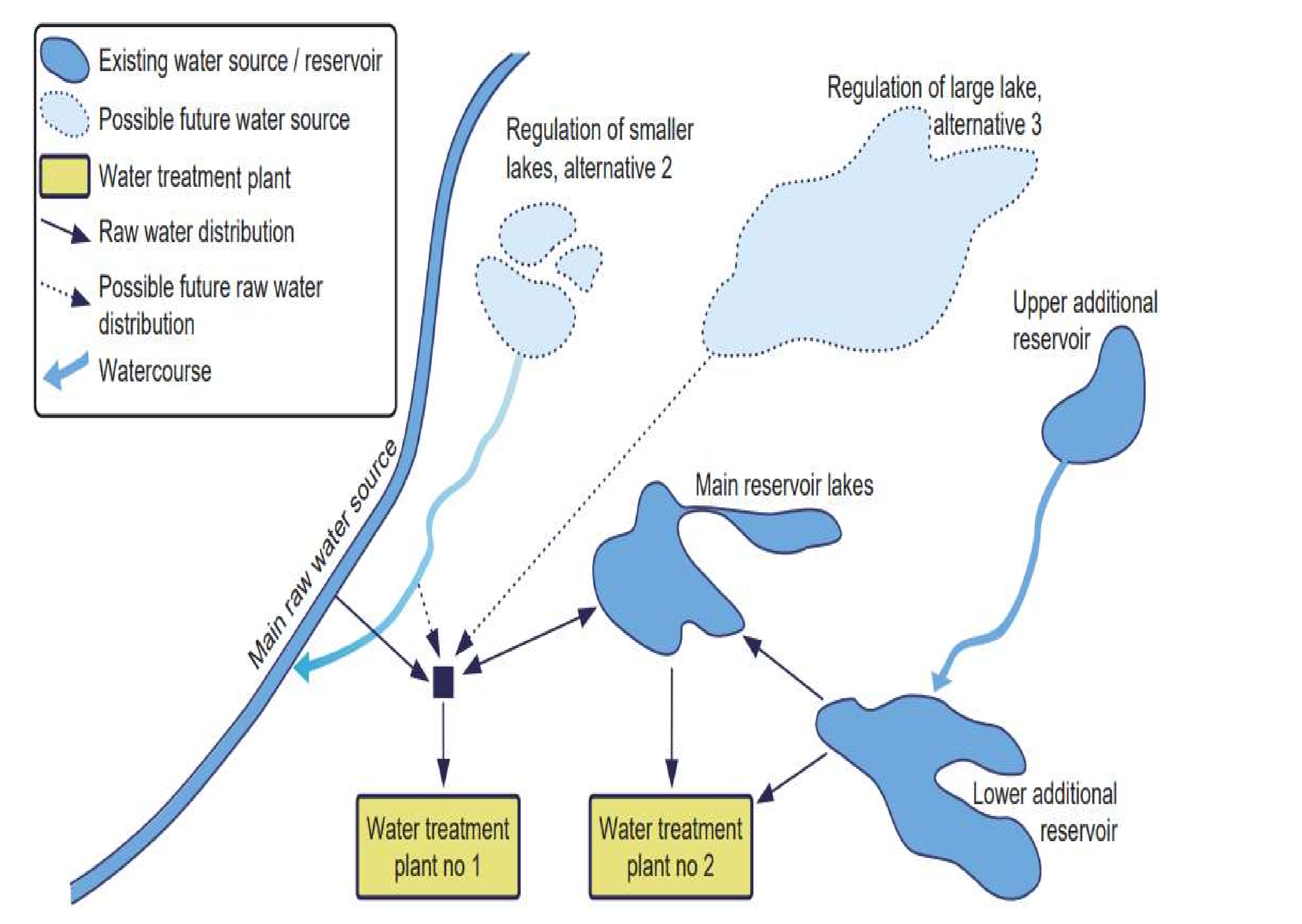
Numbers of sewer pipes in each category of probability of failure

Case Study 3: water supply risk assessment using Fault Tree Analysis

- Gothenburg-Sweden

Lindhe et al. 2008-2010

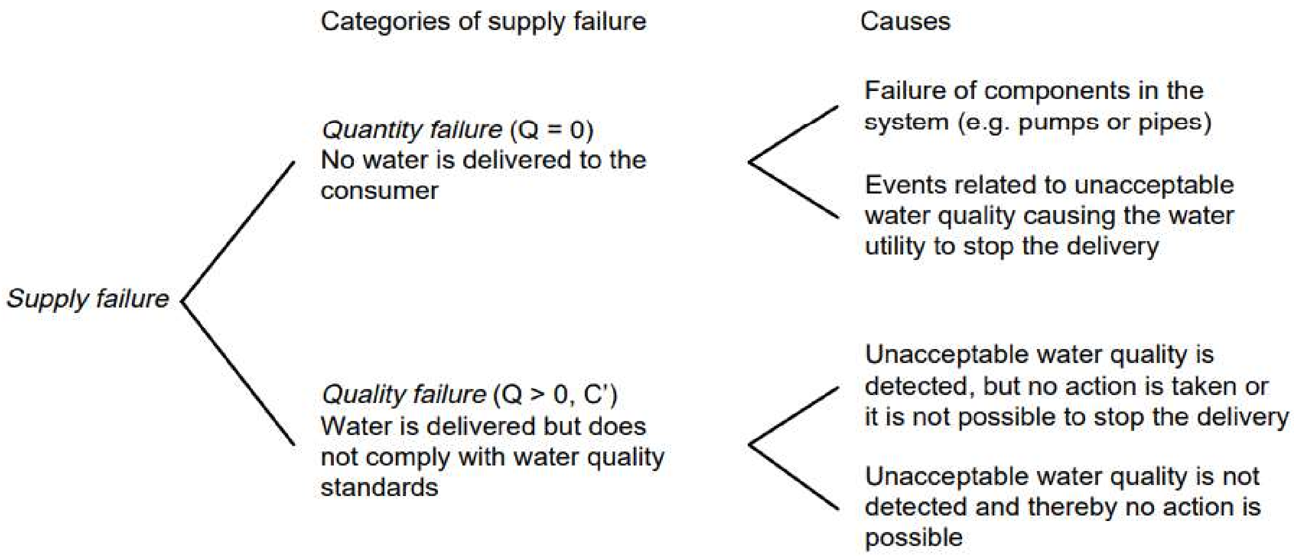




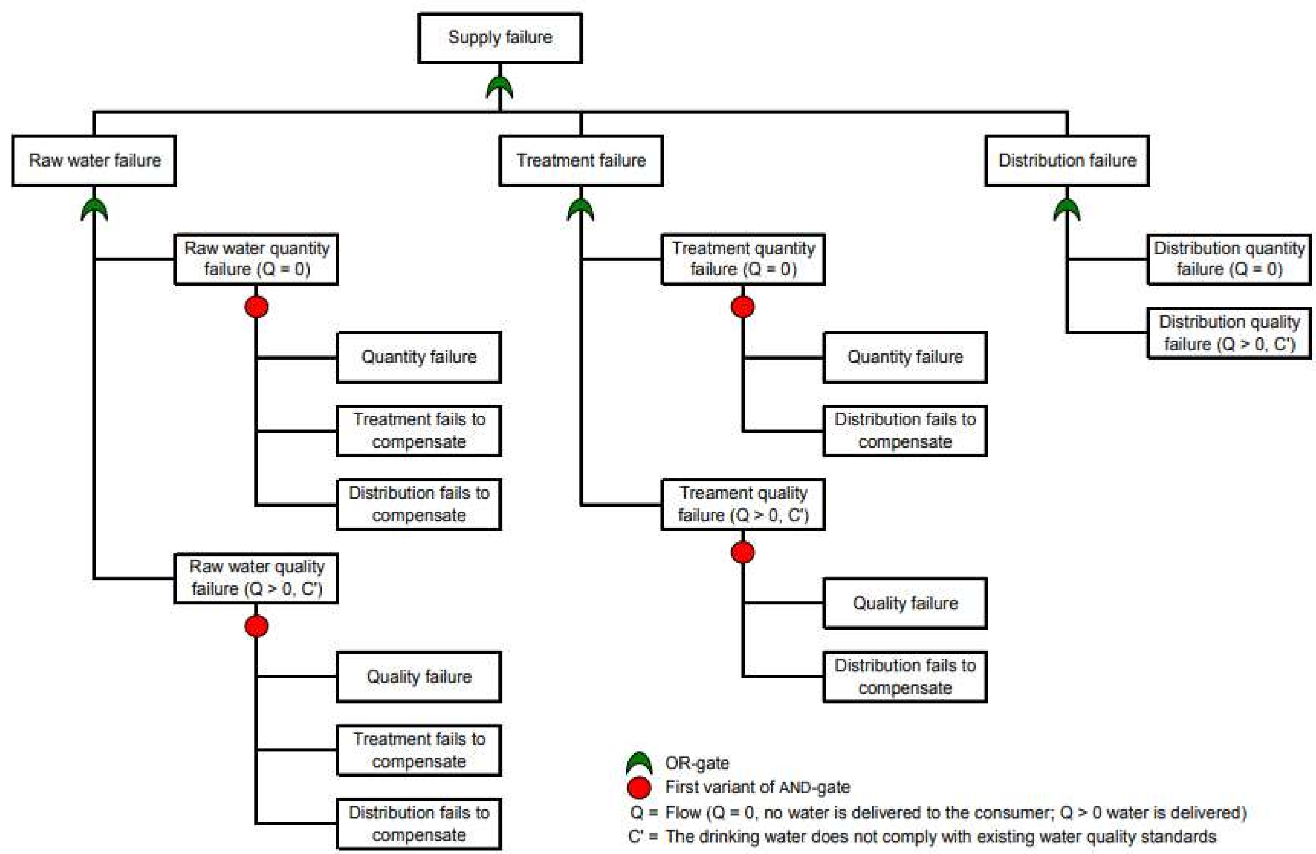
Schematic description of the Gothenburg raw water system. Possible future raw water supplies included in the analysis are further described in the *Risk-reduction alternatives* section.

Goal: reaching specified water safety targets

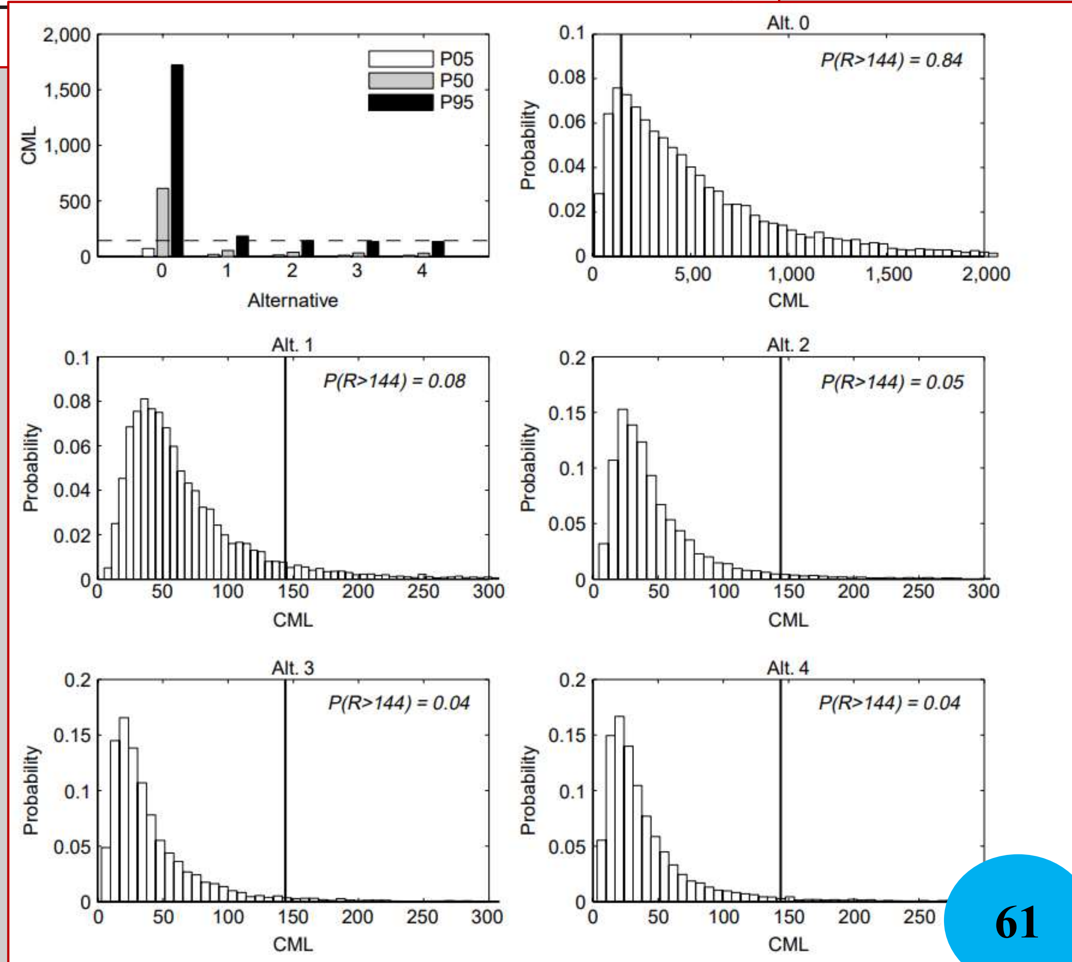
Risk indicator:
Customer Minutes Lost (CML)



Q = Flow (Q = 0, no water is delivered to the consumer; Q > 0,water is delivered)
C'= The drinking water does not comply existing with water-quality standards



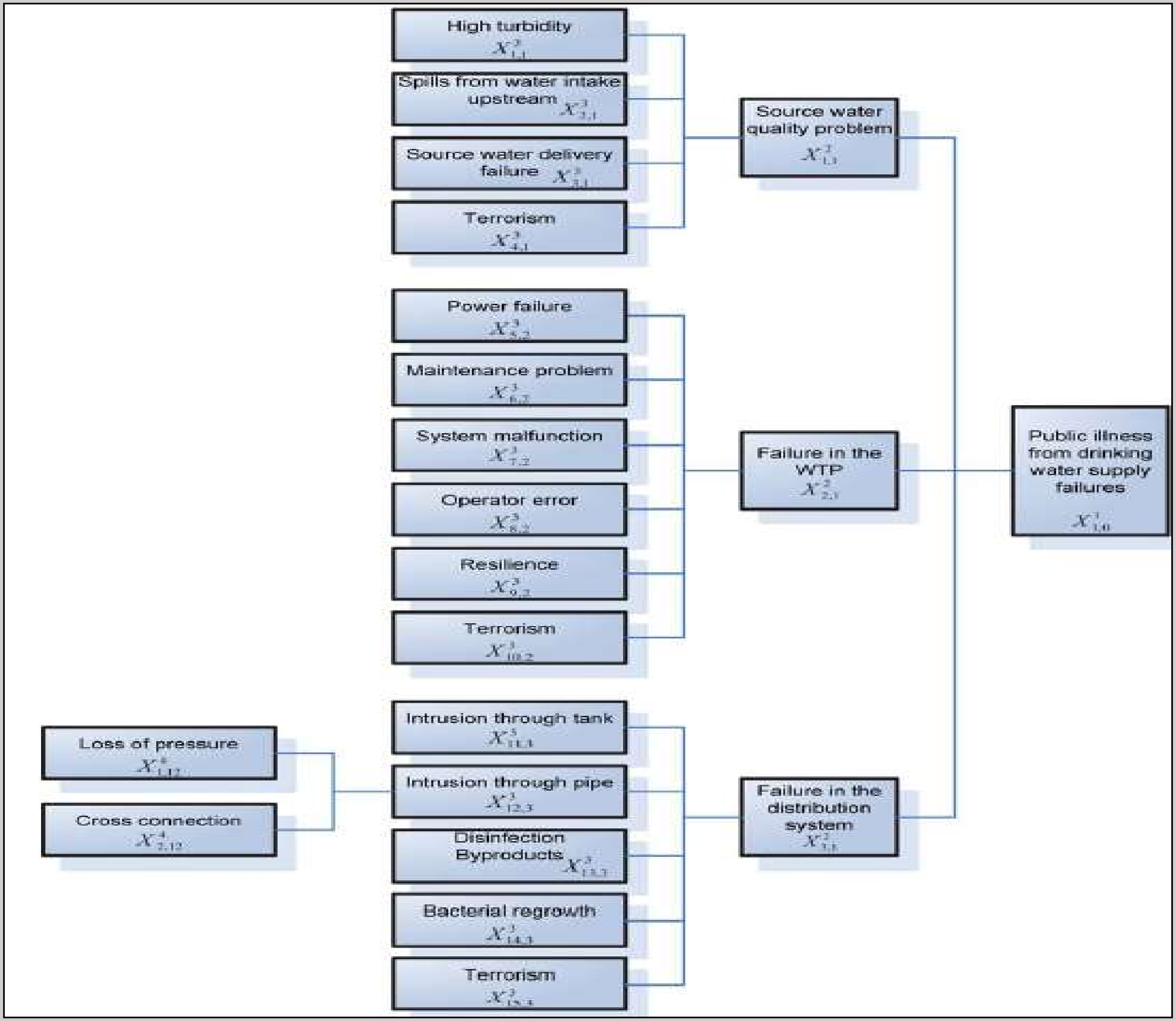
Alternative	Major changes in input variables of the fault tree model
0. No measures taken	–
1. Increased treatment capacity	Based on statistical data on water demand and estimations regarding the reliability of the treatment plants, the time for compensation (uptime) was estimated to be between 3–120 days (90%-interval) and the probability of failure on demand 0.0025–0.01 (90%-interval)
2. Increased treatment capacity combined with regulation and supply from smaller lakes	If available and if only treatment plant no 1 needs supply, the source is available (uptime) 25–35 days (90%-interval), whereas if both treatment plants need to be supplied the available time (uptime) is restricted to 8–18 days (90%-interval). When the lakes are not available, the duration (downtime) is 7–60 days (90%-interval)
3. Increased treatment capacity combined with regulation and supply from larger lake	The time to failure (uptime) is 5–15 (90%-interval) for all three events considered (water shortage, failures in the transfer of raw water and unacceptable water quality in the lake). When failure occurs the duration (downtime) is estimated to be 1–30 days for water shortage, 0.5–2 days for transfer failures, and 5–30 days for water quality failures (all 90%-interval)
4. Combination of alt. 2 and 3	See alternatives 2 and 3



Case Study 4: Fuzzy-Logic Modeling of Risk Assessment for Small Drinking-Water Supply Systems

- North Battleford –Canada

Lee et al. 2009


High turbidity $X^3_{1,1}$
Spills from water intake upstream $X^3_{2,1}$
Source water delivery failure $X^3_{3,1}$
Terrorism $X^3_{4,1}$
Source water quality problem $X^2_{1,1}$
Power failure $X^3_{5,2}$
Maintenance problem $X^3_{6,2}$
System malfunction $X^3_{7,2}$
Operator error $X^3_{8,2}$
Resilience $X^3_{9,2}$
Terrorism $X^3_{10,2}$
Failure in the WTP $X^2_{2,1}$
Public illness from drinking water supply failures $X^1_{1,0}$
Loss of pressure $X^4_{1,12}$
Cross connection $X^4_{2,12}$
Intrusion through tank $X^3_{11,3}$
Intrusion through pipe $X^3_{12,3}$
Disinfection Byproducts $X^3_{13,3}$
Bacterial regrowth $X^3_{14,3}$
Terrorism $X^3_{15,3}$
Failure in the distribution system $X^2_{3,1}$

Linguistic Definition of Partitions and TFNs for Likelihoods and Consequences

Partition (p)	Likelihood	Consequences	TFN_l or TFN_c
1	Extremely low	Extremely unimportant	(0.0, 0.0, 0.17)
2	Low	Unimportant	(0.0, 0.17, 0.33)
3	Moderately low	Moderately unimportant	(0.17, 0.33, 0.50)
4	Medium	Neutral	(0.33, 0.50, 0.67)
5	Moderately high	Moderately important	(0.50, 0.67, 0.83)
6	High	Important	(0.67, 0.83, 1.0)
7	Extremely high	Extremely important	(0.83, 1.0, 1.0)

Linguistic Definitions of Partitions and TFNs for Risk Factors

Partitions (p)	Risk	(TFN_{lc})
1	Very low (VL)	(0.0,0.0,0.25)
2	Low (L)	(0.0,0.25,0.50)
3	Medium (M)	(0.25,0.50,0.75)
4	High (H)	(0.50,0.75,1.0)
5	Very high (VH)	(0.75,1.0,1.0)

$$F(X) = [\mu_1^R \quad \mu_2^R \quad \mu_3^R \quad \mu_4^R \quad \mu_5^R]$$

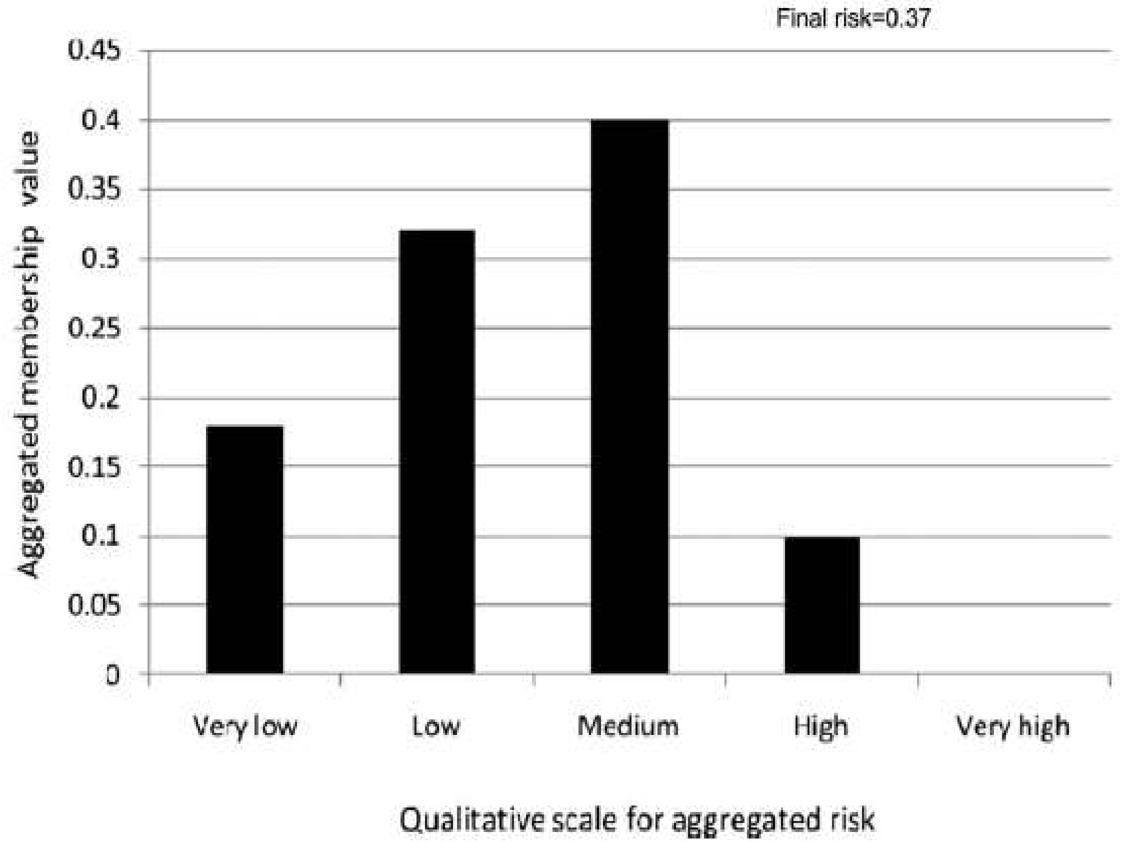
Failure scenario	Factors contributing failure/risk
	Source water
Source water quality problem by natural events	• High turbidity during flood or heavy rainfall runoff into the source water. • Snowmelt events; rain on snow. • Contamination from infected animals.
Spills	• Industrial spills or spills from transportation upstream of intake (closer to intake, more difficult to avoid because of less notification time). • Source water monitoring failure-unaware of the spills. • High potential risk if many factories or a wastewater plant upstream.
Source water delivery failure	• Pipe breakage. • Pump failure. • Power outage.
Terrorism/vandalism to source water	• Contaminant injection to source water storage. • Physical damage to source water delivery equipment. • Damage to source water infrastructure such as dams or storage, etc.

	Water treatment plant
Power failure	• Natural hazards. • No backup power generator or backup power generator failure. • Inability to treat water or monitor water quality in case of both power/backup power failure.
Maintenance problem	• Many treatment facilities and hardware to maintain. • Poor water quality on startup if only seasonal use.
System malfunction	• Monitoring malfunction, hardware malfunction. • It may take a long time to repair/fix when system malfunctions. • Power failure causes system malfunction or error.
Operator error	• Untrained or inexperienced operator errors. • No trained manager to offer advice when unusual incidents occur or lack of system-specific experienced operators. • No redundancy for employee (i.e., available to back up someone else's job when sickness) although usually better, compared to small systems.
Lack of resilience	• Lack of water treatment equipment. • Poorly designed treatment plant. • Failure of multibarrier facilities.
Terrorism/vandalism	• Power disruption. • System disruption/damage. • Supervisory Control and Data Acquisition (SCADA) disruption.

Distribution system	
Intrusion of contaminants through reservoir/tank	• Cracks on the underground reservoir/tank floor. • Pipe breakage near the entry of the reservoir/tank.
Intrusion of contaminants through pipes due to loss of pressure	• Power failure causing pump disability. • Pump out of order. • Pipe breakage. • Fire fighting.
Intrusion of contaminants through pipes due to cross connection	• No backflow preventer. • Failure of backflow preventer. • Unintentional connection between drinking water pipe and another type of pipe.
Disinfection by-products	• High turbidity, High water temperature. • High chlorine residual. • Improper pH value.
Bacterial regrowth	• Low chlorine residual. • High turbidity/high water temperature. • Pipe material/age. • Biofilm. • Excessive hydraulic detention time.
Terrorism/vandalism	• Monitoring disruption. • Injection of contaminant to finished water storage/pipes. • Destruction of storage facilities/pipes.

Risk Ranks and Defuzzified Risks of Basic Risk Items for North Battleford Case Study

Risk/failure item	Definition	Small surface water $l_{i,j}^k$	$c_{i,j}^k$	$g(l_{i,j}^k, c_{i,j}^k)$
$X_{1.1}^3$	Water quality problem by natural events	4	6	0.44
$X_{2.1}^3$	Spills	5	7	0.32
$X_{3.1}^3$	Source water delivery failure	2	6	0.16
$X_{4.1}^3$	Terrorism/vandalism	1	5	0.05
$X_{5.2}^3$	Power failure	3	6	0.30
$X_{6.2}^3$	Maintenance problem	6	5	0.35
$X_{7.2}^3$	System malfunction	3	6	0.35
$X_{8.2}^3$	Operator error	5	6	0.44
$X_{9.2}^3$	Lack of resilience	3	5	0.24
$X_{10.2}^3$	Terrorism/vandalism	1	6	0.06
$X_{11.3}^3$	Intrusion through tank/reservoir	3	6	0.30
$X_{1.12}^4$	Intrusion through pipe by loss of pressure	4	6	0.44
$X_{2.12}^4$	Intrusion through pipe by cross connection	4	7	0.48
$X_{13.3}^3$	Disinfection by-products	4	7	0.48
$X_{14.3}^3$	Bacterial regrowth	5	6	0.44
$X_{15.3}^3$	Terrorism/vandalism	1	7	0.06



Final aggregated risk of potential failure of North Battleford drinking water system

Case Study 5: Risk analysis of urban stormwater systems

- Tehran-Iran

Roozbahani et al. (2017)

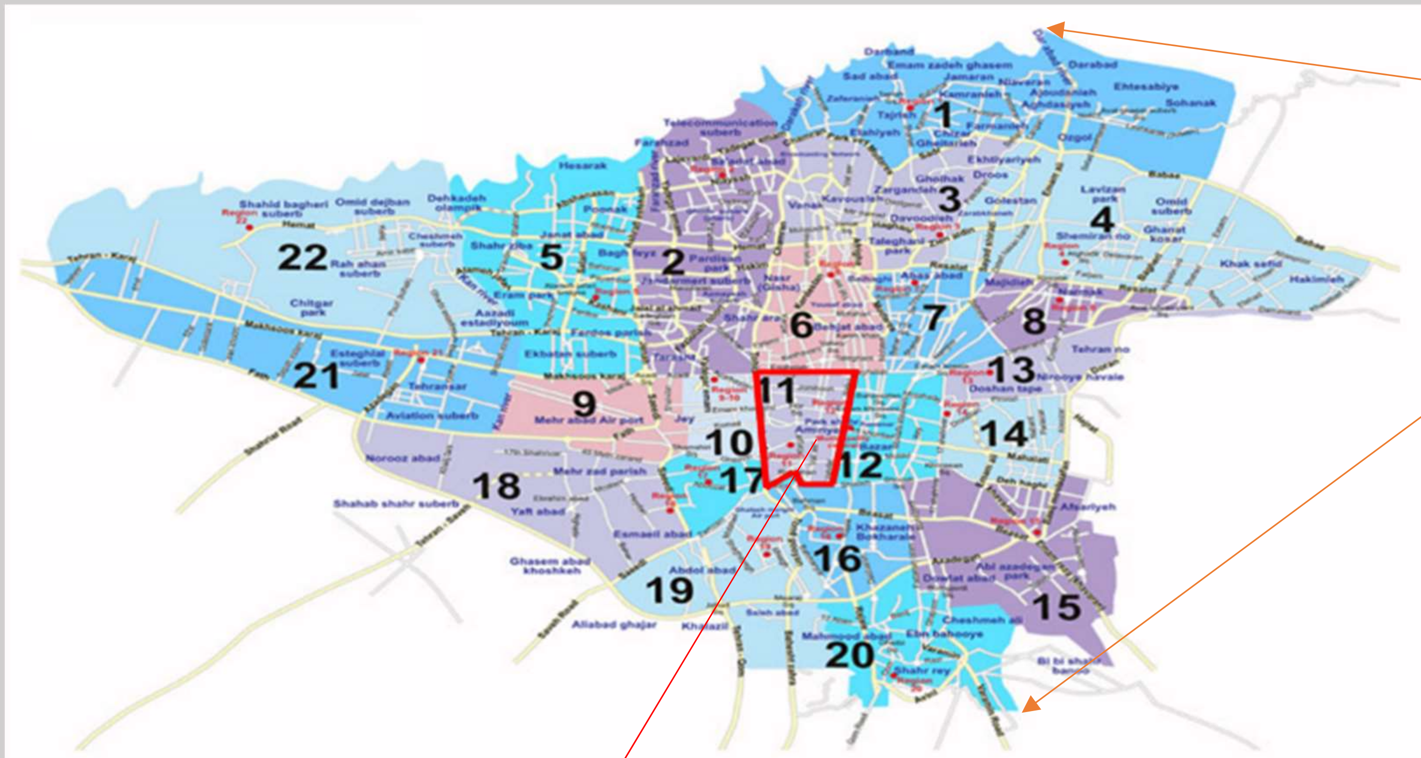
University of TEHRAN

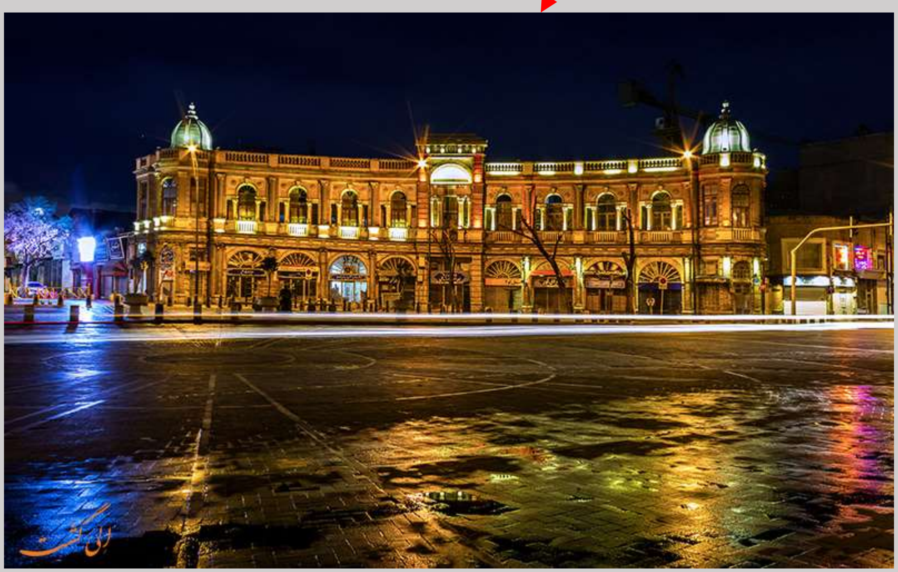
VILLANOVA UNIVERSITY

❖ Design and performance of stormwater infrastructure systems in urban areas have direct implications in social, environmental and public health problems.

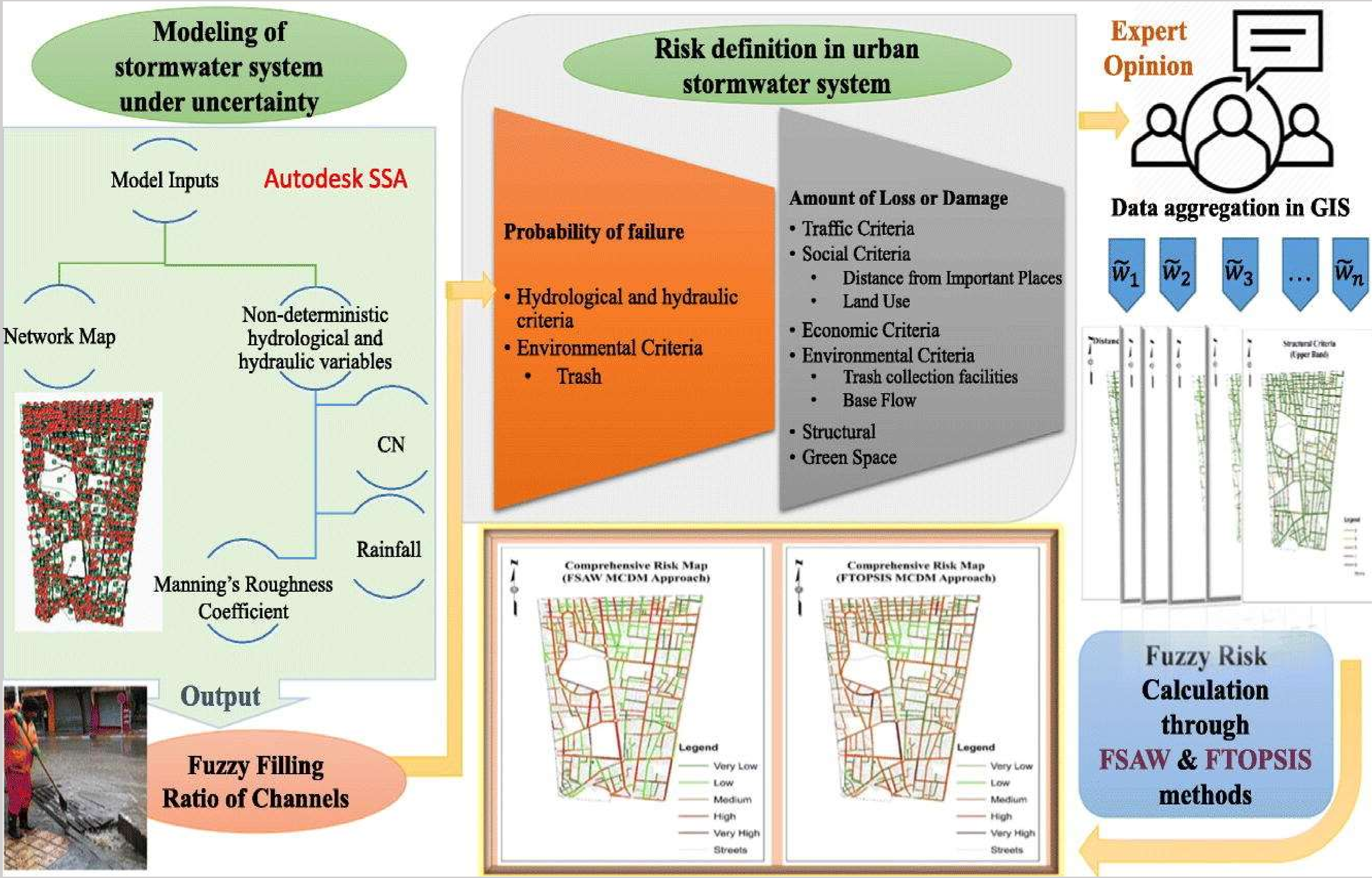
❖ Urbanization and climate change are among issues that increase the potential of flooding in urban areas and bring more uncertainty to rainfall and runoff characteristics

Risk analysis in urban stormwater systems is essential because of the extensive consequences of flooding in urban areas and limited funding for rehabilitation and renovation of stormwater systems.



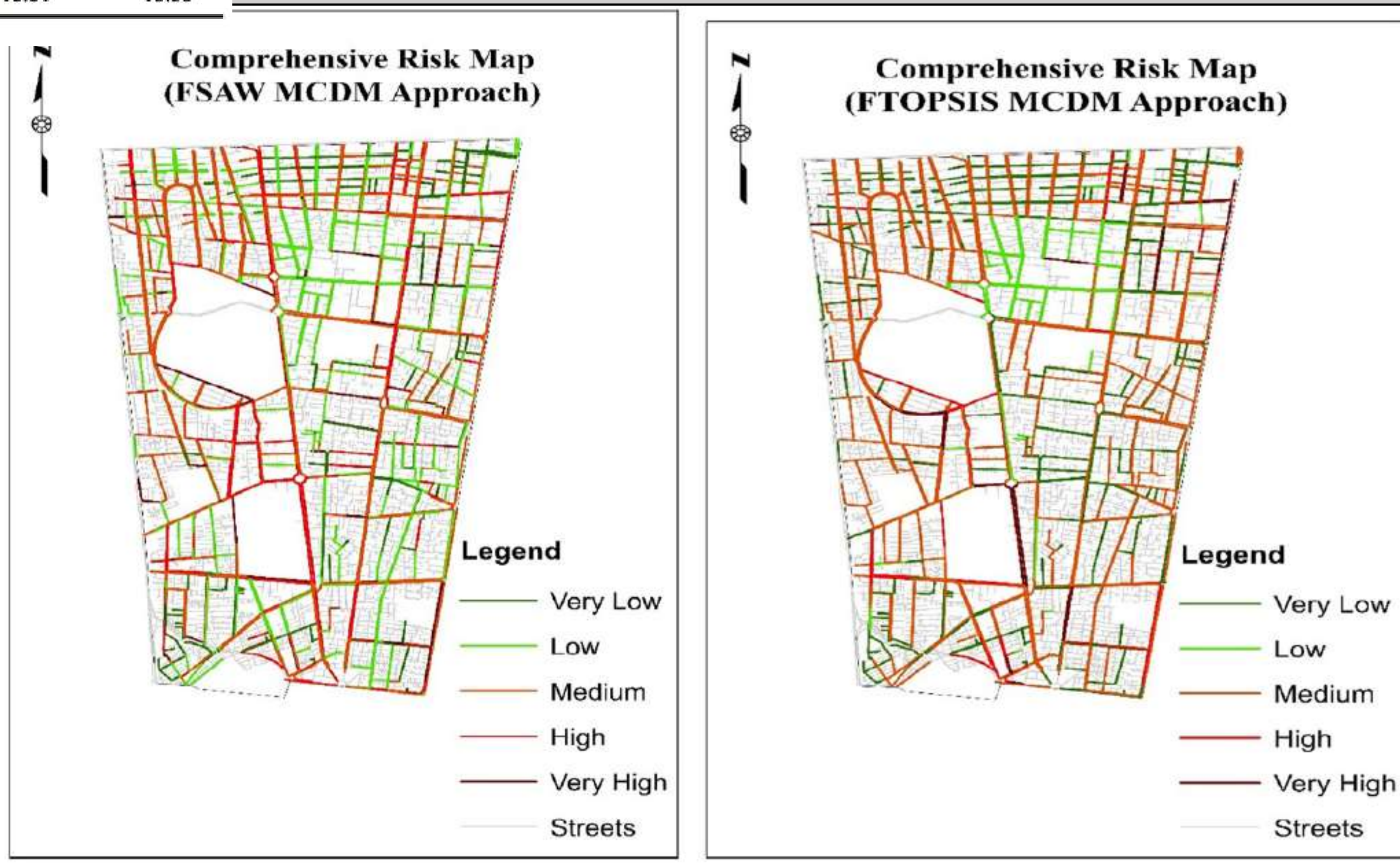


Study area: Zone 11 Municipality, Tehran


Modeling of stormwater system under uncertainty
Model Inputs
Autodesk SSA
Network Map
Non-deterministic hydrological and hydraulic variables
CN
Rainfall
Manning's Roughness Coefficient
Output
Fuzzy Filling Ratio of Channels
Risk definition in urban stormwater system
Probability of failure
• Hydrological and hydraulic criteria
• Environmental Criteria
• Trash
Amount of Loss or Damage
• Traffic Criteria
• Social Criteria
• Distance from Important Places
• Land Use
• Economic Criteria
• Environmental Criteria
• Trash collection facilities
• Base Flow
• Structural
• Green Space
Expert Opinion
Data aggregation in GIS
$\tilde{w}_1$ $\tilde{w}_2$ $\tilde{w}_3$ … $\tilde{w}_n$
Fuzzy Risk Calculation through FSAW & FTOPSIS methods
Comprehensive Risk Map (FSAW MCDM Approach)
Comprehensive Risk Map (FTOPSIS MCDM Approach)
Legend
Very Low
Low
Medium
High
Very High
Streets

Maximum 6-h precipitation data during the future period (mm).

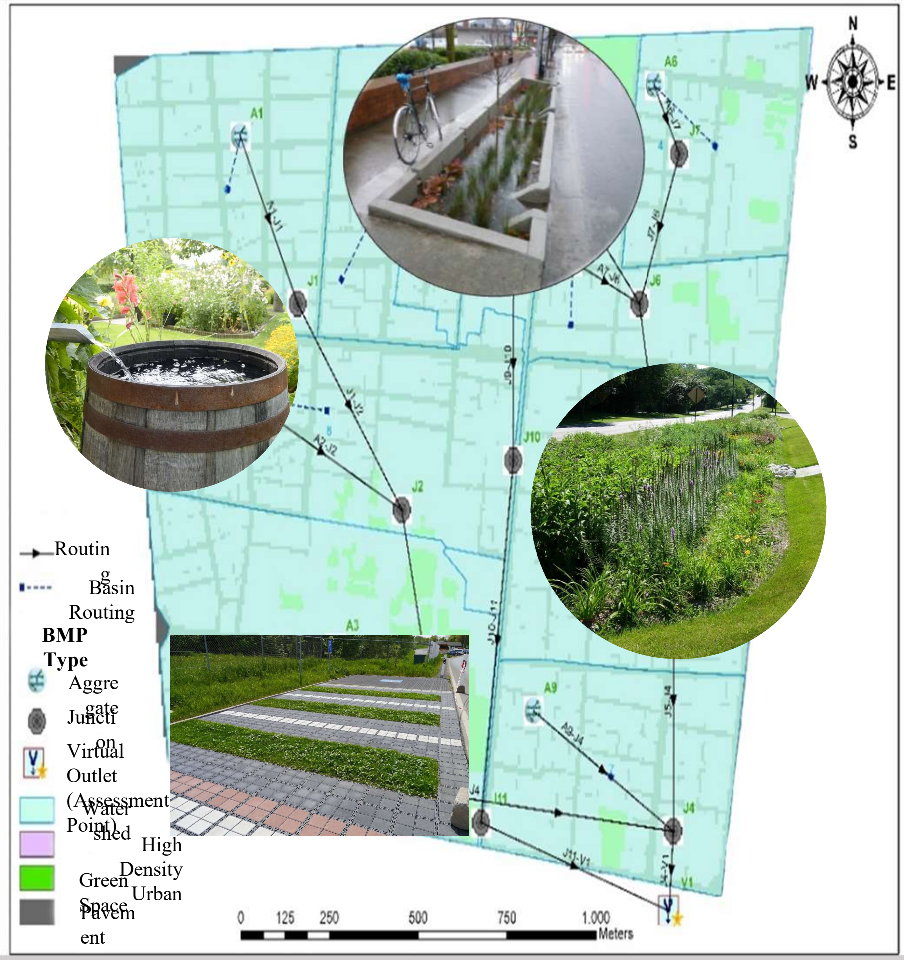
Climatic model	RCP 2.6		RCP 8.5	
	T=5	**T=10**	**T= 5**	T = 10
MIROC-ESM	18.24	21.09	18.81	20.52
GISS-E2- R	16.53	17.67	15.39	17.67
CESM1-WACCM	14.25	16.53	19.95	22.23
CSIRO-Mk3-6-0	20.52	22.8	18.81	20.52
MPI-ESM-LR	18.24	19.38	19.95	21/66
GISS-E2-H	19.38	21.09	19.38	21.09
CanESM2	21.66	23.94	19.38	23.23
HadGEM2- es	20.52	22.23	18.81	20.52
CNRM-CM5	18.81	21.66	19.38	21.09
GFDL-CM3	17.67	19.38	17.67	18.81
MEDIAN	18.24	19.38	18.81	19.95

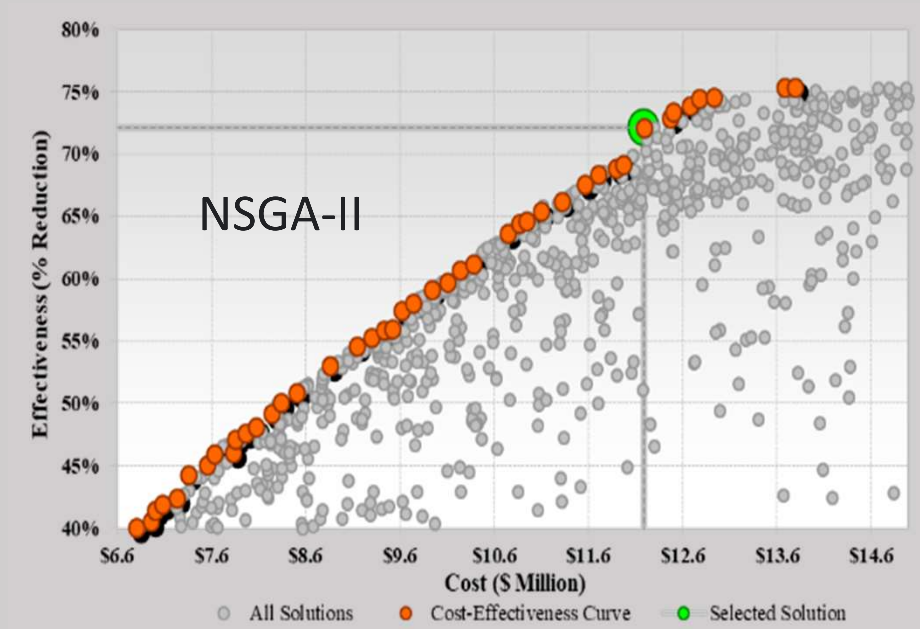


(i) (ii)

Final risk map by using: (i): FSAW approach and (ii): FTOPSIS approach.

Implementation of LIDs





LID Type	Number of Units	Area(m^2)	Total Surface Area (m^2)	Total Cost (M$)	Flood volume Reduction(%)
Rain Barrel	1370	0	75820	12.2	**72**
Permeable Pavement	1410	75423			
Bioretention	16	178			

- **Case Study 6: Risk-Based Approach in Rehabilitation of Water Distribution Networks**
  - **Trondheim, Norway**

Raspati et al. 2022

TRONDHEIM MUNICIPALITY

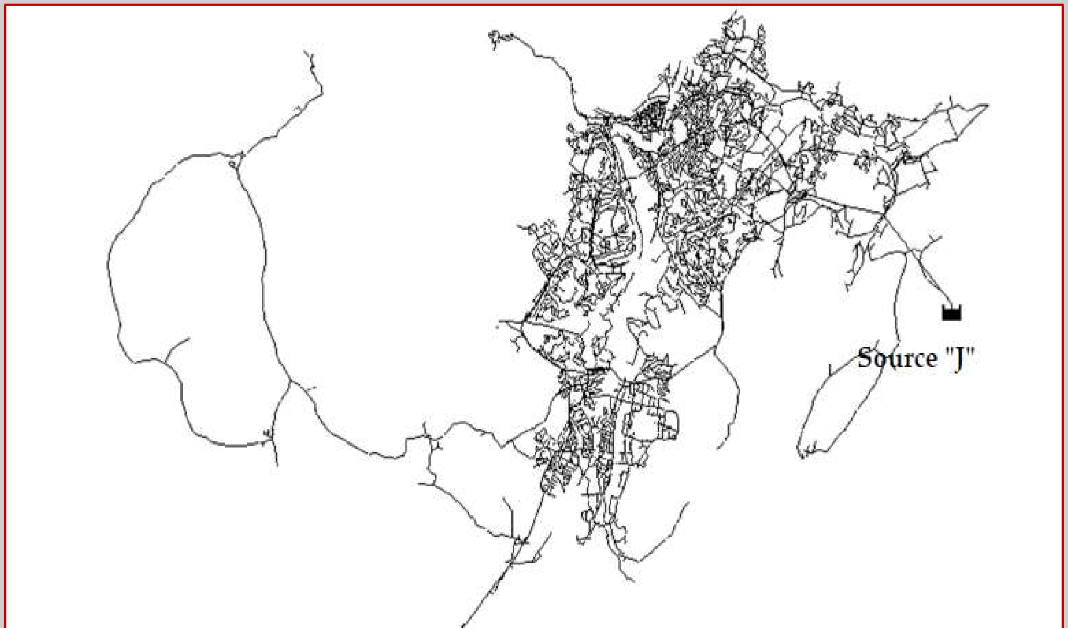
STOP-IT

SINTEF

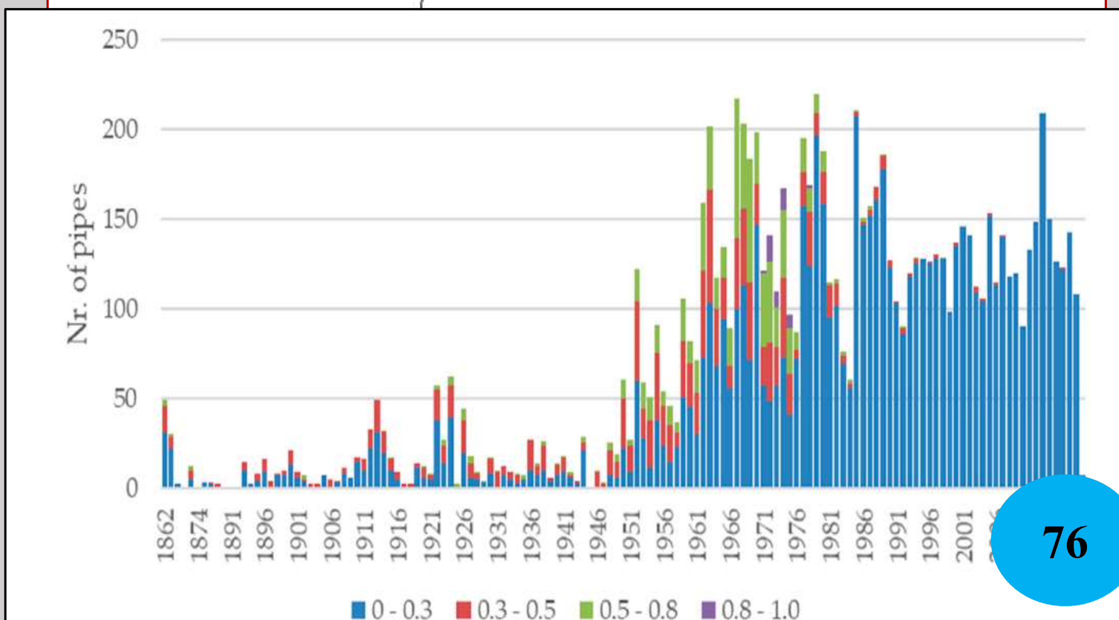
The water distribution network is crucial for ensuring a well-functioning centralized water supply system.

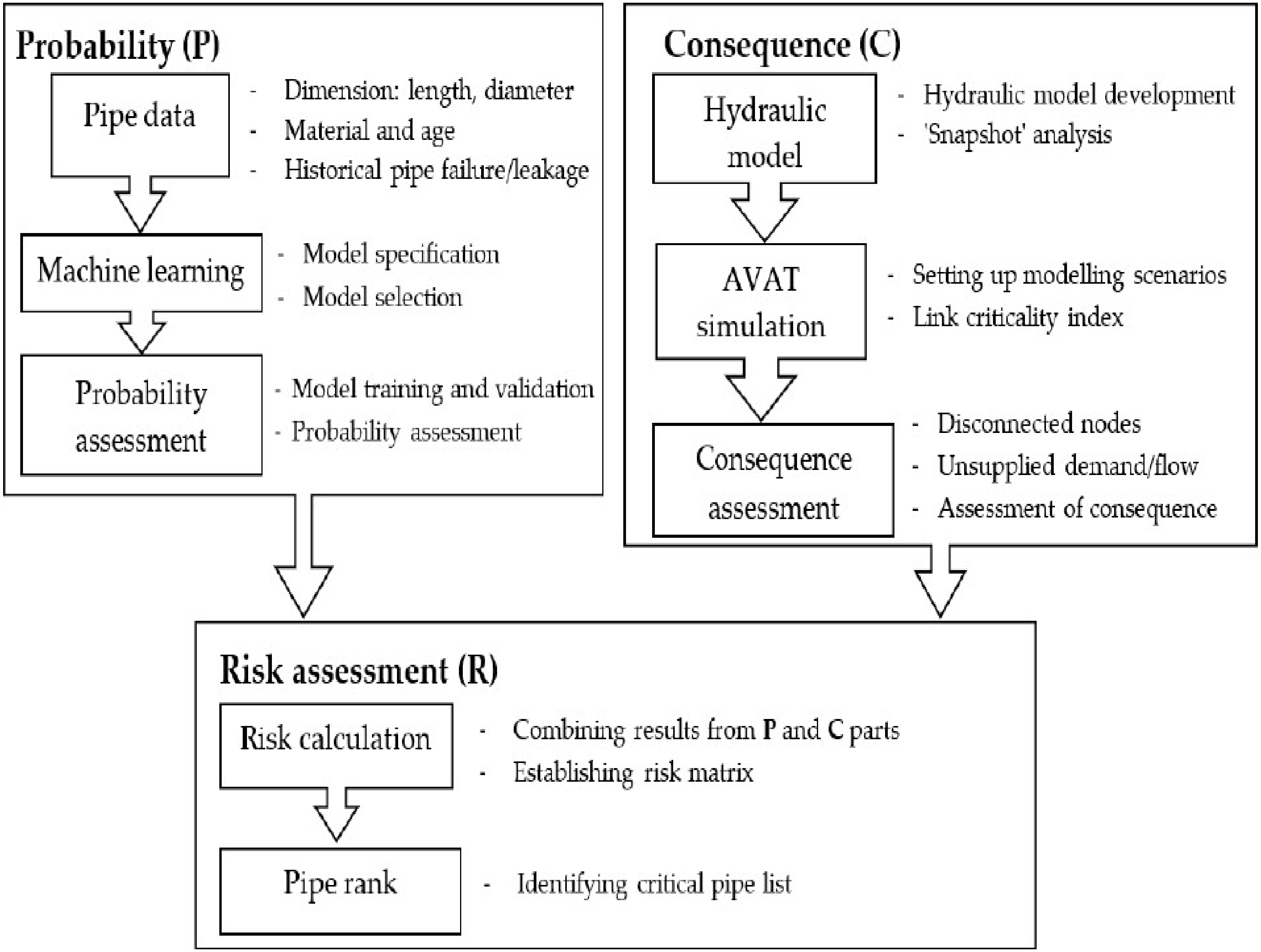
Aging of the WDN has become one of the major issues that demand attention to uphold the objectives of drinking water provision. This issue requires a long-term rehabilitation strategy and water utility providers are often challenged to set their priorities correctly

The implementation of infrastructure asset management (IAM) principles may help the water utility providers make better decisions under such constraints, avoid reactive approaches, and improve the process of WDN rehabilitation planning.



Element type	Number
Junctions	9585
Reservoirs	3
Tanks	12
Pipes	10,669
Pumps	66
Valves	120

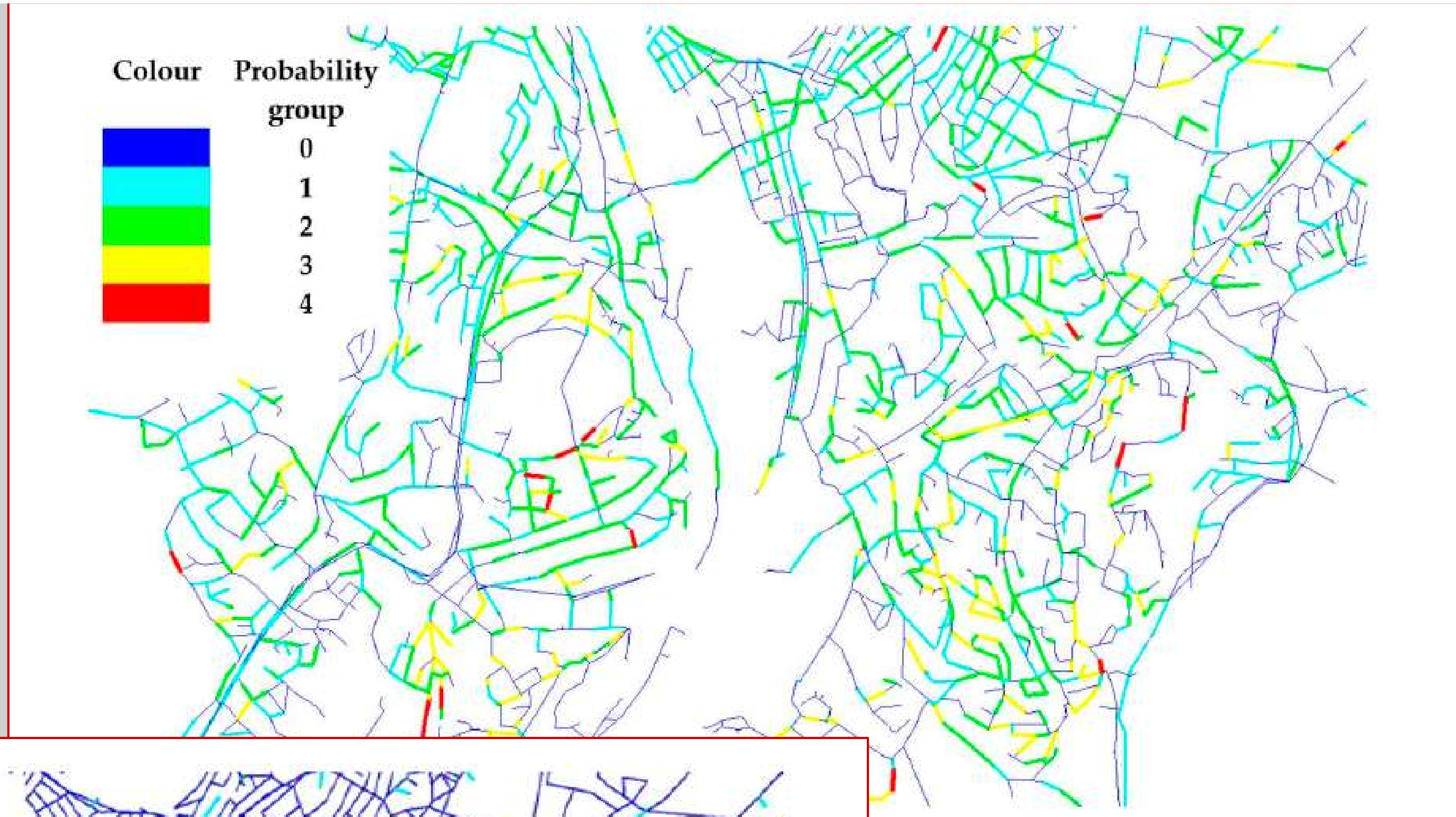



Probability (P)
Pipe data
- Dimension: length, diameter
- Material and age
- Historical pipe failure/leakage
Machine learning
- Model specification
- Model selection
Probability assessment
- Model training and validation
- Probability assessment
Consequence (C)
Hydraulic model
- Hydraulic model development
- 'Snapshot' analysis
AVAT simulation
- Setting up modelling scenarios
- Link criticality index
Consequence assessment
- Disconnected nodes
- Unsupplied demand/flow
- Assessment of consequence
Risk assessment (R)
Risk calculation
- Combining results from P and C parts
- Establishing risk matrix
Pipe rank
- Identifying critical pipe list

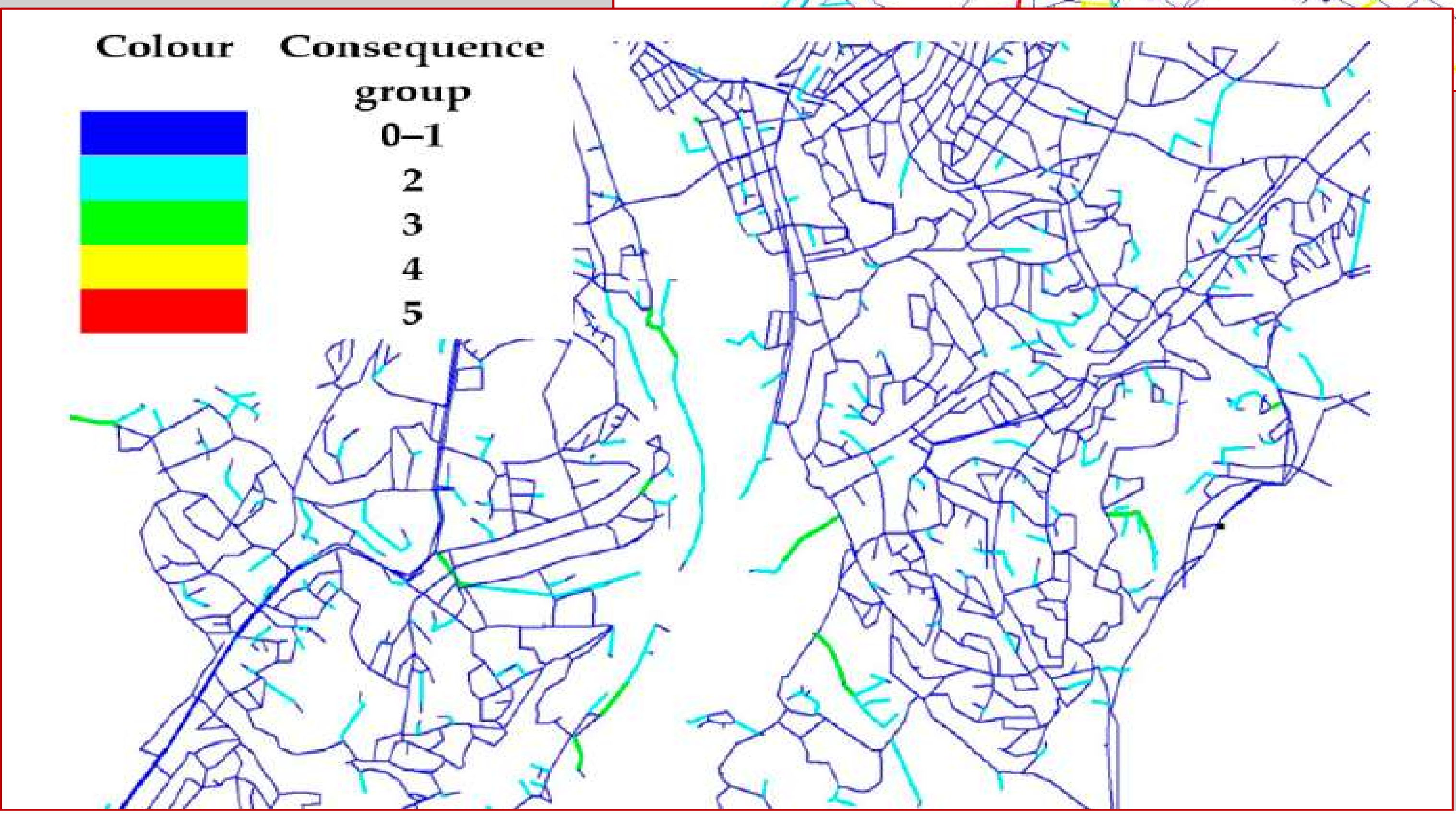
		Consequence (C)					
		C0	C1	C2	C3	C4	C5
Probability (P)	P4	(4,0)	(4,1)	(4,2)	(4,3)	(4,4)	(4,5)
	P3	(3,0)	(3,1)	(3,2)	(3,3)	(3,4)	(3,5)
	P2	(2,0)	(2,1)	(2,2)	(2,3)	(2,4)	(2,5)
	P1	(1,0)	(1,1)	(1,2)	(1,3)	(1,4)	(1,5)
	P0	(0,0)	(0,1)	(0,2)	(0,3)	(0,4)	(0,5)

Risk Group	PC Value
Red	8–20
Yellow	2–6
Green	0–1

Probability Group	Probability Value	Consequence Group	Consequence Value
P0	$P < 0.20$	C0	$C < 1.10^{-5}$
P1	$0.20 \leq P < 0.40$	C1	$1.10^{-5} \leq C < 1.10^{-4}$
P2	$0.40 \leq P < 0.60$	C2	$1.10^{-4} \leq C < 1.10^{-3}$
P3	$0.60 \leq P < 0.80$	C3	$1.10^{-3} \leq C < 1.10^{-2}$
P4	$P \geq 0.80$	C4	$1.10^{-2} \leq C < 1.10^{-1}$
		C5	$C \geq 1.10^{-1}$



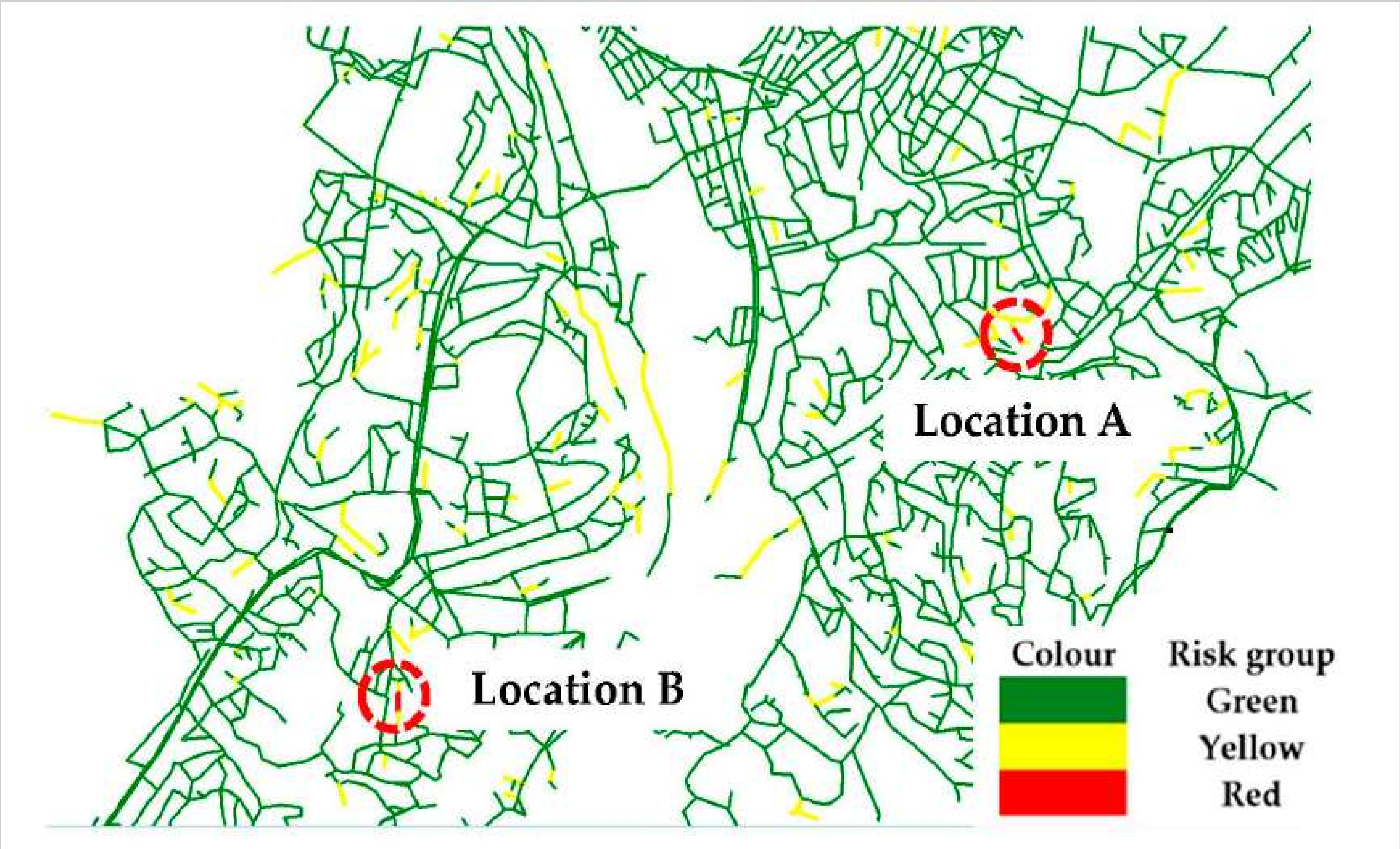
Colour
Probability group
0
1
2
3
4



Colour
Consequence group
0–1
2
3
4
5

Risk matrices of pipes based on their combined failure probability and consequences

		Consequence (C)						
		0	1	2	3	4	5	Sum Row
Probability (P)	4	40	0	4	3	0	0	47
	3	311	12	25	2	1	0	351
	2	832	36	70	10	2	0	950
	1	1780	87	182	26	14	0	2089
	0	5193	280	617	124	21	26	6261
sum column		8156	415	898	165	38	26	9698



Case Study 7: Risk Assessment of Non-Revenue Water Using Bayesian Networks and Fuzzy Logic

- Tehran-Iran

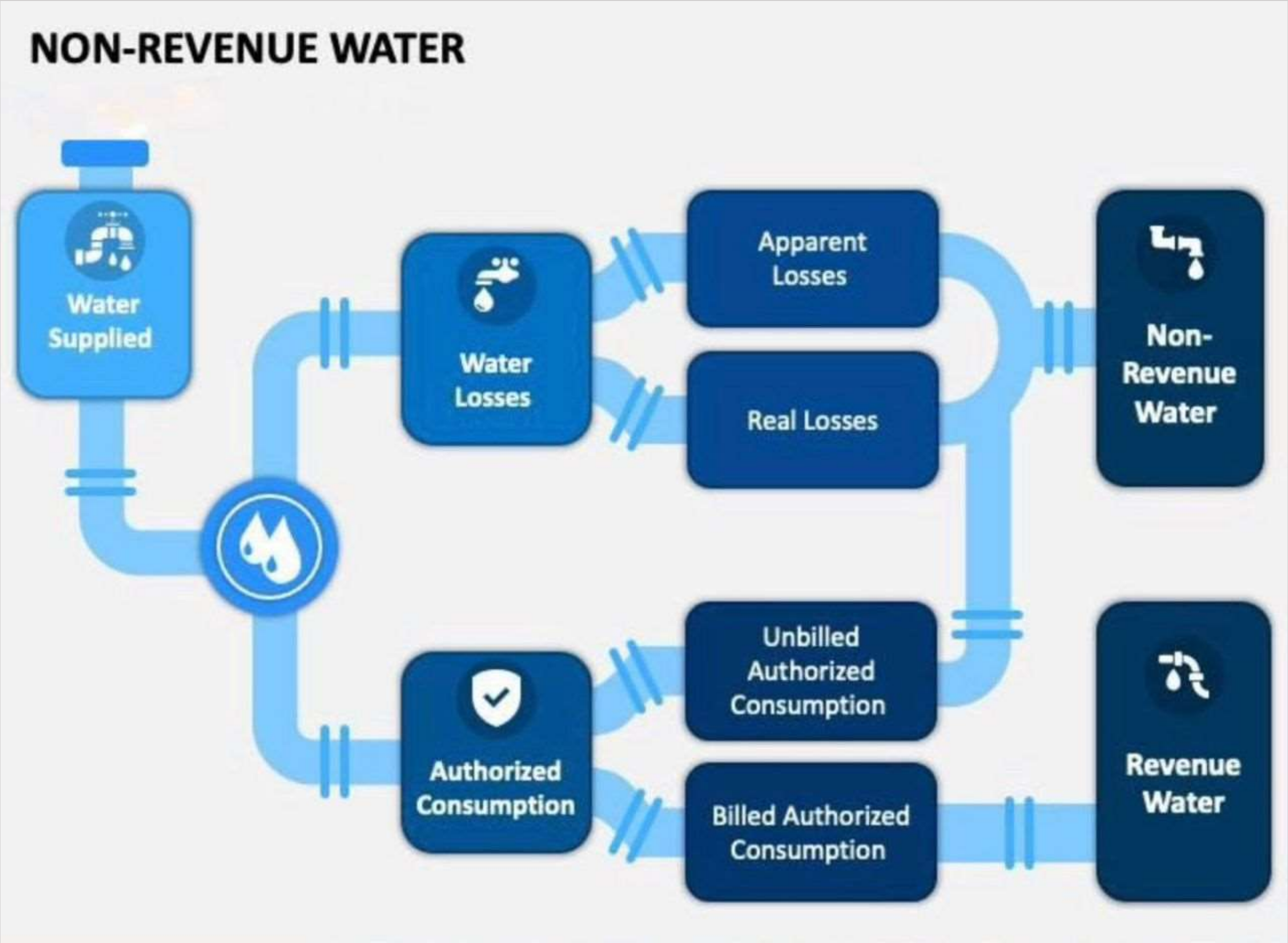
Tabesh & Roozbahani (2020)

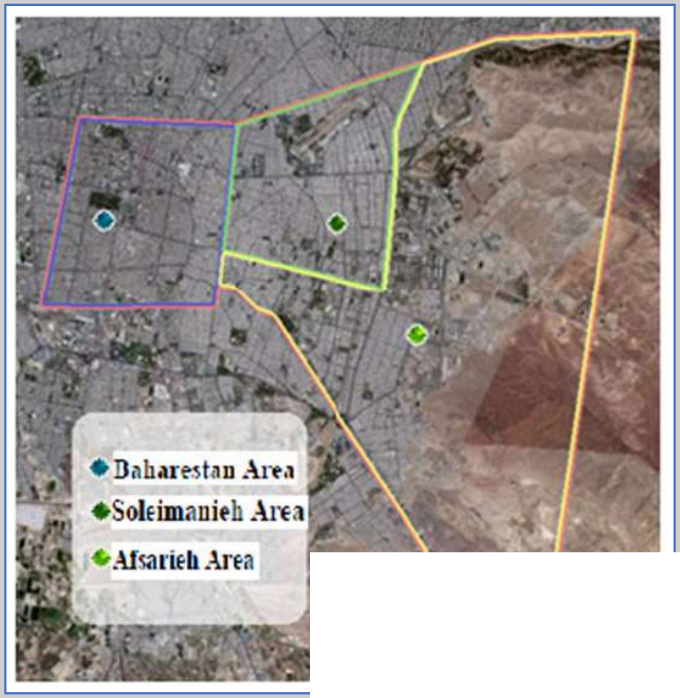
Tehran Province Water and Wastewater Co.

Tehran Municipality

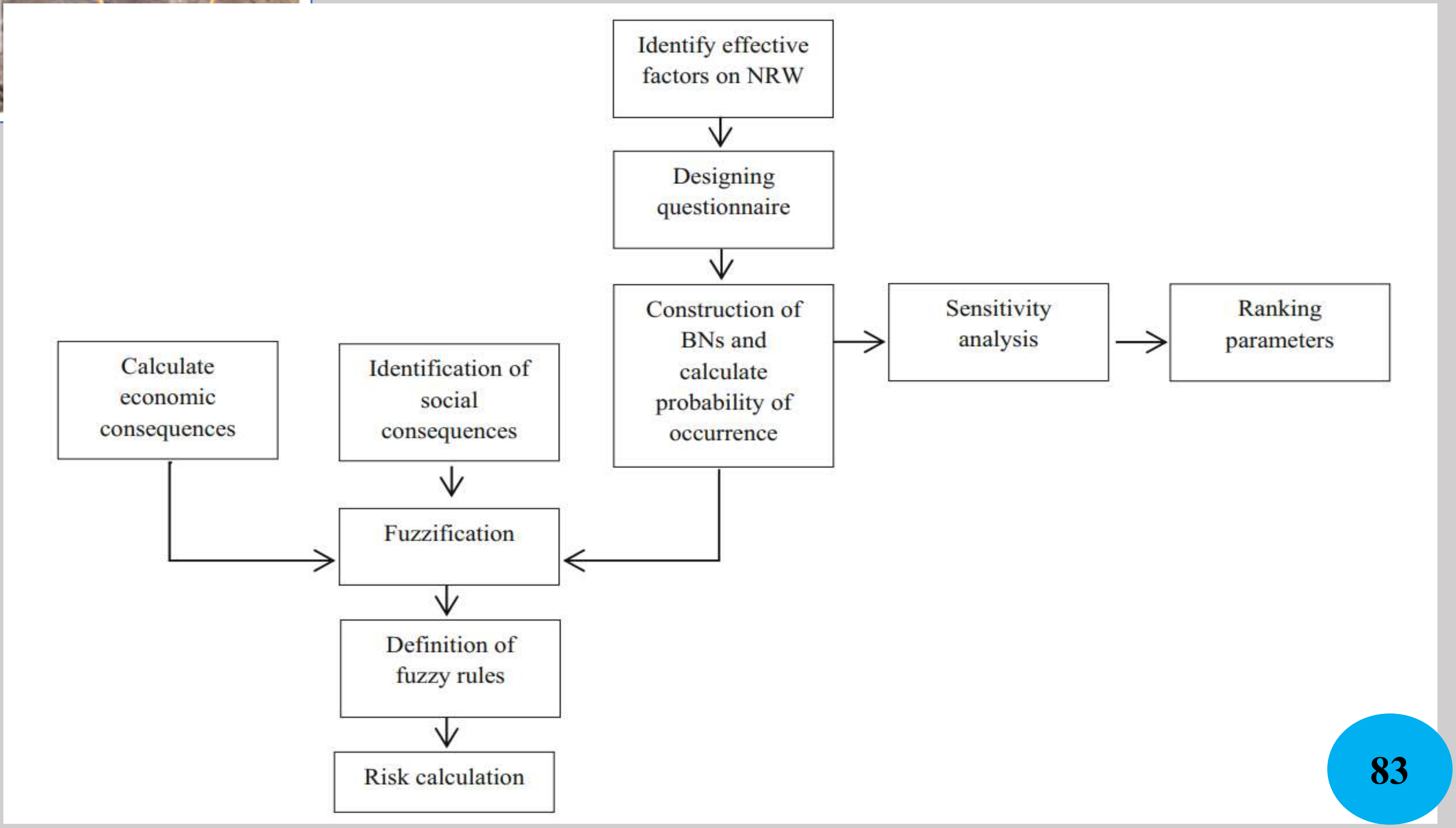
One of the major issues affecting water utilities in most countries is the considerable difference between the amount of water provided into the water distribution networks and the amount of water billed to consumers which is called non-revenue water (NRW).

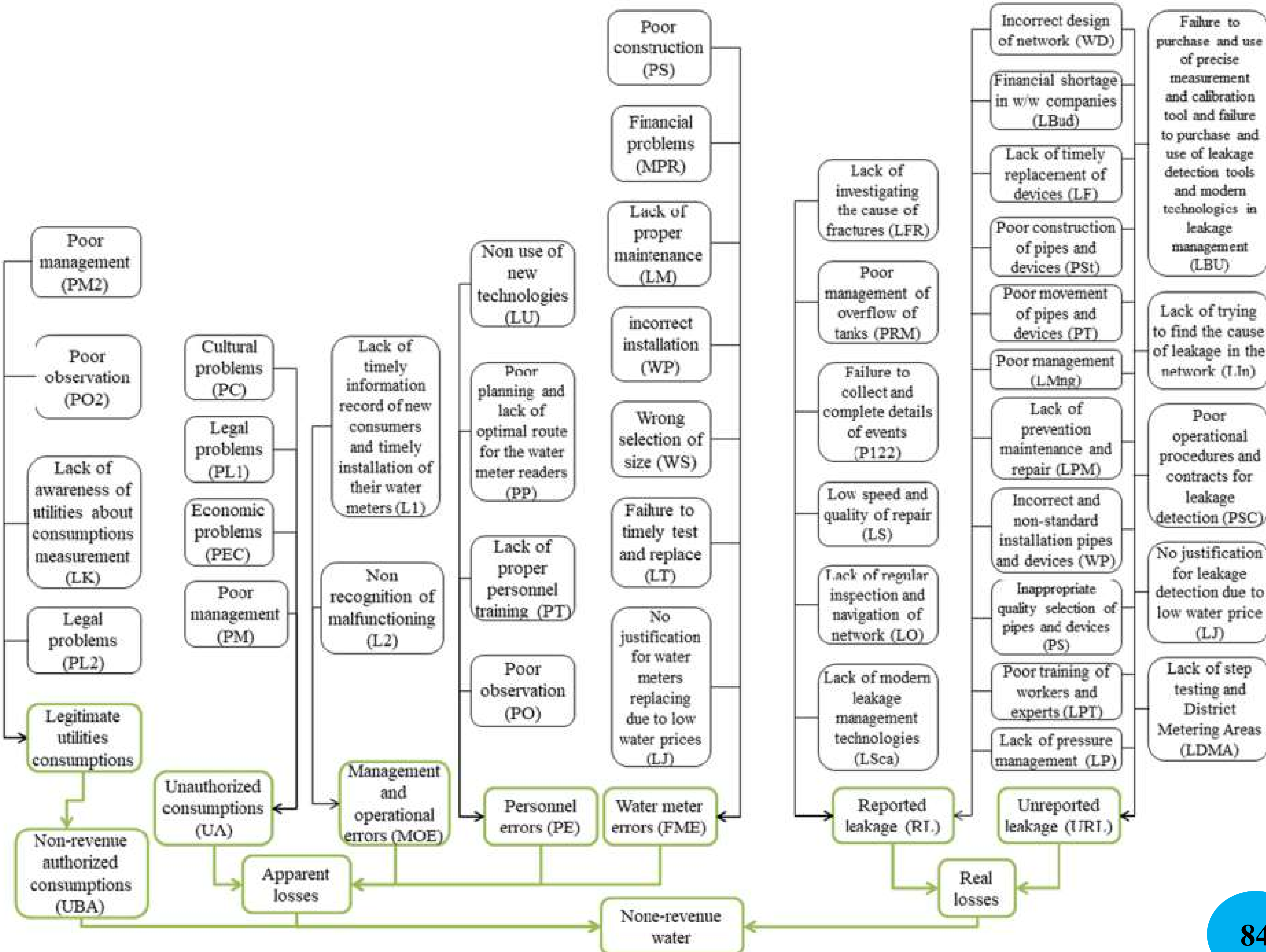
Globally, more than 48 billion cub meters/year of water are wasted as NRW and real losses represent 66% of this amount (Kingdom et al. 2006; Loureiro et al. 2015).

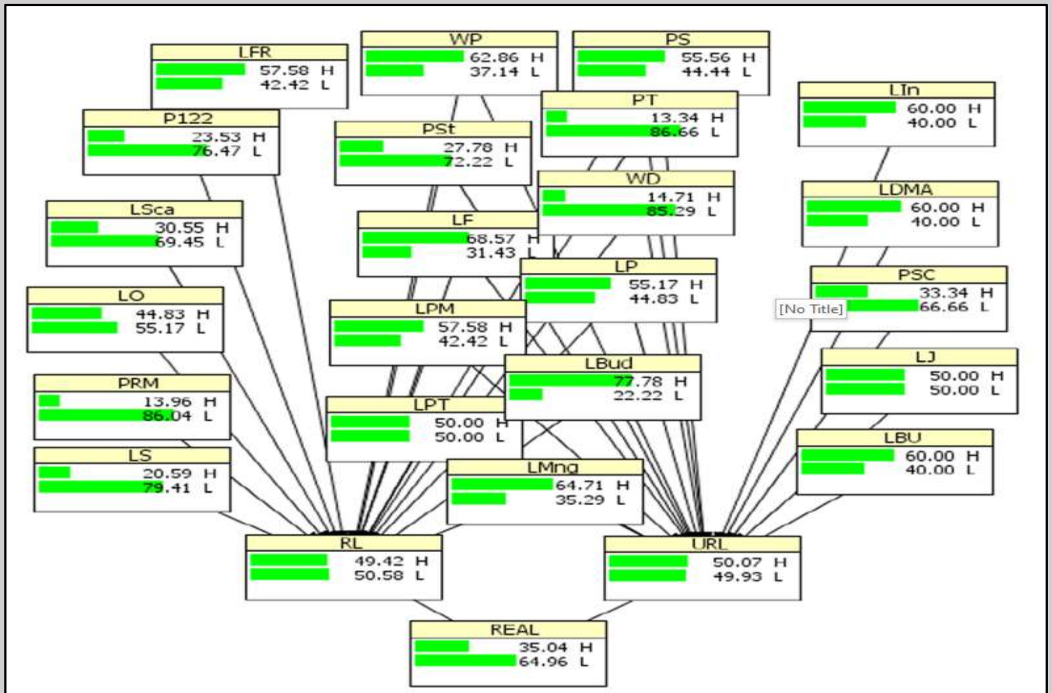




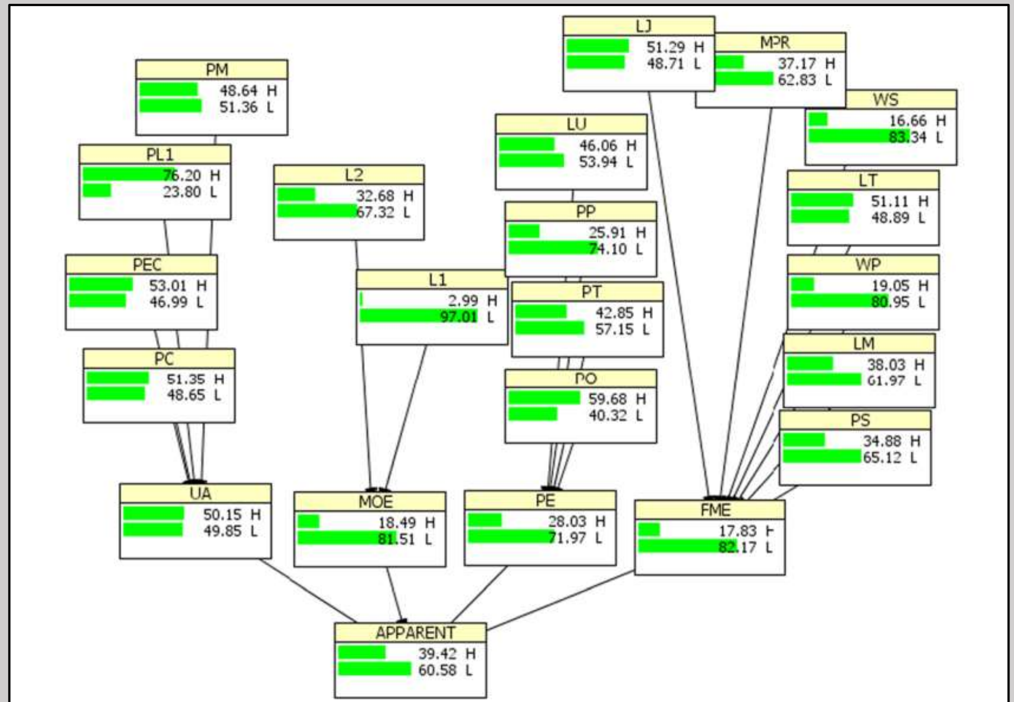
District 4 of Tehran Water and Wastewater Company
Population under service: ***1.5 million people***
Age: ***over 40 years***



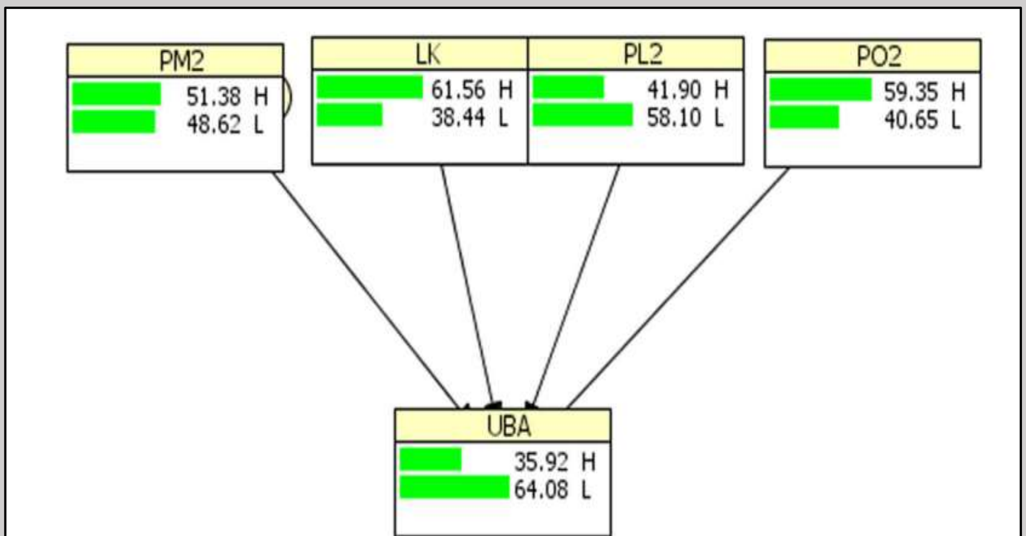

Poor management (PM2)
Poor observation (PO2)
Lack of awareness of utilities about consumptions measurement (LK)
Legal problems (PL2)
Legitimate utilities consumptions
Non-revenue authorized consumptions (UBA)
Cultural problems (PC)
Legal problems (PL1)
Economic problems (PEC)
Poor management (PM)
Unauthorized consumptions (UA)
Lack of timely information record of new consumers and timely installation of their water meters (L1)
Non recognition of malfunctioning (L2)
Management and operational errors (MOE)
Non use of new technologies (LU)
Poor planning and lack of optimal route for the water meter readers (PP)
Lack of proper personnel training (PT)
Poor observation (PO)
Personnel errors (PE)
Poor construction (PS)
Financial problems (MPR)
Lack of proper maintenance (LM)
incorrect installation (WP)
Wrong selection of size (WS)
Failure to timely test and replace (LT)
No justification for water meters replacing due to low water prices (LJ)
Water meter errors (FME)
Apparent losses
None-revenue water
Lack of investigating the cause of fractures (LFR)
Poor management of overflow of tanks (PRM)
Failure to collect and complete details of events (P122)
Low speed and quality of repair (LS)
Lack of regular inspection and navigation of network (LO)
Lack of modern leakage management technologies (LSca)
Reported leakage (RL)
Incorrect design of network (WD)
Financial shortage in w/w companies (LBud)
Lack of timely replacement of devices (LF)
Poor construction of pipes and devices (PSt)
Poor movement of pipes and devices (PT)
Poor management (LMng)
Lack of prevention maintenance and repair (LPM)
Incorrect and non-standard installation pipes and devices (WP)
Inappropriate quality selection of pipes and devices (PS)
Poor training of workers and experts (LPT)
Lack of pressure management (LP)
Unreported leakage (URL)
Real losses
Failure to purchase and use of precise measurement and calibration tool and failure to purchase and use of leakage detection tools and modern technologies in leakage management (LBU)
Lack of trying to find the cause of leakage in the network (LIn)
Poor operational procedures and contracts for leakage detection (PSC)
No justification for leakage detection due to low water price (LJ)
Lack of step testing and District Metering Areas (LDMA)



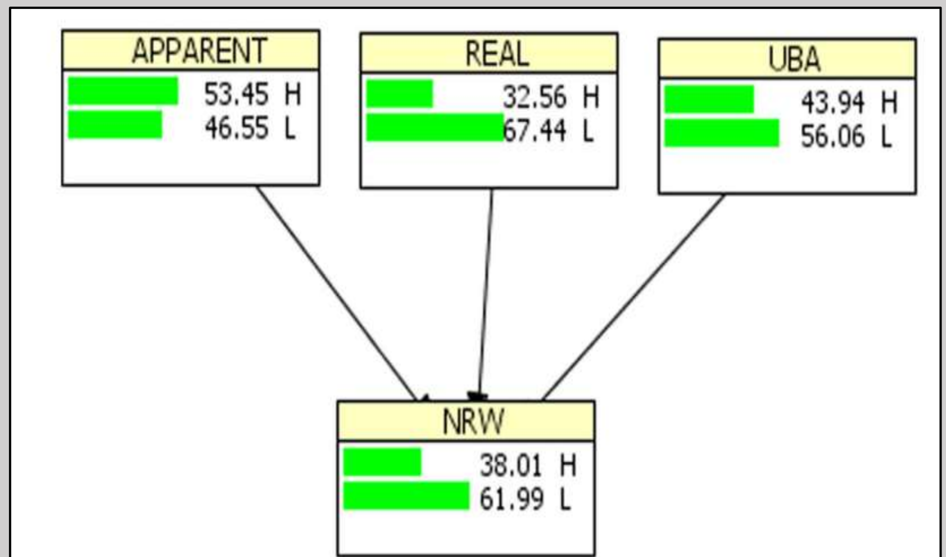
Output of real losses model



Output of apparent losses model

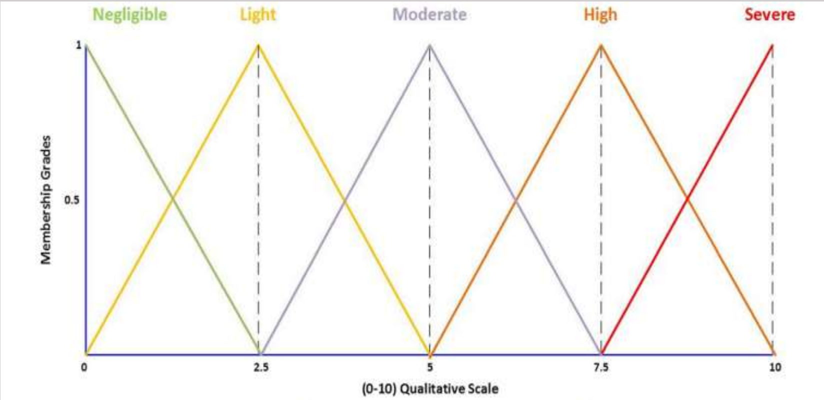


Output of non-revenue authorized consumptions model

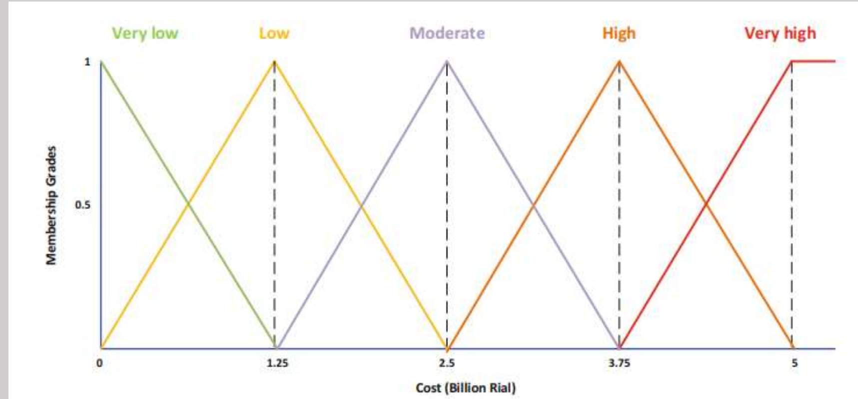


NRW model

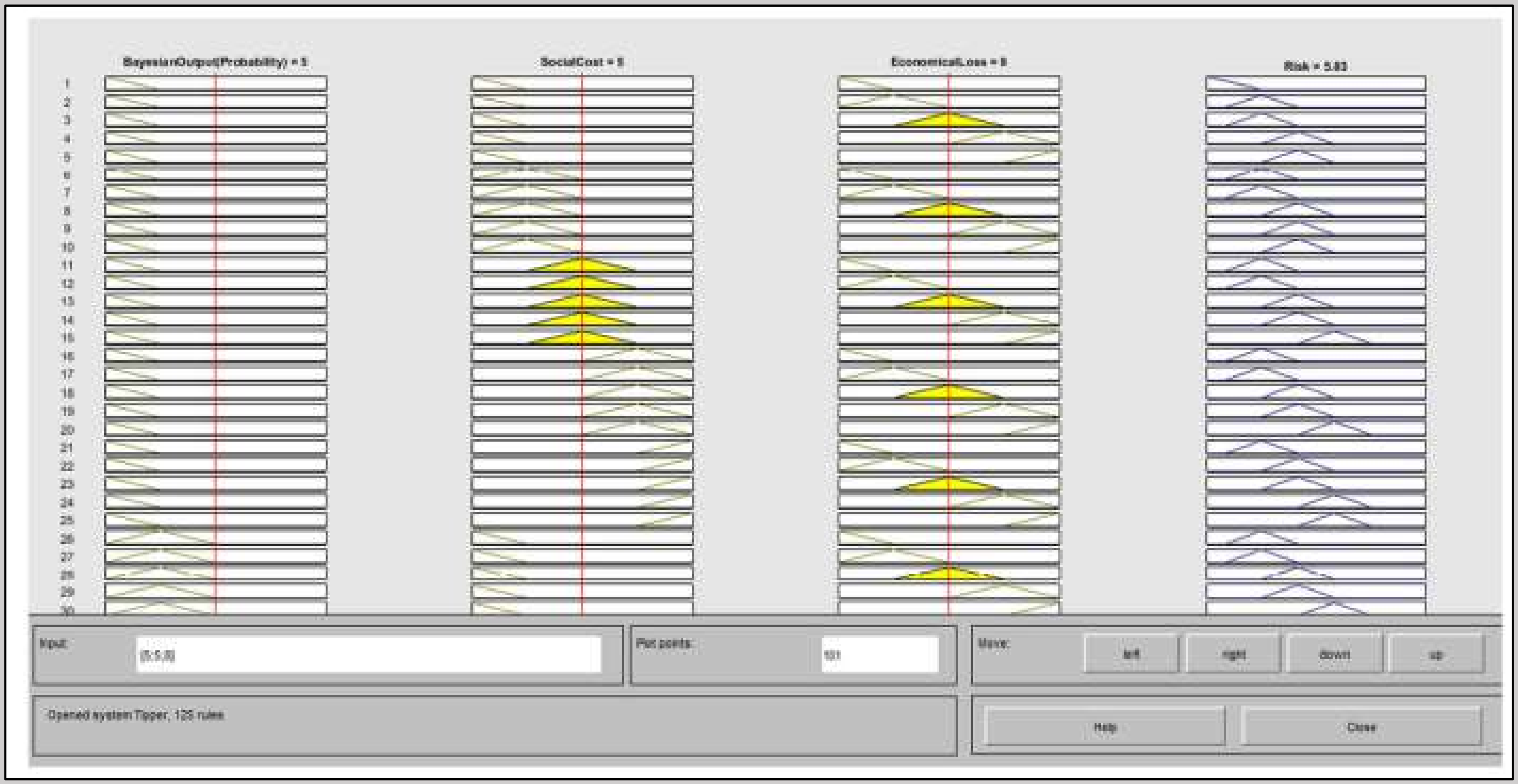
	Factors
Visible leakage	Inappropriate quality selection for pipe and other devices
	Wrong and non-standard installation
	Failure to collect and complete details of events
	Low speed and quality of repair
	Lack of regular inspection and navigation of networks
	Poor movement of pipes and other devices
	Poor construction of pipes and other devices
	Wrong design of network
	Lack of timely replacement of devices
	Lack of pressure management
	Lack of investigating the cause of fractures
	Poor management of overflow of tanks
	Lack of modern leakage management technologies (telemetry-SCADA)
	Lack of prevention maintenance (PM)
	Financial shortage in w/w companies
	Poor training for workers and experts
	Poor management (lack of updated maps and GIS)
Invisible Leakage	Lack of step testing
	Lack of District Metering Areas (DMA)
	Lack of trying to find the cause of leakage in the network
	Poor management (lack of updated maps and GIS)
	Failure to purchase and use of precise measurement and calibration tool
	Failure to purchase and use of leakage detection tools and modern technologies in leakage management
	Inappropriate quality selection for pipes and other devices
	Incorrect and non-standard installation
	Lack of prevention maintenance (PM)
	No justification for leakage detection because of the low price of water
	Poor movement of pipes and other devices
	Poor construction of pipes and other devices
	Incorrect design of network
	Lack of timely replacement of devices
	Lack of pressure management
	Lack of timely and continuous leakage detection
	Financial shortage in w/w companies
	Poor training for workers and experts
	Poor operational procedures and contracts



Fuzzy membership function of social consequences of NRW's components



Fuzzy membership function of financial damages



Probability values (percent)		
Non-revenue authorized consumptions	Real losses	Apparent losses
42.96	42.52	44.71

	Probability (percent)	Financial consequences (Rial)	Social consequences	Risk value	Quantitative risk value
Apparent losses	44.71	77,888,413,120	6	7.01	Moderately high
Real losses	42.52	130,712,388,800	7	6.97	Moderately high
Non-revenue authorized consumptions	42.96	4,581,671,360	2	6.4	Moderately high

NRW components	Policies
Apparent loss	Proper testing and selection of the water meter
	Replace water meter
	Improve water meter reading
	Improve bill issuing
	Identify unauthorized connections
Real loss	Increase speed and quality of repairs
	Active leakage control
	Pressure management
	Rehabilitation

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