Water Security & System Resilience

United Nations Educational, Scientific and Cultural Organization

i-WSSM
International Centre for Water Security and Sustainable Management

Water Security & System Resilience

United Nations Educational, Scientific and Cultural Organization
i-WSSM International Centre for Water Security and Sustainable Management

Overview of Resilience

Water Security and System Resilience

1. Overview of Resilience

United Nations Educational, Scientific and Cultural Organization

i-WSSM International Centre for Water Security and Sustainable Management

Aims & Objectives

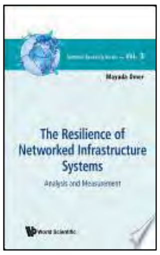
- The aims of the course are to:

  (1) Explain the basic understanding of "Resilience"

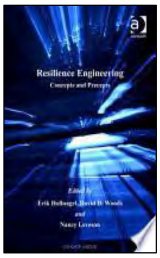
- The objectives are that trainees will understand:

  (1) How to define resilience in corresponding field
  (2) How to integrate resilience into corresponding system design/operation

References



The Resilience Of Networked Infr astructure Systems: Analysis And Measurement (Omer M., 2013)



Resilience Engineering: Concepts and Precepts (Hollnagel et al., 2006)

Key Organisational Factors to Bu ilding Supply Chain Resilience: a Multiple Case Study of Buyers an d Suppliers (Pereira et al., 2015)

Assessing and mea suring resilience (Pr oag, 2014)

Towards a Conceptual Framew ork for Resilience Engineering (Madni et al., 2009)

System resilience: capabilities, culture and infrastructure (Jac kson, 2007)

Contents

1. Introduction to Resilience

1. Definition of Resilience
2. Resilience Engineering
3. Visualization of Resilience
4. Example of Resilience
5. Need for Resilience
6. Factors Affecting Resilience

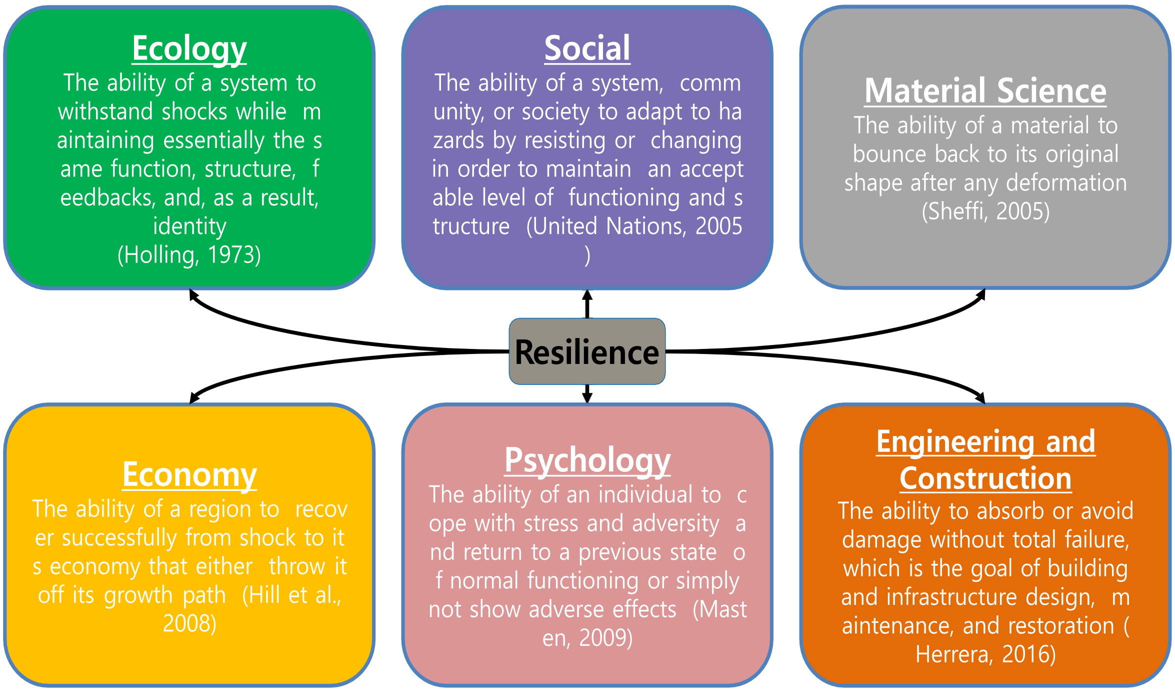
1.1 Definition of Resilience

- Definitions from Oxford Languages
  1. The capacity to recover quickly; toughness
  2. The ability of a substance or object to spring back into shape; toughness

[Words related to resilience]

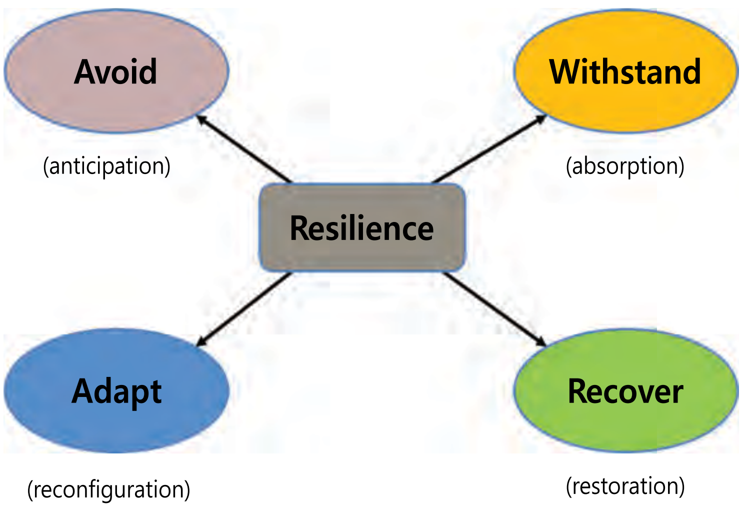
1.1 Definition of Resilience

- **Different fields have different interpretation for resilience**



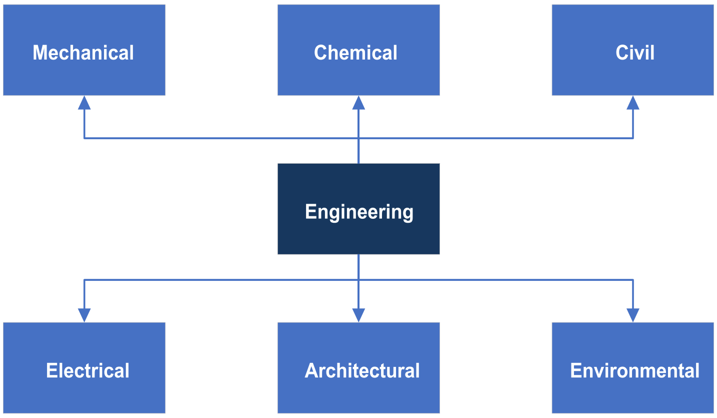
1.1 Definition of Resilience

- **Conceptually, resilience is the many-sided capabilities of a complex system that covers avoiding, absorbing, adapting to, and recovering from disrupti ons**



1.2 Resilience Engineering

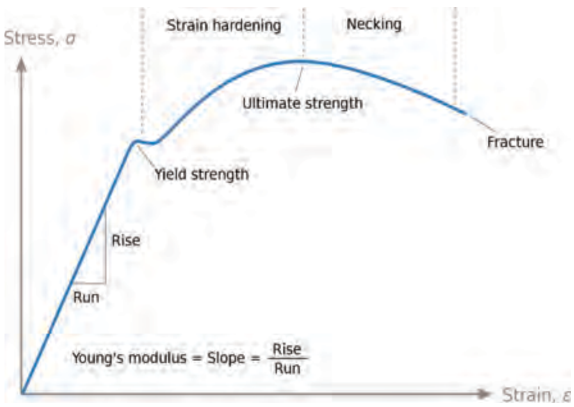
- Engineering is the application of science to create an optimum solution for problems in the related field



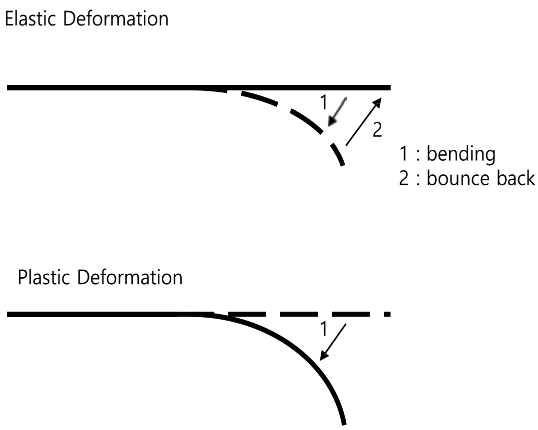
- "Resilience engineering" is to consider the complexity of the problem and balance the performance variability to satisfy safety requirements

1.3 Visualization of Resilience

- Material can bend in response to stress, elastic deformation will happen until the yield strength, and when it is elapsed, plastic deformation occurs until the fracture point



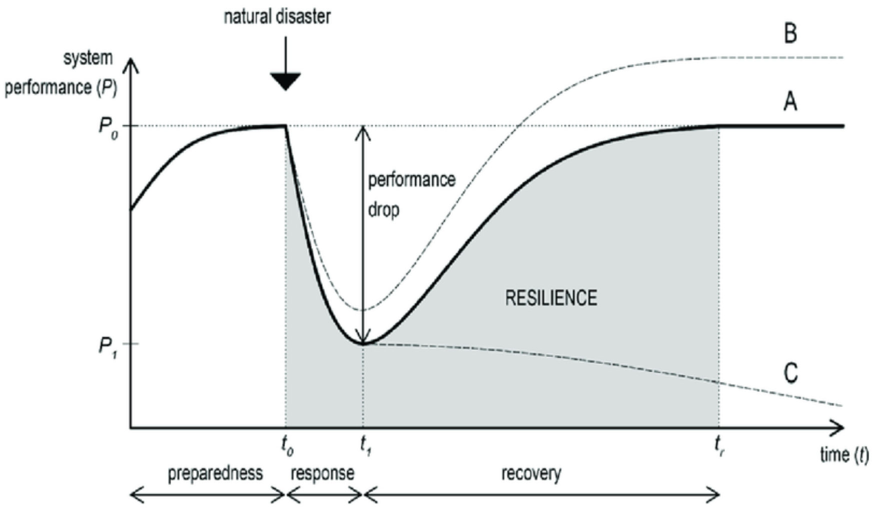
[Stress vs strain diagram]



[Bending of metal bar]

1.3 Visualization of Resilience

- **Resilience function shows the system performance over time**



[Resilience function]

Case A: returns to the same level of performance as before the disruption Case B: enhance the performance compared to the level before the disruption Case C: not capable of returning to the same level of performance

Source:
Koren et al. (2017)

1.4 Example of Resilience

Ecology
- Coastal defense
- Forest density

Social
- Disaster response
- Information accessibility

Economic
- Employment rate
- Home ownership

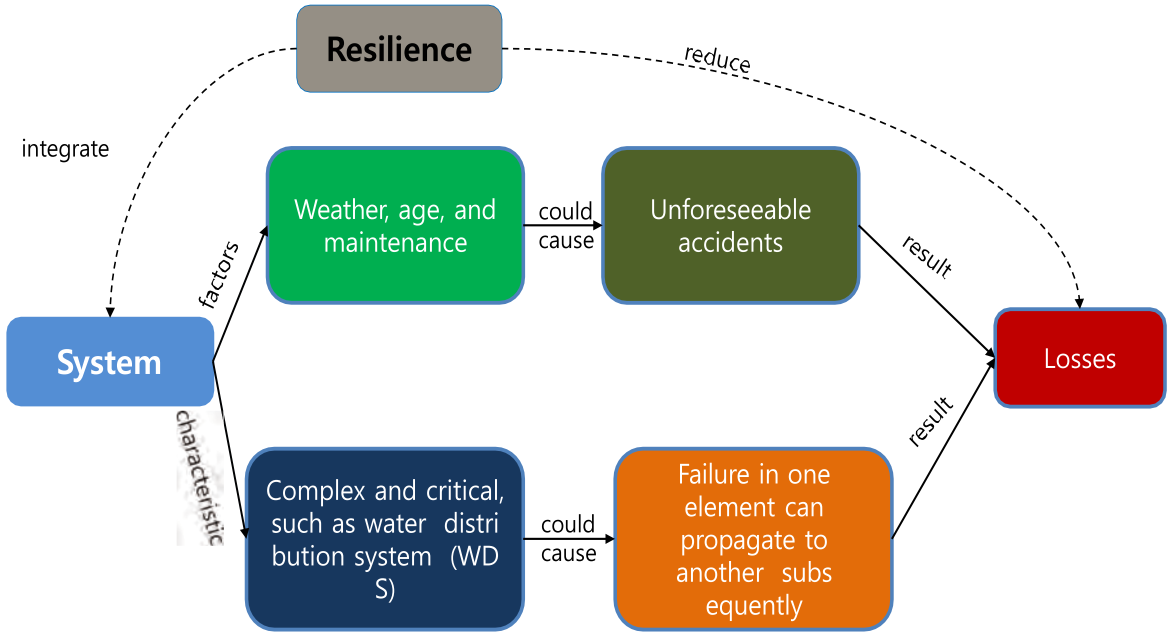
Infrastructure
- Earthquake resistant building
- Hospital







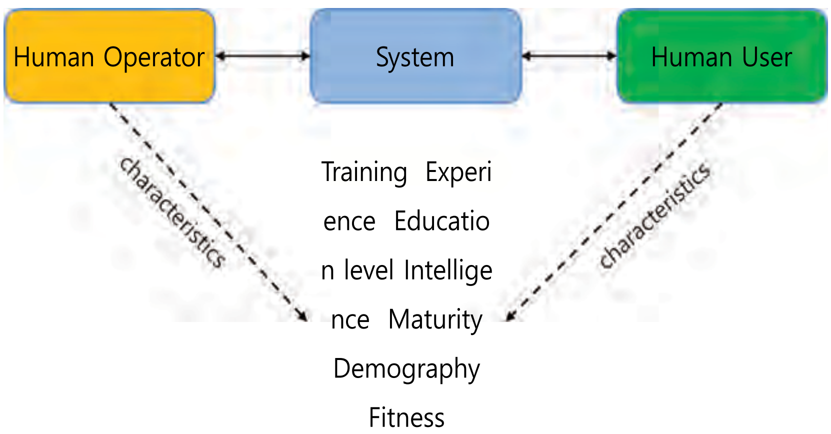

1.5 Need for Resilience



- The attack on September 11 is an example of cascading failures due to interdependency
  - The water mains ruptured, resulting in decreased pressure and impairing the firefighters
  - The communication cable vault was flooded due to the ruptured pipes, affecting 14,000 businesses and 20,000 residential customers of telecommunication

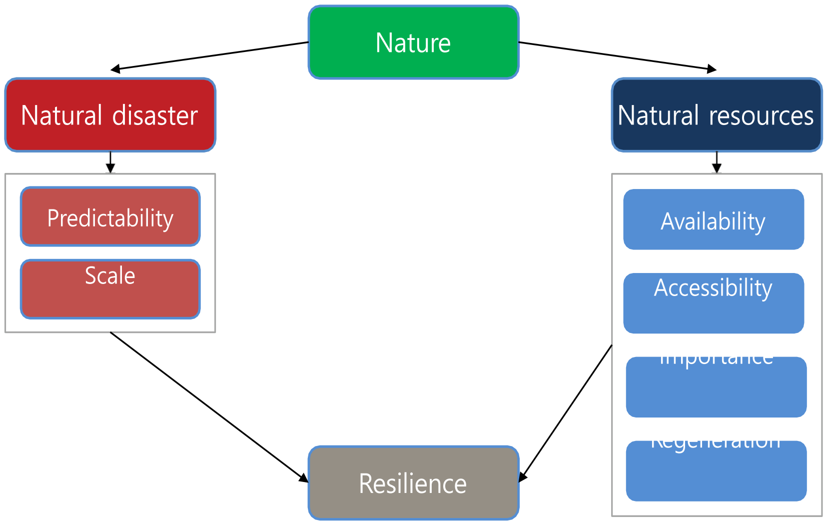
1.6 Factors Affecting Resilience

- **Human plays an integral part in resilience as they directly interact with the concerned system**
- **Humans can be the user and the operator in the system**



1.6 Factors Affecting Resilience

- Nature should always be considered for resilience
- Natural disasters are often unpredictable
- Climate change is affected by many factors



2. Disruptive Events

1. Things Could Go Wrong
2. Disruption
3. Types of Disruption
4. Disruption Profile

2.1 Things Could Go Wrong

- **"Anything that can go wrong will go wrong" - Murphy's law**

- Nothing in the universe works at 100% efficiency. Things might go wrong naturally if we speak on probability, even if it is at a minuscule chance
- Things can go wrong at any time, and it is significantly more dangerous if it happens at an inopportune time
- When everything goes too well, we tend to let our guard down and become exposed to unforeseeable disruption
- There are many factors that are sometimes not recognized affecting the system. A butterfly flapping with its wings could cause a typhoon
- In resilience, besides acknowledging that things could go wrong, it is also essential to know ***why*** things go wrong

2.2 Disruption

- **Disruption is an event that interrupts normal operation by creating a discontinuity, disorder, or displacement (Madni, 2007)**
- **Disruption can occur in many forms**

Natural
- Earthquake
- Hurricane
- Flood

Operations
- Human error
- Out of supply

Terrorism
- 9/11 WTC attack
- Political instability

Financial Meltdown
- Stock market collapse

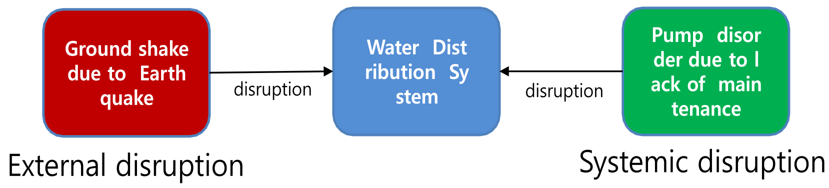



2.3 Types of Disruption

- **Disruption can be classified to external and systemic disruptions**

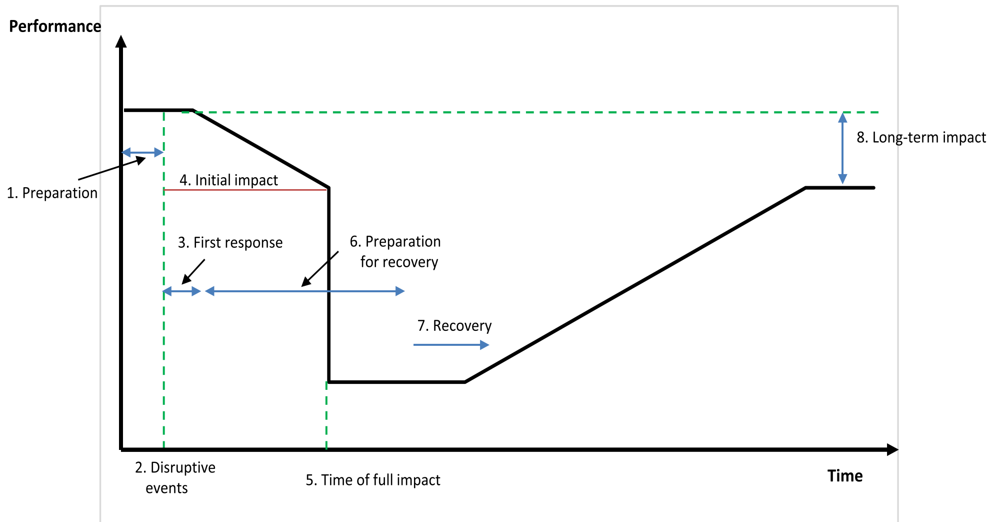
- Factors from outside of the system cause external disruptions
  - Examples include natural disasters
  - They have a high uncertainty / cannot be accurately predicted
  - Designing resilience against this kind of disruption needs a safety margin to account for the uncertainty

- Systemic disruptions are caused when a component in the system failed
  - It interrupts the function, capability, or capacity of the system
  - This type of failure typically results from inadequate reliability or safety measures and can be addressed by traditional analytical methods



2.4 Disruption Profile

- **When a disaster happens, a typical profile usually occurs and it can be categorized into 8 phases**

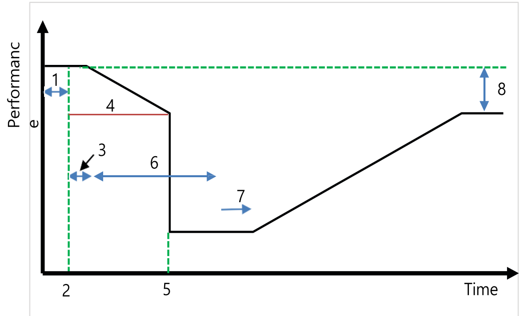


[Time to performance graph]

Source: Sheffi & Rice (2005)

2.4 Disruption Profile

1. **Preparation**
   - In some cases, disruption can be foreseen and be prepared to minimize its effects
2. **Disruptive Event**
   - When a disruptive event happens, such as when a tornado hits or terrorists attack
3. **First Response**
   - First response is aimed at controlling the situation, saving and protecting lives, shutting down affected systems, and preventing further damage
4. **Initial Impact**
   - Depending on the scale of the disruption, the effect might not be felt instantaneously
5. **Full Impact**
   - The time when performance hits the lowest
6. **Recovery Preparations**
   - Typically done in parallel with the first response. Preparing the needed resources to recover from the disruptions
7. **Recovery**
   - Utilizing the available resource to try to return to acceptable performance
8. **Long-term Impact**
   - Sometimes, after a disruption, the performance will not return to the performance as before



3. Enhancing the Understanding of Resilience

1. Attributes of Resilience
2. Resilience Phase
3. Differentiating Resilience to Other Properties

3.1 Attributes of Resilience

- **Resilience can be defined by the following 4 attributes** (Bruneau and Reinhorn, 2007):
  - Robustness
  - Redundancy
  - Resourcefulness
  - Rapidity

Robustness:
The ability of the system to withstand a level of stress without suffering degradation or loss of function

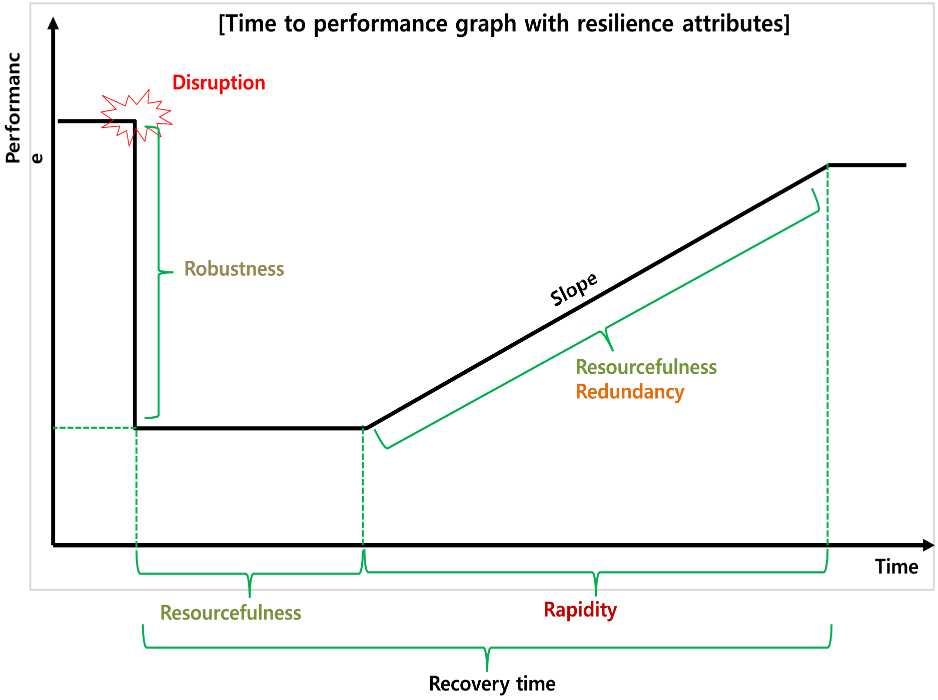
Redundancy:
The ability to substitute parts in the system that is affected to maintain functionality

Resourcefulness:
The ability to identify, prioritize problems, and allocate resources to recover from stress

Rapidity:
The capacity to recover and achieve goals quickly in order to limit loss and prevent future disruptions

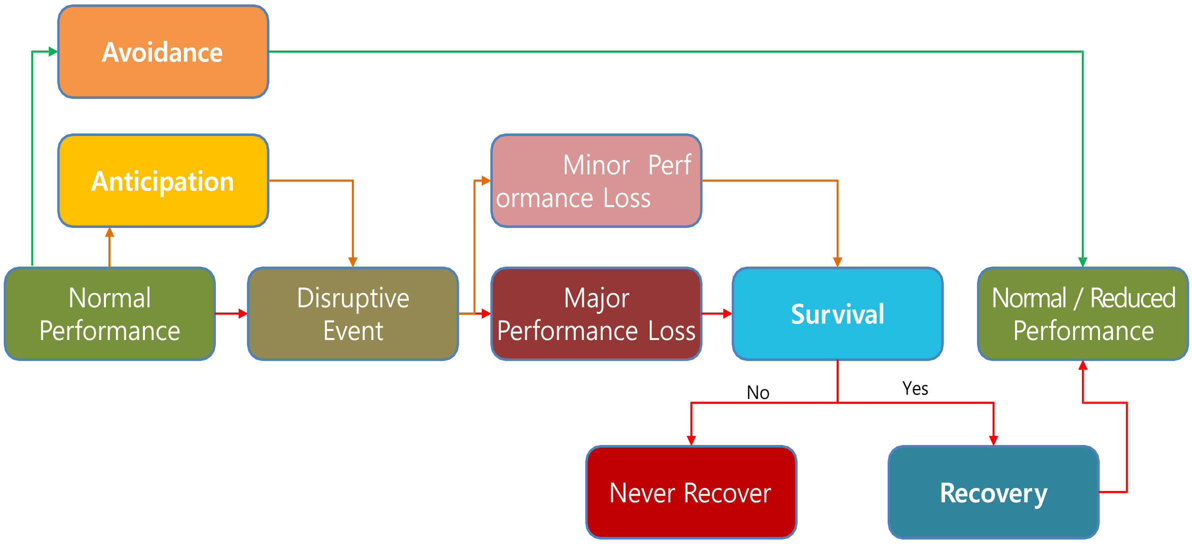
3.1 Attributes of Resilience

[Time to performance graph with resilience attributes]



3.2 Resilience Phase

- Resilience can be divided into 2 phases:
  - Phase 1 - anticipation / avoidance
  - Phase 2 - survival / recovery



3.3 Differentiating Resilience to Other Properties

- Resilience vs. Reliability

The ability of a system to **function satisfactorily** over its predicted lifetime under **specified conditions** is defined as ***reliability***. It is a quantitative assessment of the likelihood of failure-free performance over a specific period of time under specified conditions

Resilience	Reliability
• Designed for unforeseen disruptive events	• Designed for known failure circumstances
• Failures are external	• Failures are internal
• System can reconfigure to continue operation	• System cannot reconfigure to avoid failure

3.3 Differentiating Resilience to Other Properties

▪ Resilience vs. Robustness

- Robustness is defined as the characteristics of the system under **various operating conditions** (Gribble 2001)
- When **changes** are made, Moses (2004) defines a robust system as one that can **maintain its original function** for as long as possible
- It is the system's ability to **maintain performance** in the face of **unforeseeable internal and external shocks** (Janssen 2007)

Resilience	Robustness
• Designed for known and unknown uncertainties	• Designed for known uncertainties
• Adapt to changing circumstances	• Maintains functionality in the same form

3.3 Differentiating Resilience to Other Properties

▪ Resilience vs. Flexibility

- The ability of a system to **adapt** to its surroundings as a result of sudden but anticipated circumstances
- Flexibility in networked systems refers to the ease with which **new nodes** can be added to the network or **new paths** for connecting nodes can be introd uced

Resilience	Flexibility
• Able to adapt to unforeseen circumstances	• Easily adapt to unforeseen circumstances
• Not fragile	• Can be fragile
• Designed to cope with abrupt changes	• Designed to cope with abrupt and gradual changes
• Used for the same purpose and functionality	• May be used to deliver different functionality

3.3 Differentiating Resilience to Other Properties

▪ Resilience vs. Agility

- The system's ability to **adapt quickly** to new situations (Schulz and Fricke 1999)
- Agile systems can be **easily reconfigured** to incorporate significant new design features in **less time** and with greater certainty (Amin and Horowitz 2008)

Resilience	Agility
• Adapts after a disruptive event	• Can adapt to new situation
• Recover quickly from disruption	• Rapidly adapts
• Maintain the systems' value delivery	• Benefits from the new situation

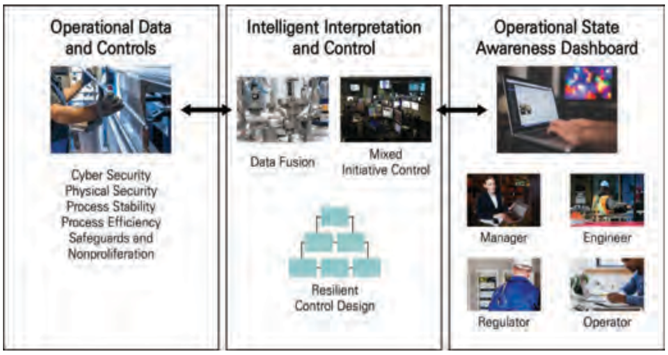
4. System Resilience

1. System as a Whole
2. Example of Systems
3. Interdependency
4. Complexity
5. Criticality
6. Conceptual Framework
7. System Resilience Architecture

4.1 System as a Whole

- **A system is a set of things working together as parts of a mechanism or an interconnecting network**

- As a system grows in size and complexity, it will have increasingly greater safety and risk management challenge
- System resilience is concerned with designing a system that are able to circumvent accidents through anticipation, survive disruptions through recovery, and grow through adaptation (Madni and Jackson, 2009)



[A resilient control system]

4.2 Example of Systems

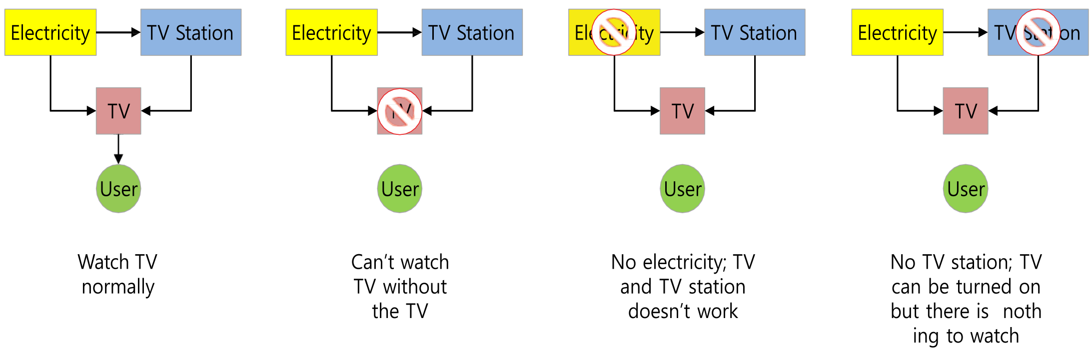
- **Many different systems exist with their own purpose, elements, and processes**

System	Functional Behavior	Elements	Processes
Solar system	Orbital movement	9 planets	Gravitational attraction
Automobile system	Transportation	Engine, wheels, drive train, seats	Combustion, torque, steering
Nervous system	Stimulus and response	Nerves, synapses	Inhibition, reinforcement
Watershed system	Storage and release of water	Surface, subsurface, rivers	Interception, infiltration, lateral flow
Water Distribution systems	Supply drinking water, provide firefighting flow	Reservoir, junction, pipe, pump, tank, valve, WTP	Distribution, pumping, storage, treatment

4.3 Interdependency

▪ Nothing truly exists in isolation

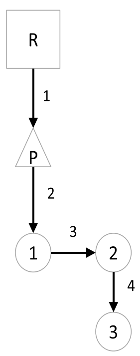
- Systems rely on the availability of each element to operate
- Example, watching TV requires electricity and a broadcaster to operate. With out electricity, the TV cannot be turned on. Without broadcaster, there is not hing to watch on the TV



4.3 Interdependency

▪ Disturbance of one of the elements can cause varying performance loss

- Water Distribution System (WDS)'s primary purpose is to deliver water with acceptable quality and quantity to users
- Elements included in WDS are the reservoir, pipes, pumps, valves, and users

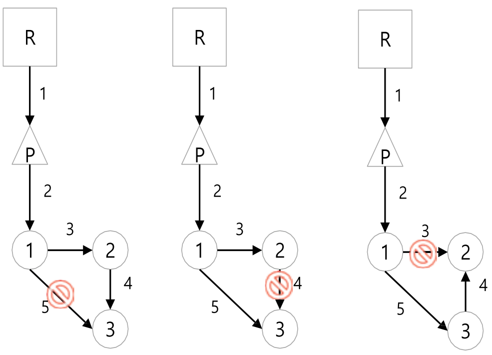


Disturbance	Effect
Reservoir	Whole WDS shuts down
Pipe 1 and 2	No water can be delivered
Pump	Reduction of pressure, risk of no water delivered to further nodes during peak hour
Pipe 3	No water delivered to node 2 and 3
Pipe 4	No water delivered to node 3

4.3 Interdependency

- **Interdependency can be tightly coupled or loosely coupled**

- When a system is tightly coupled, a failure at one part of the system (critical path) can cascade to the rest immediately, like in the example before
- By adding pipe 5 (adding redundancy), the interdependency is loosened

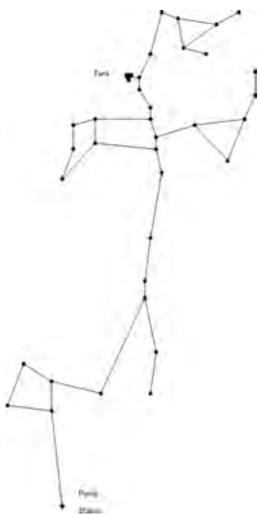


[a] [b] [c]

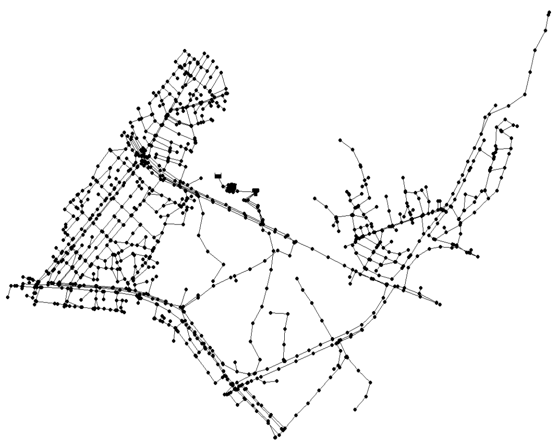
a. When pipe 5 is broken, the system behaves the same as in the previous example
b. If pipe 4 is broken, pipe 5 now provides a path to node 3
c. If pipe 3 is broken, the water path to node 2 becomes longer, risking pres sure reduction. However, the system can still deliver water to all nodes

4.4 Complexity

- **As system gets bigger or providing more functionality it will get more complex**



[Small WDS]

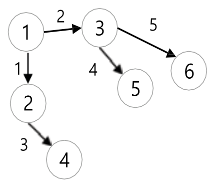


[Large WDS]

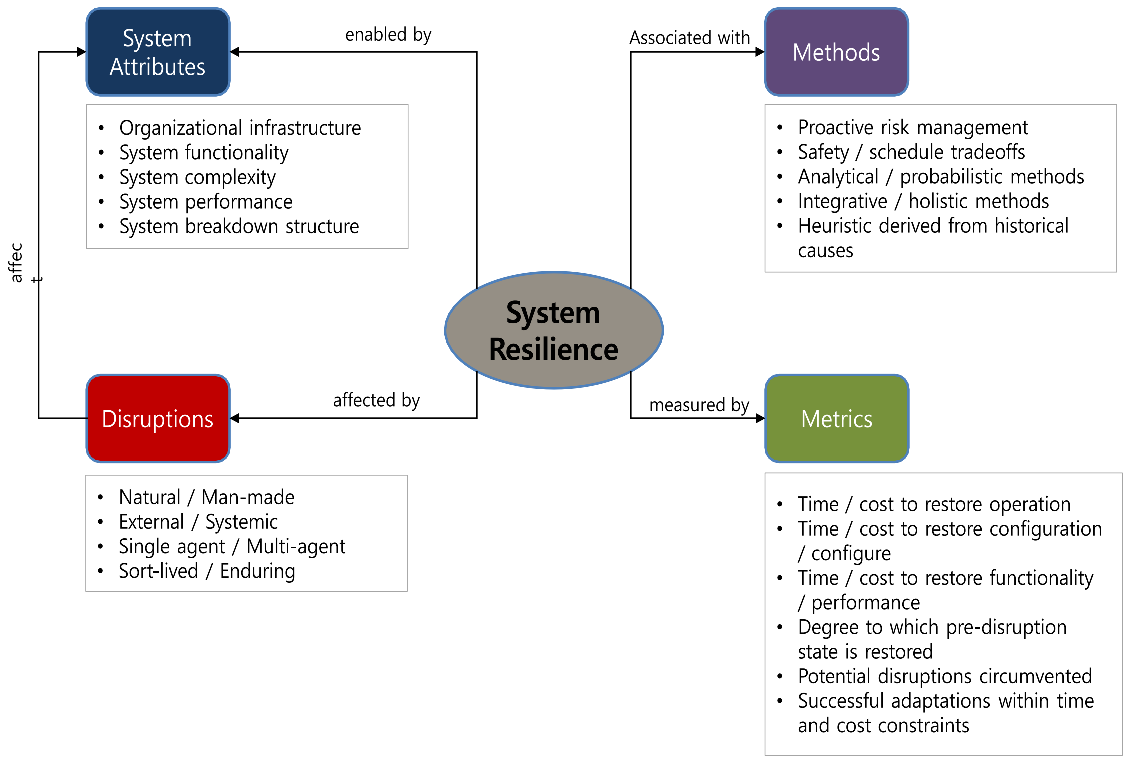
4.5 Criticality

- Not all system components are equally important

- The reduction of system performance is dependent on the disturbance of the system
- Especially apparent on a complex system, like the large WDS
  - ✓ If a pipe that serves many users in upstream is broken, it is more critical than a pipe at the downstream area
- The criticality in WDS can be defined in several aspects, such as social, economic, hydraulic, and water quality
  - ✓ Social : loss of water supply
  - ✓ Economic : price of parts replacement or maintenance
  - ✓ Hydraulic : insufficient water pressure
  - ✓ Quality : degradation of water quality

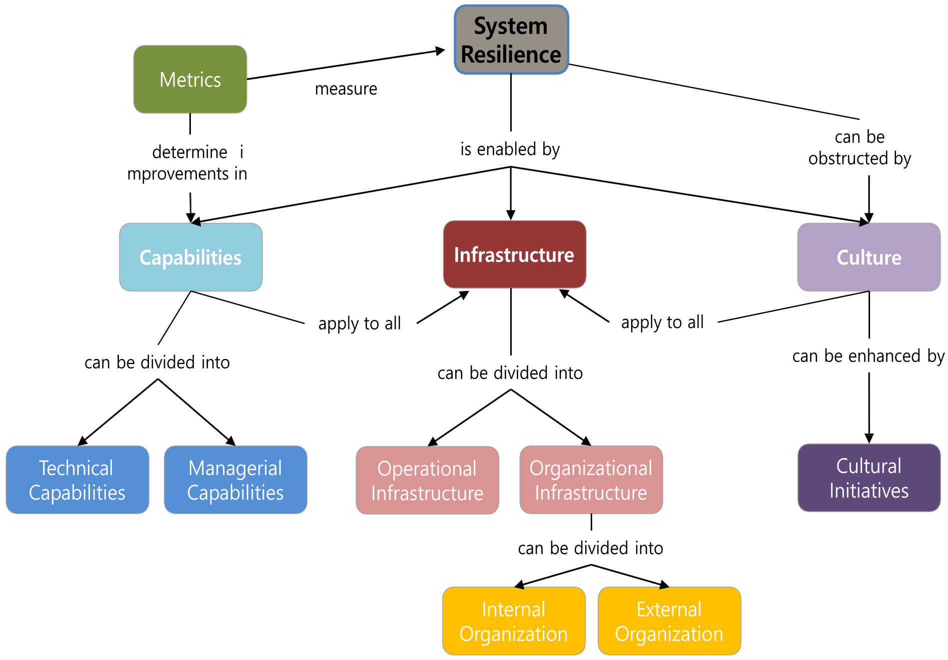


4.6 Conceptual Framework



4.7 System Resilience Architecture

- **System resilience has three principal enabling elements: Culture, Capabilities, and Infrastructure**



5. Quantifying Resilience

1. Identifying a Resilient System
2. Measurement of Resilience
3. System Modeling for Resilience Quantification
4. Accounting for Uncertainty

5.1 Identifying a Resilient System

▪ Identifying system resilience quantitatively is challenging

- As resilience is designed to assess a system against probable risk, a degree of uncertainty needs to be considered
- Resilience needs a goal. We cannot evaluate a system to be resilient against every kind of disturbance
- The steps to identify system resilience:
  1. Define the system
  2. Define the critical functionality
  3. Identify the critical components
  4. Identify the possible disruptions
  5. Asses system resilience

5.2 Measurement of Resilience

▪ Resilience can be measured by quantitative analysis

- In the simplest term, resilience can be measured by comparing normal performance to performance during disruption
- Ex, in a production line, if a disruption happens, the output reduces; then the resilience can be defined as:

$$Resilience = \frac{Output\ during\ disruption}{Output\ during\ normal\ condition}$$

- Another simple and measurable factor is the time it takes for the system to recover. The more time the system needs to recover, the less resilient it is
- Cost is also a good measure. The cost needed to recover the system signifies resilience

5.2 Measurement of Resilience

▪ Resilience measurement metrics

- Todini (2000) defined the resilience index (RI) for WDS, which measures the excess internal energy. With more internal energy, the WDS is more resilient when a disruption occurs

$$I_r = \frac{\sum_{i=1}^{n_n} q_i^*(h_i - h_i^*)}{\sum_{r=1}^{n_r} Q_k H_k - \sum_{r=1}^{n_r} q_i^* h_i^*}$$

where I_r=resilience index; n_n=number of nodes; n_r=number of reservoir; q_i^*=demand at node i; h_i=head at node i; h^* = required head at node i; Q_k = discharge at reservoir k; H_k = head at reservoir k

- Shinozuka et al. (2004) measured the resilience of power systems by the speed of restoration and repair efficiency
- In WDS, the mean time to repair (MTTR) is measured (Walski and Pelliccia, 1982)
- Werner et al. (2005) used the function of travel time increase of post-earthquake as a resilience measurement for highway systems

5.2 Measurement of Resilience

▪ Resilience can also be assessed qualitatively

- In project management, risk analysis is carried out before and during the project implementation (Young, 2003)
- A brainstorming is carried out to:
    - Identify source and type of risk
    - Classify the type of risk and its effect
    - Analyze the consequences associated with the risk
    - Consider how to respond to the risk
- After the assessment is made, each risk is ranked by probability of occurrence and scale of the impact

		Impact on the Project		
		Low	**Medium**	**High**
Probability	**7–9**	Medium	High	Unacceptable
	4–6	Low	High	Unacceptable
	1–3	Low	Medium	High

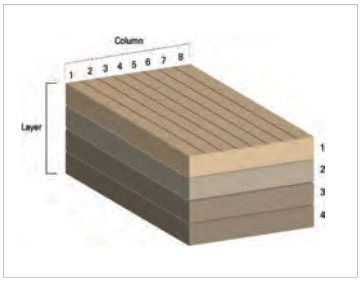
[Example of risk probability and impact parameters]

5.3 System Modelling for Resilience Quantification

- **A model is a physical, mathematical, or other logical representation of a system, entity, phenomenon, or process**

- A model is useful to simplify complex systems

[Map]



[Numerical model]

[Physical model]

5.3 System Modelling for Resilience Quantification

- **Model Development Step**

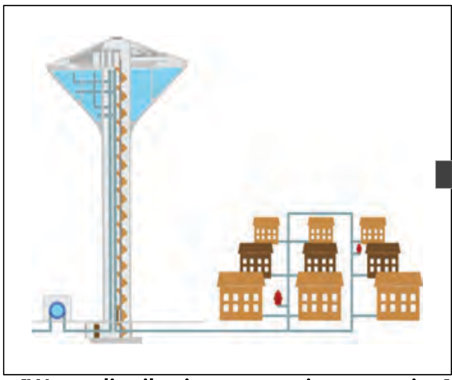
Perceptual Model → Conceptual Model → Mathematical Model → Computational Model

Perceptual Model	Conceptual Model	Mathematical Model	Computational Model
Precepting phenome non through senses	Understanding the phenomenon	Formalize using mathematical expression	Develop the tool for solving the mathe matical model
Example) If rain falls in the m ountains, the water l evel in the river incr eases	Example) Draw watershed boun daries and define the relations between rai nfall and discharge	Example) • Horton's infiltration equation • SCS Effective ra infall equation	Example) • HEC-HMS • HEC-RAS • Develop own model

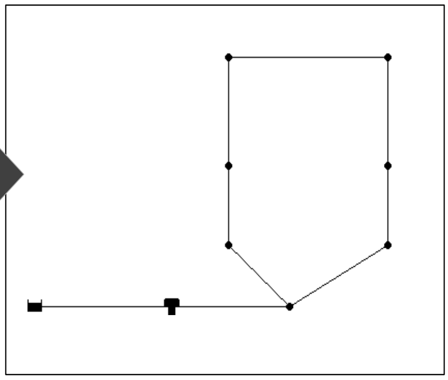
5.3 System Modelling for Resilience Quantification

▪ Tuning the model for resilience analysis

- Example case evaluating the resilience of a WDS
  1. Choose the computational model
  2. Select inputs (network elements, pipe specifications, etc.)
  3. Make simulation (run the model)
  4. Model tuning (calibration)
  5. Refine model
  6. Use the model for simulation, resilience analysis



[Water distribution system in perception]

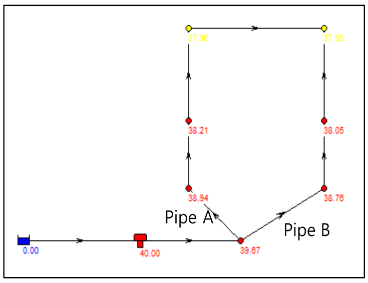


[Water distribution system in computer model]

5.3 System Modelling for Resilience Quantification

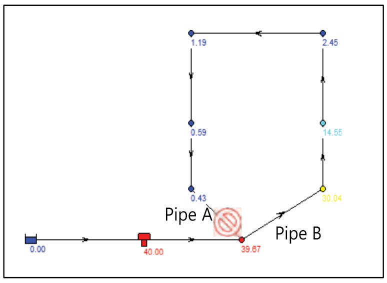
▪ Tuning the model for resilience analysis

- Using the model we can conduct resilience analysis

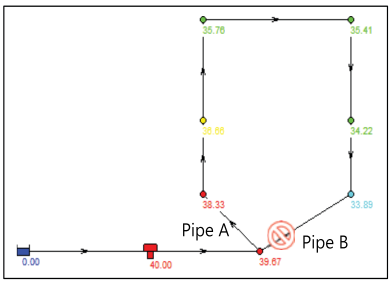


[Normal pressure]

VS.



[Pressure when Pipe A is broken]

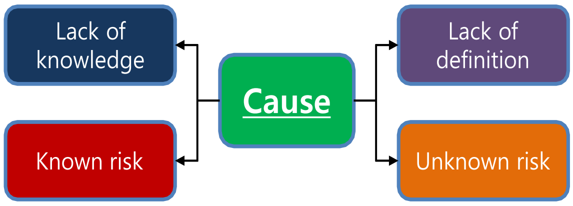


[Pressure when Pipe B is broken]

5.4 Accounting for Uncertainty

▪ Uncertainty is integral in resilience

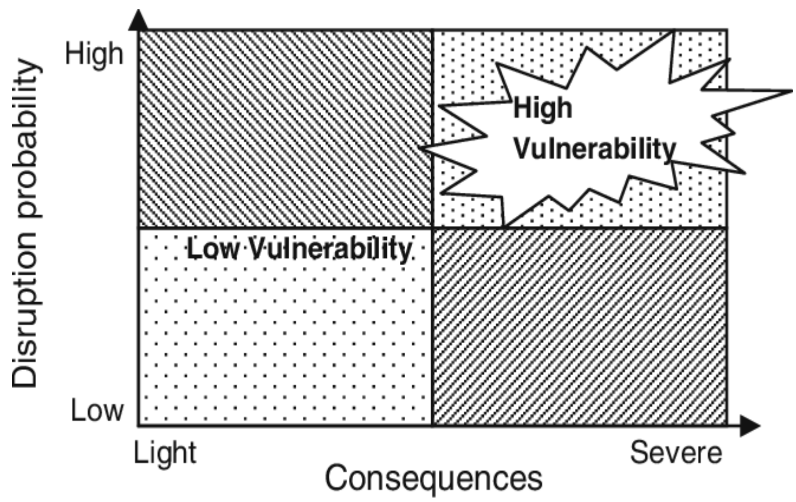
- Uncertainties have different levels (Hastings and McManus, 2004)



- Disruption from known risk are dependent on the probability that it might occur
- Unknown risks are unexpected and unforeseen. Such as natural disasters, technological failures, and terrorist attacks
- System reliability to known risks can be increased through higher quality components and redundancy optimization
- Against unknown risks, robustness, flexibility, and agility are the important aspects to be considered

5.4 Accounting for Uncertainty

▪ Vulnerability of system due to disruption probability

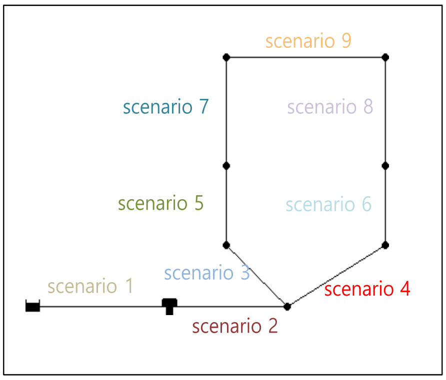


[Dimensions of vulnerability] Source: Sheffi 2005, p.20

5.4 Accounting for Uncertainty

▪ Application in modeling

- In a WDS, uncertainties can be applied by generating many random disruption scen arios
- On a small scale, all the disruptions might be able to be defined
- On a complex system, it would be too much to exhaust all possible risks
- The Monte Carlo Method can be applied to simulate random disruptions



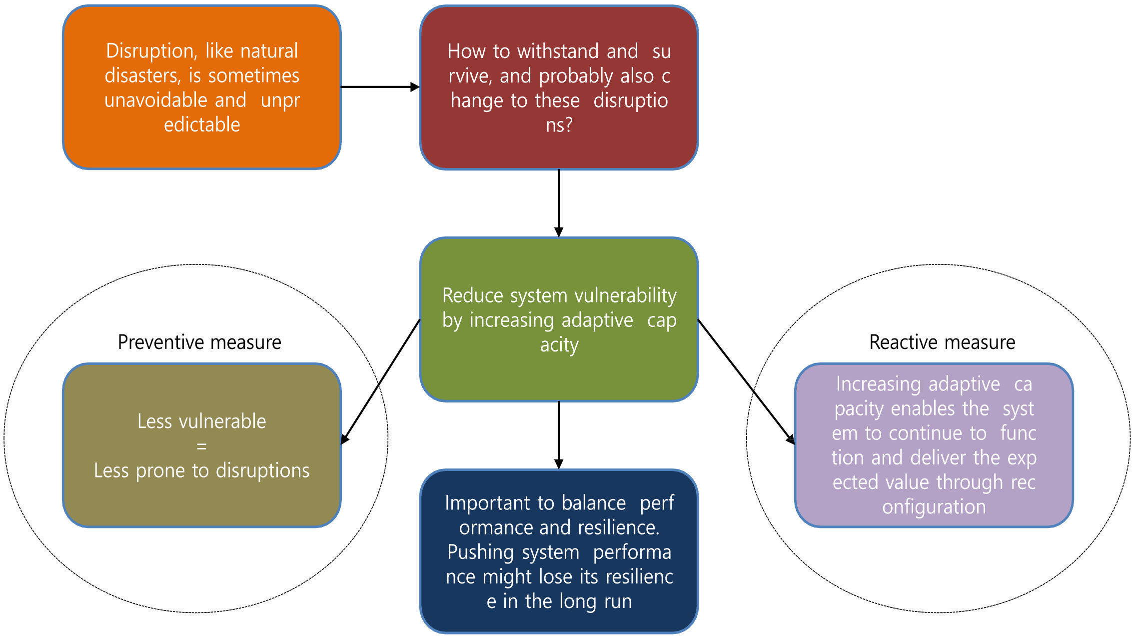
[Scenario variance]

6. Applying Resilience

1. Concepts to Achieve a Resilient System
2. Integrating Resilience Concept into System Design
3. Adaptivity for Resilience
4. System Failures
5. Agents in Disruption
6. Interfacing Human and Software
7. Adaptation to the System Requirement
8. Experience and Historical Knowledge

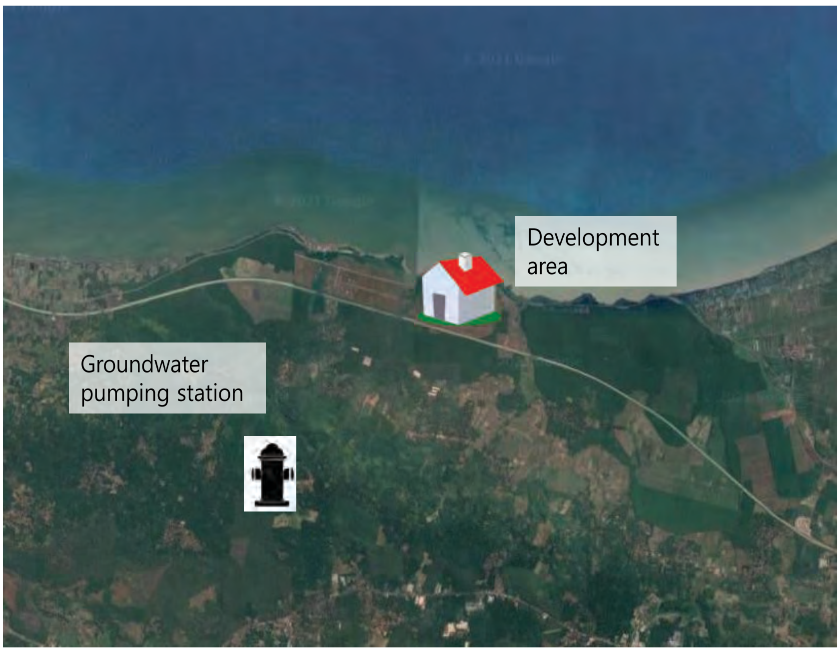
6.1 Concepts to Achieve a Resilient System

- **Unknown risk are unavoidable**



6.2 Integrating Resilience Concept into System Design

- **Example) designing a water supply system for a coastal area**



Planning for a resilie nt water supply for t he coastal develop ment area

Source: Google Map data ©2021

6.2 Integrating the Concepts into System Design

▪ **Example) designing a water supply system for a coastal area**

Source: Google Map data ©2021

- Increase **robustness** and provide **redundancy** by installing 2 large parallel pipes
- Using a surface pipe would be better for f aster repair (**rapidity**)
- Ready repair station s tocked with materials along the pipe path (**resourcefulness & ra pidity**)

6.3 Adaptivity for Resilience

▪ **Adaptability is the quality of being able to adjust to new conditions**

- A system is adaptive if it can change its behavior in response to the environment
- The adaptive change occurs to keep up with the primary goal and objective of the system
- In nature, adaptation can be viewed in plant growth around obstacles.

[Plant adapting to environment]

[Tree grows around the temple stones]

6.3 Adaptivity for Resilience

▪ Adapting brings opportunities

- Supply chain can be modeled as pure mathematical formulation (Moncada, 2015). However, the actual application supply chain consists of inter-dependencies among different entities, processes, and resources

- The delivery of the product can change with growth in technology. Recently demonstrated by Amazon Prime Air

[Amazon Prime Air delivery drone]

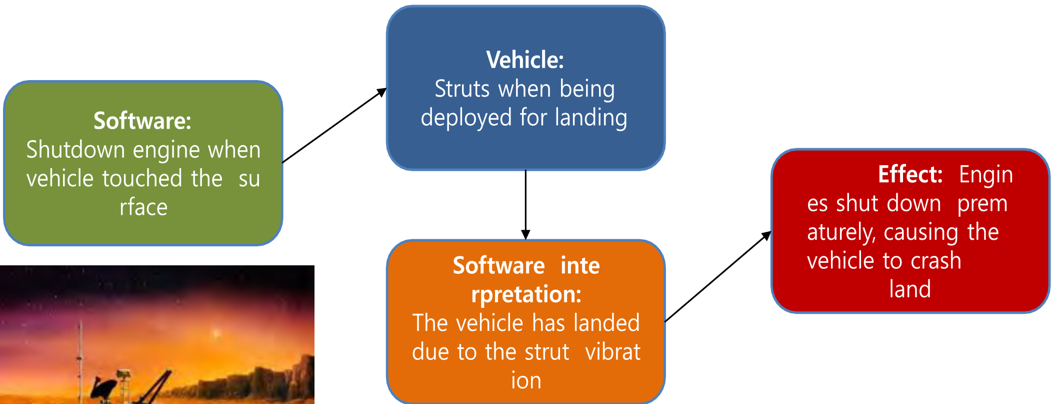
- Situation such as the COVID19 pandemic also changes supplier and customer behavior. Most notably in work hours and face-to-face interaction

[Online meeting

6.4 System Failures

▪ Unpredicted interaction (events) lead to system failure

- The mars polar lander landed catastrophically (Leveson, 2002)



[Mars Polar Lander on Mars]

6.4 System Failures

▪ Human error leads to casualties

- Airbus A300 struct the ground due to bad interaction between pilot and autopilot (Zarboutis and Wright, 2006)

Autopilot: Was put to take off mode by the pilot

Pilot: Tried to land the plane while not knowing the autopilot was put to take off mode

Interaction: The plane configuration tried to fight back the pilot attempt to land

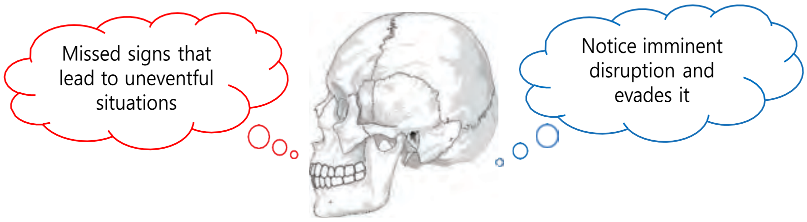
Effect: The plane enters an aerodynamic stall and crashed

[B-1816, the aircraft involved in the accident]

6.5 Agents in Disruption

▪ Human factors are double-edged sword in disruptions

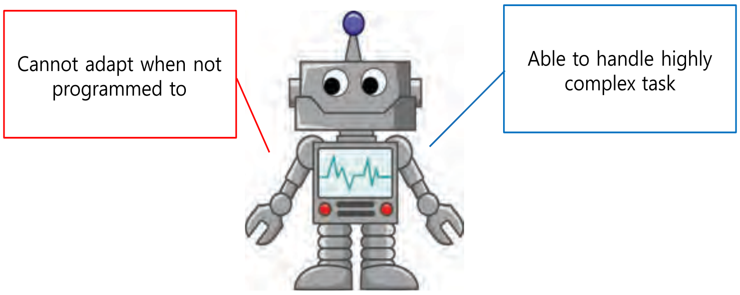
- Human behavior is unpredictable. In the Nagoya accident, the human pilot plays a central part in the leading result
- However, humans can also be clever or improvise to avoid a dire result. This was shown in the Apollo 13 mission, which was saved by the actions of the crew. Noticing the power loss in the main module, the crew demonstrated flexibility moved to an available smaller landing module
- Many large-scale systems tend to be human-intensive. Most notably is that air traffic controls are not fully automated. Humans are viewed to be more capable of detecting and handle unpredicted situations



6.5 Agents in Disruption

▪ **Most complex systems need software to control it**

- Software deficiencies can contribute to disruptions
- In both the Nagoya accident and the mars polar lander, software plays a part
- The software performance is highly dependent on the software creator, where one must carefully design it to be ready for unexpected things
- If the software is not programmed to handle the situation, it can be the source of disruptions



6.6 Interfacing Human and Software

▪ **Adaptability principles** (Billings, 1997)

- The human operator must be in command
- To be involved, the human operator must be informed
- The human monitor must be able to monitor the automated systems
- Automated systems must be predictable
- The automated system must also be able to monitor the human operator
- Each element of the system must have knowledge of the others' intent
- Functions should be automatic, only if there is a good reason for doing so
- Automation should be designed to be simple to train to learn and to operate

6.7 Adaptation to the System Requirement

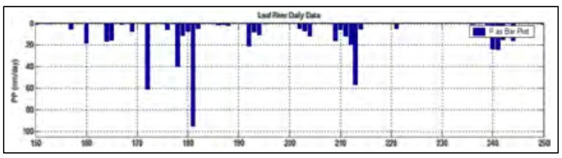
▪ Resilience cannot be easily adapted

- A system has to follow the **proper safety standards** that are within its **capability**, forcing it to adapt to the same level as the best performer could result in the system's collapse
- The **ecology of resilience** needs to be respected instead of systematically adopting force and adaptation of functions. The normal resilience of the system might be suitable for the system to be well-performing
- A good knowledge of the characteristics and the causal events in **transitioning resilience stage** is crucial
- All systems will **naturally transition** to new resilience stages associated with better safety through natural adaptation from **running experience**

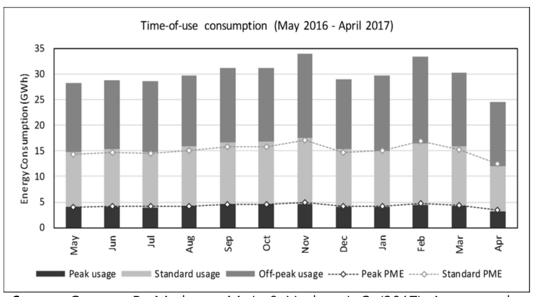
6.8 Experience and Historical Knowledge

▪ Past experience is important to increase resilience

- **Reviewing** the case histories of events can provide an understanding of the root cause of said events
- By **understanding the root causes** of events, one can **prevent** disaster from happening again by accounting for t he cause when designing a system
- Historical data such as traffic density or precipitation are helpful. Using the data, the design can be adjusted to the right amount to mitigate events
- As future events are unpredictable, it is important to put a **margin of safety** even when going from historical data



[Precipitation data]



Source: Goosen, P., Mathews, M. J., & Vosloo, J. C. (2017). Automated electricity bill analysis in South Africa. *South African Journal of Indust rial Engineering*, *28*(3), 66-77.

[Electricity usage time-of-use breakdown]

7. Social Factors in Resilience

1. Social Behavior
2. Destructive Social Behavior
3. Approaches to Mitigate Destructive Social Behavior
4. Organizational Resilience

7.1 Social Behavior

- **Social behavior plays an important part in resilience**

- It is Important to be remembered that human behavior is **unpredictable**
- Training, lectures, well engineered processes are not enough to change cultural behavior
- System resilience model often included a culture element, which is the belief or paradigms of the people who are part of the system
- Weick and Sutcliffe (2001) and Reason (1997) defined the principal characteristics of a high-reliability organization:
  - Preoccupation with failure
  - Reluctance to simplify interpretations
  - Sensitivity to operations and a reporting culture
  - Commitment to resilience and learning a culture
  - Deference to expertise and a flexible culture
  - Just culture

7.2 Destructive Social Behavior

- **Vaughn (1996) and Leveson (1995) pointed many belief that have contributed to many disasters**

- Small problems are not important
- Irrational confidence that system is not vulnerable
- A program cannot afford to verify all requirements
- Suppliers can figure out what to build without giving them requirements
- Resilience only depends on technical qualities
- If everyone were ethical, there would be no disaster
- Staying away from safety issues in order to avoid legal liability
- Focusing on systemic problems will reduce the incentive for individual responsibility
- Safety analyses have already taken into account all aspects of human errors

7.2 Destructive Social Behavior

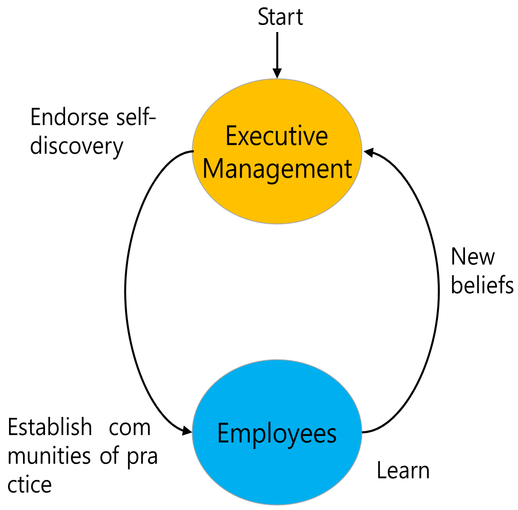
- **Vaughn (1996) and Leveson (1995) pointed many belief that have contributed to many disasters**

- Nothing can be done to reduce the probability of disasters
- All non-technical subjects are the purview of program management
- Unwillingness to take risk management seriously
- Nothing can be done to deal with external factors, such as cost and schedule
- Contractual constraints cannot be dealt with
- Human error cannot be reduced
- Not enough statistical data to create indicators of disaster
- Belief cannot be changed
- Some aspects of the program take precedence over safety

7.3 Approaches to Mitigate Destructive Social Behavior

▪ **Mitigating destructive social behavior is challenging**

- Two of the most prevalent method are:
  - Lectures by charismatic leader
  - Training
- Alternatives:
  - Socratic teaching
  - One-to-one coaching
  - Independent reviews
  - Cost and schedule margins
  - Standardized process
  - Rewards and incentives
  - Management selection
  - Communities of practice



[Behavior improvement model]

7.4 Organizational Resilience

▪ **An organization should possess a basis set of capabilities in order to develop a resilient system**

- These are the *primary capabilities* form the governing capabilities that enable the system's resilience
  - **System resilience supervision**
    - ✓ Involves organizational supervision at both the organizational level and infrastructure level
  - **Cultural initiatives**
    - ✓ Efforts to instill positive behavior in all members of the organization
  - **System resilience infrastructure**
    - ✓ The formation of both organizational structures and infrastructures architectures. The objective is to achieve system resilience capabilities across organizational and contractual boundaries

7.4 Organizational Resilience

- **An organization should possess a basis set of capabilities in order to develop a resilient system**

- The primary capabilities to be supported by *supporting capabilities* include:
  - Adaptability
  - Risk management
  - Schedule management
  - Cost management
  - Technology management
  - Verification
  - System Safety
  - Configuration management
  - Expertise
  - Software
  - Manufacturing
  - Operations
  - Work environment
  - Information management
  - Regulatory environment
  - Technical management
  - Maintenance
  - Supplier management

8. Conclusions

8. Conclusions

- **Resilience need to be implemented at the beginning and maintained**

- Failures are bound to happen. It is always essential to integrate resilience in system design. By reviewing the trade-off from implementing resilience, sys tem longevity can be achieved, and safety levels can be increased
- One must keep a broad view of factors in system design and assumptions should not be made blatantly. As more assumptions are made, the more rigid the system gets
- Resilience is a broad view, but in order to apply it, we need to set a certain goal
- Application of resilience needs to be adjusted with the needs of the system

Thank you very much

Issues in Water Security and Resilience

Water Security and System Resilience

2. Issues in Water Security and Resilience

Aims & Objectives

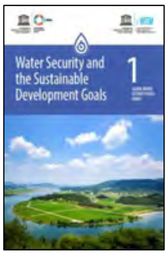
- The aims of the course are to:

  (1) Explain the concept of water security
  (2) Explain the relation between water security and resilience
  (3) Present real-world water security issues

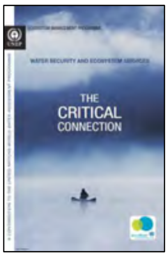
- The objectives are that trainees will understand:

  (1) Ongoing issues of global water security
  (2) How to incorporate water security and resilience
  (3) How to view problems in corresponding fields of water security and resilience

References



Water Security and the Sustainable Development Goals (Series I). Global Water Security Issues (GWSI) Series (UNEP, 2009)



Water security and ecosystem services: The critical connect ion (UNEP, 2009)

Urban water security: A r eview (Hoekstra et al., 2014)

Water, security and conflict (Gleick and Iceland, 2018)

Contents

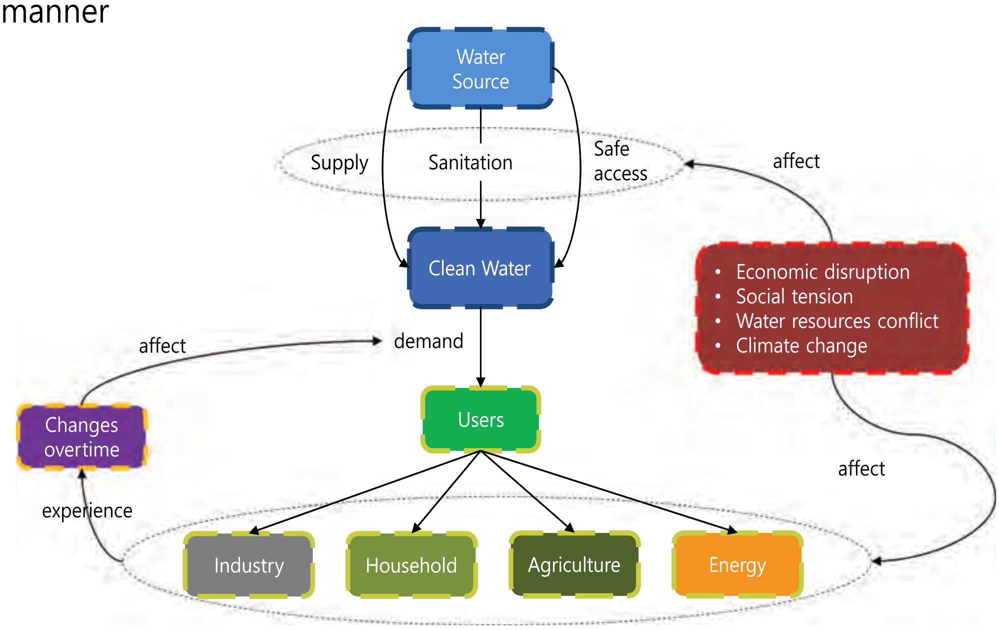
1. Introduction to Water Security

1. Understanding Water Security
2. UN Infographic
3. Dimensions of Water Security and Sustainability
4. Related Terms
5. Sustainable Development Goals (SDGs)

1.1 Understanding Water Security

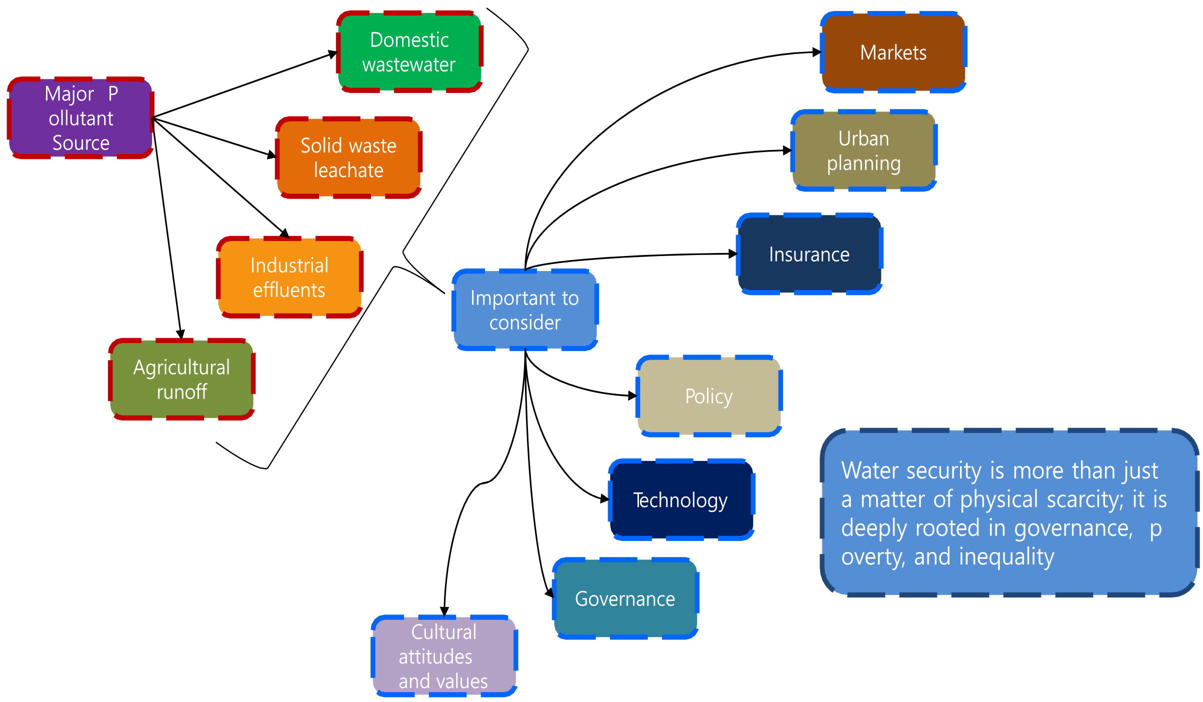
- **As water demand increases, many challenges arise likewise**

- The geography of water supply, demand, and use changes in a complex and rapid manner



1.1 Understanding Water Security

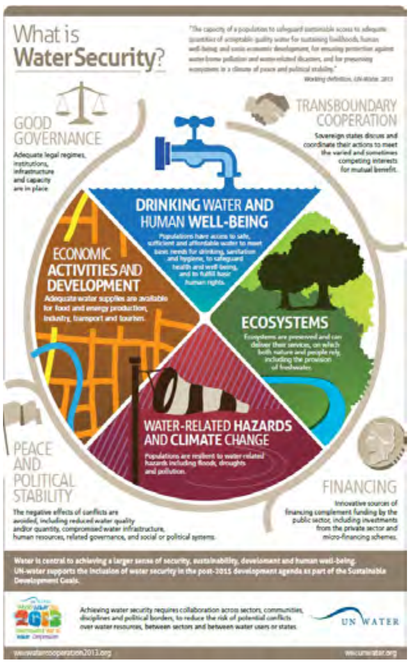
- **Water pollution is one of the easily visible problem in water security**



1.2 UN Infographic

- **What is Water Security?**

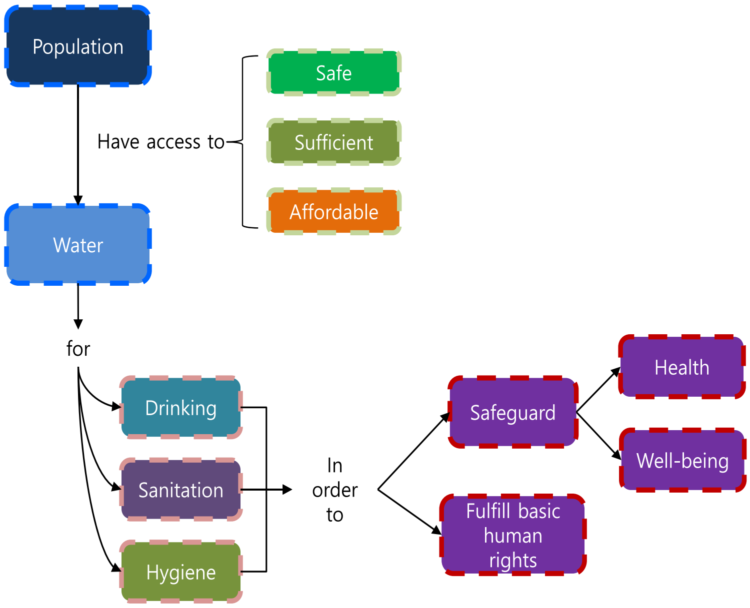
"The capacity of a population to safeguard sus tainable access to adequate quantities of acce ptable quality water for sustaining livelihoods, human well-being, and socio- economic devel opment, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peac e and political stability" **Working definition, U N-Water, 2013**



[water security definition and cross sectors]

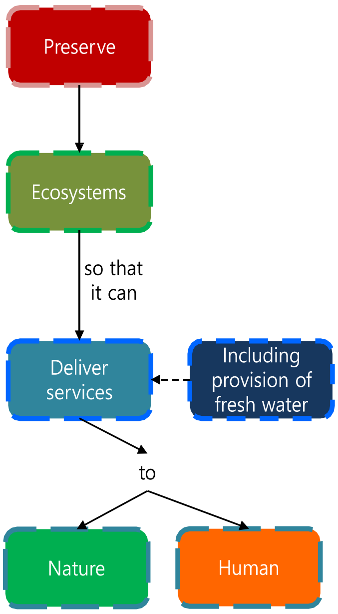
1.2 UN Infographic

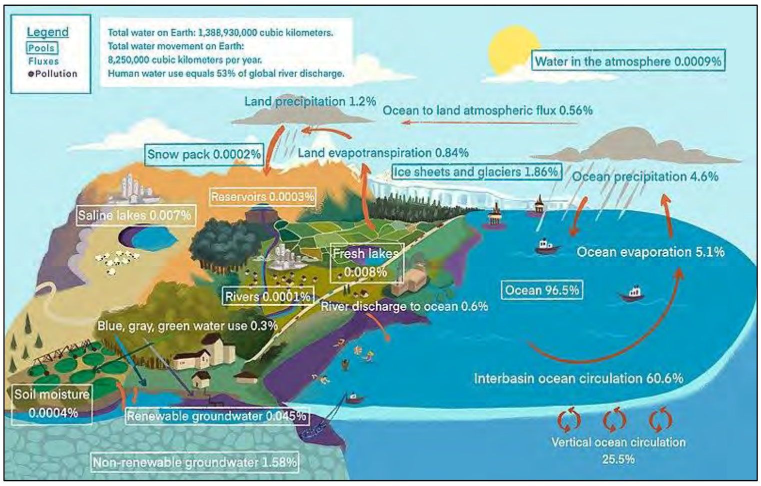
▪ Drinking water and human well-being



1.2 UN Infographic

▪ Ecosystems



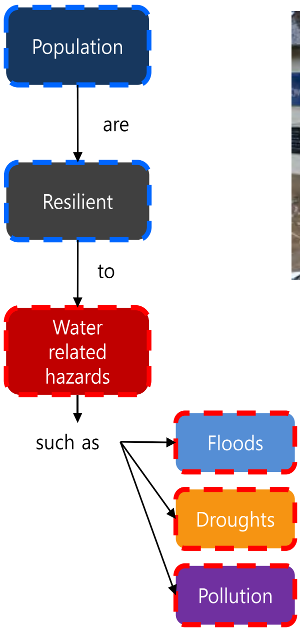


Source: LangeLeslie and Anna Wright, 10 August 2020

[Human Integrated water cycle]

1.2 UN Infographic

▪ Water related hazards and climate change



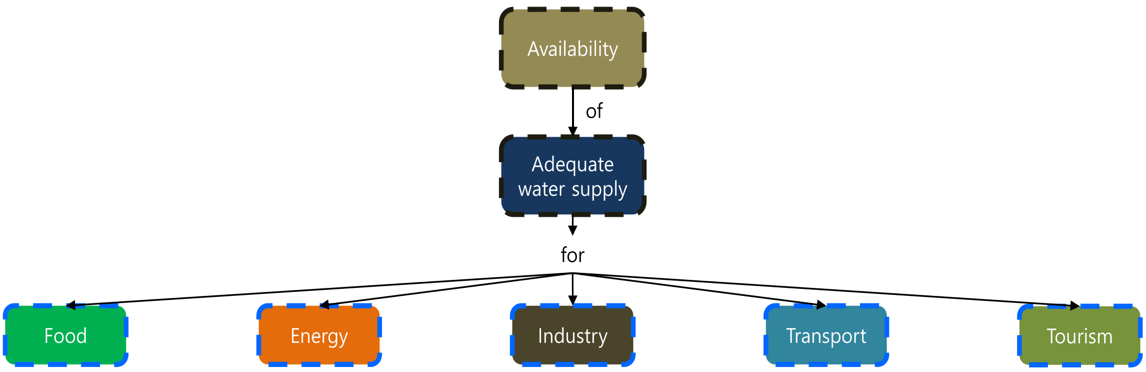

[Flood]


[Drought]


[Pollution]

1.2 UN Infographic

▪ Economic activities and development




[Agriculture]


[Hydro-power plant]


[Manufacturing]


[Cargo transport]


[Holiday destination]

1.2 UN Infographic

- **Supporting factors for Water Security**

Good Governance
Adequate legal regimes, institutions, infrastructure, and capacity are in place

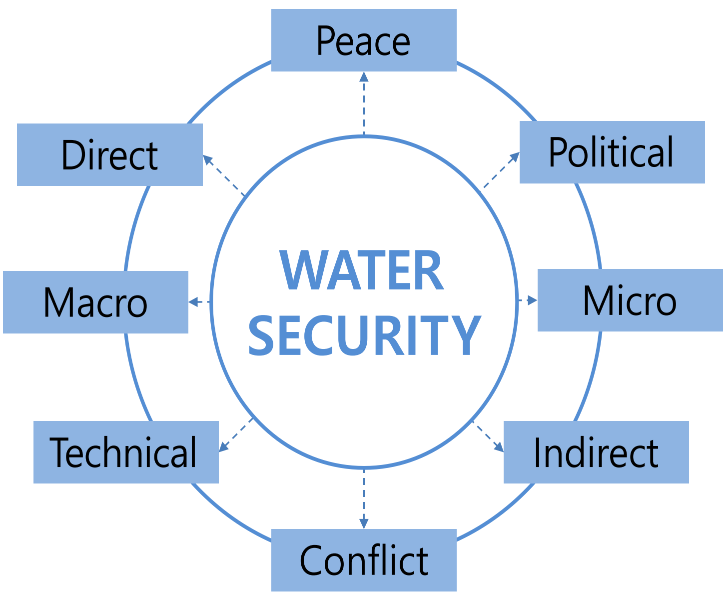
Transboundary Cooperation
Sovereign states discuss and coordinate their actions to meet the varied and sometimes competing

Financing
Innovative sources of financing complement funding by the public sector, including investments from the private sector and micro-financing schemes

Peace and Political Stability
The negative effects of conflicts are avoided, including reduced water quality and/or quantity, compromised water infrastructure, human resources, related governance, and social or political systems

1.3 Dimensions of Water Security

- **Definition of water security involves many aspects**



[Varis et al., 2017]

Water security is a multifaceted co ncept with numerous aspects and dimensions. Varis et al. (2017) ide ntify four dimensions, each with tw o complementary aspects: direct-indirect, macro-micro, t echnical-political, and peace-conflict

The influence of water security on other concepts such as food sec urity can be examined using thes e aspects

1.4 Related Terms

▪ Definitions of several terms that interact with Water Security

Human Security
Overall human health and well-being, including economic and social conditions that promote a high quality of life.
It includes "people's freedom from want and freedom from fear," as well as individual security from threats such as disease, poverty, violence, and human rights violations

National Security
A formal state's condition of peaceful governance and the absence of violent conflict. The concept of national security also refers to national governments' roles in providing security for citizens and institutions

Global Security
A broader set of mutual safety, non-violence, and positive quality of life conditions for groups of states and the international community. "Military and diplomatic measures that nations and international organizations take to ensure mutual safety and security" are included in global security

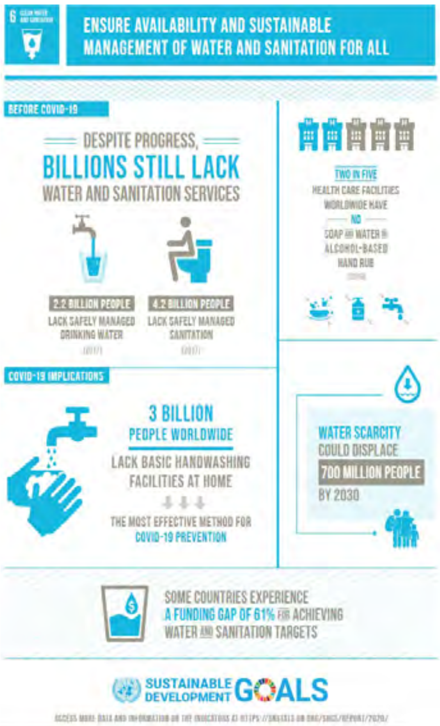
1.5 Sustainable Development Goals (SDGs)

▪ Relationship between water, environment, and human security

- Human security is a paradigm in which security is defined by the needs of **individuals** rather than those of states. Water, as a **critical and scarce resource**, plays an important role in the creation and **maintenance of human security** in relation to the environment.
- "The human security aspect of water scarcity appears to be the most likely source of national and international security threats" (Wolf, 1999)
- Due to a lack of fresh water, poor irrigation practices are used, resulting in the use of salt water and poorly treated wastewater. Soil salinity destroys nearly a million hectares of arable land in the Middle East and North Africa every year
- Water scarcity reduces food production, which is closely related to population growth. This combination leads to deteriorating living conditions and additional environmental issues. Poverty, malnutrition, and famines are the result of environmental changes
- Poor countries that are unable to change their irrigation and agricultural practices may become more reliant on foreign food aid as food production, arable land, and water decline

1.5 Sustainable Development Goals (SDGs)

▪ Goal 6: Clean water and sanitation



- One in every three people **lacks access** to safe drinking water and sanitation. According to the World Health Organization (WHO), more than 6 73 million people still practice open defecation. According to estimates, more than billion people do not have access to safe drinking water or sa nitation
- According to the World Health Organization (W HO), handwashing is one of the most effective w ays to reduce pathogen spread and prevent infe ctions. Despite this, billions of people continue t o lack access to safe drinking water and sanitati on, and funding is insufficient. Handwashing is a n essential part of preventing and controlling dis eases such as COVID-19

1.5 Sustainable Development Goals (SDGs)

▪ The 6 Goals to be achieved by 2030

6.1 Achieve universal and equitable access for all to safe, affordable drinking water

6.2 Achieve universal access to adequate and equitable sanitation and hygiene for all

6.3 Improve water quality globally by reduci ng pollution, eliminating dumping, and mini mizing the release of hazardous chemicals a nd materials, halving the proportion of untre ated wastewater, and significantly increasing recycling and safe reuse

6.4 Significantly increase water-use efficiency across all sectors and ensure sustainable fre shwater withdrawals and supply to reduce th e number of people suffering from water sc arcity

6.5 Implement integrated water resource management at all levels, including tran sboundary cooperation as needed

6.6 Protect and restore water-related e cosystems such as mountains, forests, wetlands, rivers, aquifers, and lakes

6.A Increase international cooperation and capacity-building assistance to developing countries for water and sanitation-related activities and programs

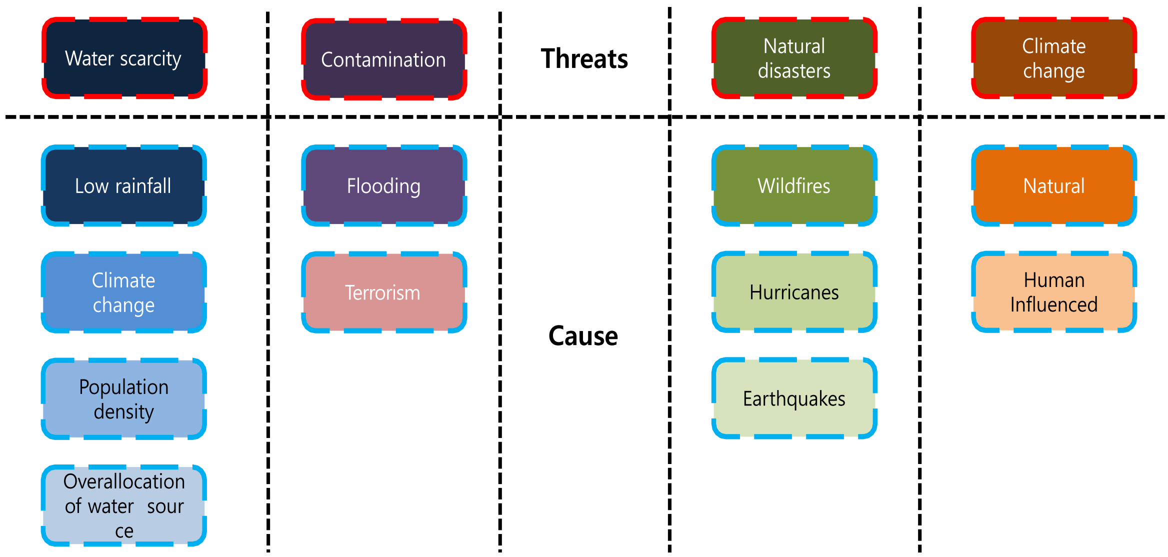
6.B Encourage and strengthen local comm unity participation in improving water and s anitation management

2. Disturbance in Water Security

1. Threats to Water Security
2. Problems in Water Security around the World
3. Water Usage
4. Factors affecting Water Usage
5. Awareness of Water Security

2.1 Threats to Water Security

- **Disturbances that can destabilize water security**



2.2 Problems in Water Security around the World

- **Cases of diminished water supply or quality**

- **Drought in failed states or drought that contributes to state failure**
  - Severe drought and its consequences contributed to Syria's state failure beginning in 2011 (Gleick, 2014)
- **Drought in countries that can influence global grain and food prices**
  - Droughts in Russia, Ukraine, China, and Argentina, as well as torrential storms in Canada, Australia, and Brazil, contributed to a spike in food prices in 2010-2011 (Mitchel, 2008; Dillon and Barrett, 2016)
- **Water rendered useless by pollution**
  - The Billings Reservoir in São Paulo is considered far too polluted to be used for public water supplies. The reservoir's deplorable state exacerbated the problems caused by a two-year drought that reduced water supplies in São Paulo's primary water system, Cantareira, to dangerously low levels

2.2 Problems in Water Security around the World

- **Cases of diminished water supply or quality**

- **Saltwater intrusion in aquifers**
  - Saline contamination due to excessive groundwater pumping that is still ongoing until now threatens the supply of fresh water in Jakarta
- **River alteration by dams**
  - Ethiopia's construction of Grand Ethiopian Renaisance Dam is straining the relations between Ethiopia and Egypt
- **Water diversion in absence of agreement**
  - The Lorian Swamp fed by the Ewaso Nyiro River in Kenya has historically provided sustenance for pastoralists. Due to people fleeing Somalia and taking refugee in t he area, the upstream water is diverted for horticulture and over abstraction of g roundwater, causing the swamp to desiccate (Madgwick et al., 2017)
- **Landscape degradation**
  - Overgrazing and tree removal left landscapes barren and degraded. Without vegetation cover, topsoil is lost, causing the land to crack and fail to retain r ainwater

2.2 Problems in Water Security around the World

▪ Cases of increased water demand

- **Chronically stressed irrigation areas**
  - Syria's food self-sufficiency policies increased food production dramatically, but they were not sustainable because they required more water than was available annually. When a drought event occurs, farmers are forced to relocate from the countryside to the cities
- **Chronically stressed urban areas**
  - Capetown faced the risk that its municipal water system would have to be shut down in mid-2018 ("Day Zero"). The crisis was precipitated by the growing po pulation, a severe three-year drought, lack of alternative water supply, and inef ficient responses
- **Rising water and land pressures in rainfed areas**
  - The Darfur conflict (2003) was influenced by resource scarcity brought on by pr olonged drought and desertification, as well as population growth. As a result, f ood availability decreased and long-standing agreements between nomadic her ders and sedentary farmers were disrupted (Iceland, 2017)

2.2 Problems in Water Security around the World

▪ Natural water is not only threatened, it is also threatening! (Lehmann et al., 2010)

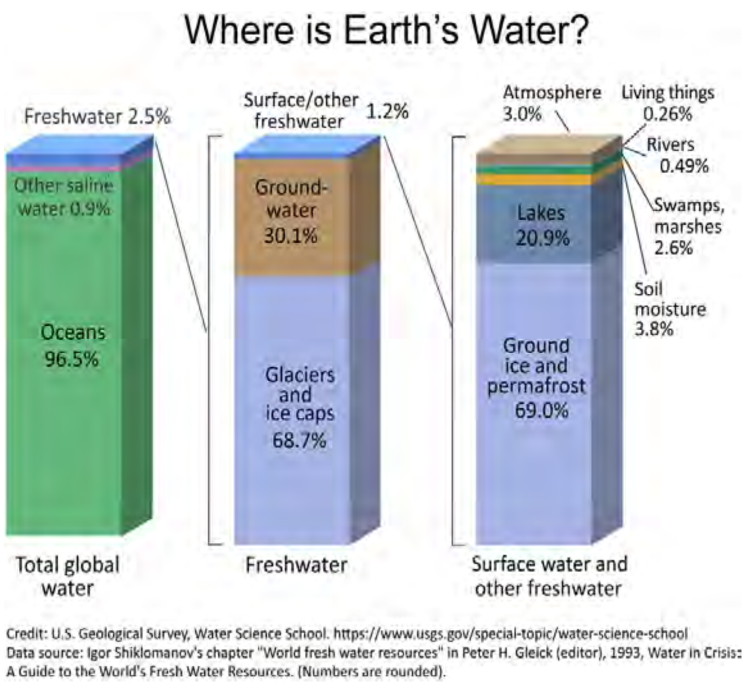
- **River floods, flash floods, and coastal storm surges can affect human health and safety**
  - In August 2017, South Asia experienced devastating rainfall, resulting in over 1,200 deaths and affecting over 40 million people directly
- **Flood can affect industrial production and the global economy**
  - Thailand's worst flooding in a half-century caused $46 billion in economic damage

[Flooding in suburban area]

[Flooding farm]

2.3 Water Usage

▪ Distribution of water source



- Although about 71% of t he earth's surface is cover ed by water, only 2.5% of those water is **fresh water** that is available to sustain human, animal, and plant l ife
- Of that 2.5%, only about 1.2% is **surface water**
- **Rivers** account for appr oximately 0.49% of surfa ce freshwater, but they p rovide a significant porti on of human water dem and

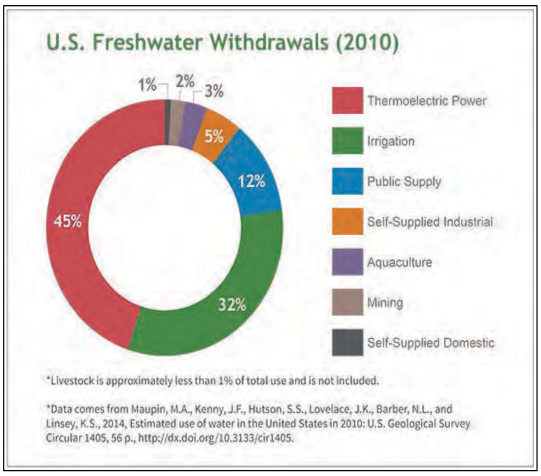
2.3 Water Usage

▪ Water usage distribution

- Water is used in our daily life, directly and indirectly
- At home, the average American family consumes more than 1100 liters of water per day. Approximately 70% of this usage occurs indoors

source: https://www.epa.gov/watersense/how-we-use-water

[Household water usage in the US]



[Residential, industrial, agricultural & power generation water use in the US]

2.4 Factors Affecting Water Usage

▪ General Factors

▪ The amount of water used in any activity is determined by the **supply** of water available to support that activity as well as the **demand** for water in that activity. However, a number of overarching factors influence water use levels regardless of location. These factors will undoubtedly be important in determining future u sage levels (White, 1999)

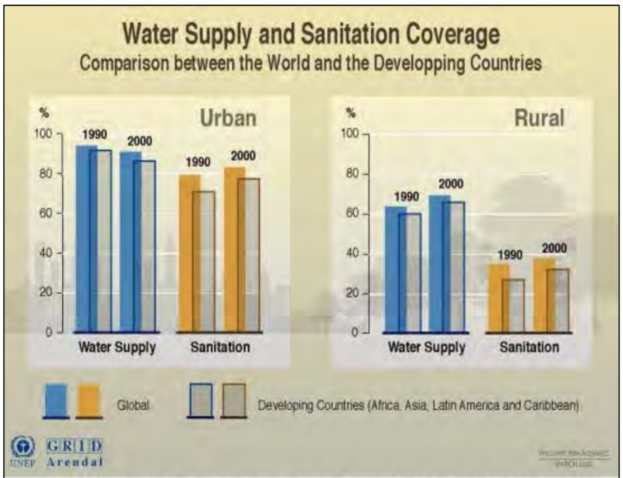
Several major factors:

- Population numbers and distribution
- Technology
- Economics
- Environmental conditions
- Instream and withdrawal uses of water

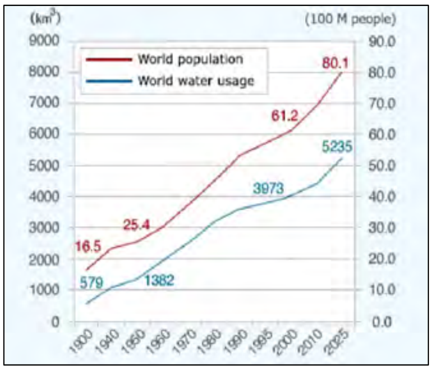
2.4 Factors Affecting Water Usage

▪ Population numbers and distribution

▪ Water is required in quantities **directly proportional** to the number of people to meet people's basic domestic needs
▪ People who live in **cities** tend to use water in a different way than people who live in **rural areas**



Source : *Global Water Supply and Sanitation Assessment 2000 Report*, World Health Organization (WHO) and United Nations International Children's Emergency Fund (UNICEF).



Source: UN, World Population Prospects 2019

[World population and water usage trends]

2.4 Factors Affecting Water Usage

▪ Technology

- Technology and technological changes may impact on the availability or supply of water, the demand for water, and the levels of water use. Water-efficient indoor plumbing fixtures, closed-conduit irrigation systems, and computerized irrigation management techniques result in reduced water consumption
- Technology can have **unintended** and **unanticipated** consequences. Some technologically induced or influenced changes in the water supply may be reversible only over thousands of years. The advantages and disadvantages of new and existing water supply technology should be explicitly specifically across time domains

[Aqueduct]

[Underground water line]

Disruption due to technology:
- Large dams
- Ground water exploitation
- Irrigation practices

2.4 Factors Affecting Water Usage

▪ Economics and Environmental Conditions

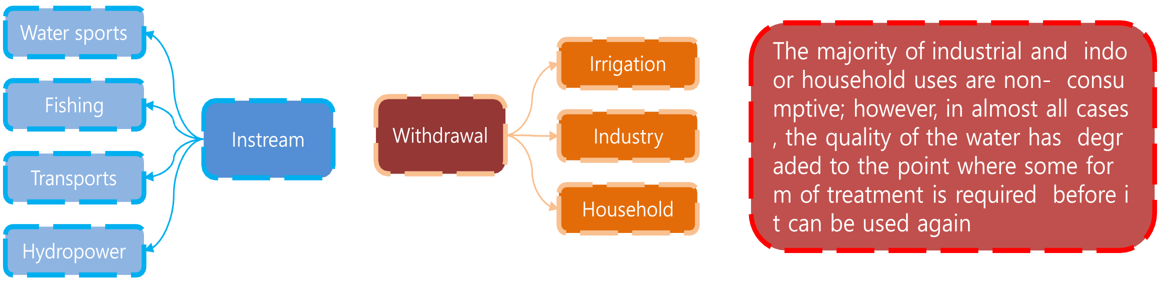
- Economic conditions in the region will have an impact on water use by affecting water users' **ability to pay** for water
- Economic conditions affect **foreign trade** in a variety of ways, the implications of which for water use are not always obvious ➔ **Water footprint**

- Temperature changes, as well as reductions in vegetated area and biological diversity, are likely to reduce available supplies. **Water quality deterioration** due to increased contamination levels and droughts reduces the available s upply of water
- Human activity can cause climate change either directly or indirectly. **Global warming** is expected to have a significant, if not profound, impact on regional water supplies and demand
- Water quality and quantity can be influenced by environmental factors, and vice versa

2.4 Factors Affecting Water Usage

▪ Instream and withdrawal uses of water

- Water use can be classified into two types: **instream** and **withdrawal**. Most recreational uses, support of aquatic habitats and other environmental uses, navigation, and hydroelectric power generation are all examples of instream uses. These uses **do not change the properties of the water**, nor do they affect the quality or quantity of water available for subsequent uses
- Water can be withdrawn from a surface water body or an aquifer and used either consumptively or non-consumptively. Consumptive uses occur when water is transformed from a usable state or location to one that cannot be used. Water that has been consumed is not available for future use



2.5 Awareness of Water Security

▪ Most people are not aware of the importance of water security

- We use so much water everyday in our life so that we take it for granted and not aware that water is a **limited resource**
- Places with abundant rainfall can still experience drought due to **poor water management and/or usage practices**
- **Water scarcity** is one of the greatest challenge **worldwide**
- If not taken care of carefully, water security could impact global security:
  - Increase global tensions
  - Diminish agriculture and reduce food security
  - Cause for population shift
  - Increase the spread of water-bound disease
  - Undermine economic development

3. Engineering for Water Security

1. Roles of Engineering
2. Smart Water
3. IWRM

3.1 Roles of Engineering

▪ Importance of engineering for water security

- Engineering solutions are especially important in the design of a water secure system
- To ensure water security, an integrated approach is essential. Multi-criteria, multi-objective, and multi-constraint integrated management is required. It must be practiced within the constraints of social, cultural, political, legal, environmental, and economic considerations
- Many water related disasters can be avoided or mitigated with good engineering plan:
  - Drainage system
  - Water treatment facility
  - Dam

[Drainage]

[Hoover Dam]

[Sewage plant]

3.2 Smart Water

▪ Preparing for the future

- According to various projections, cities will house 70% of the world's population by 2050. Making cities smarter is becoming a priority for both governments and private sectors. Cities around the world will invest USD108 billion in smart city i nfrastructure this decade. The phrase "**smart cities**" is gaining popularity amon g governments, urban planners, and even the private sectors
- Smart cities include six key sectors that must work together to make a city more livable, sustainable, and efficient:
  - ✓ Smart energy
  - ✓ Smart integration
  - ✓ Smart public services
  - ✓ Smart mobility
  - ✓ Smart buildings
  - ✓ **Smart water**

3.2 Smart Water

▪ Implementation methodology

- In the coming years, new IT-related technologies will have an impact on the ent ire water cycle and the management of water-related services. The strategy's m ain driver is to achieve a comprehensive architecture of an Information System (I S) dedicated to water uses and linked to other systems involved in human activi ties. This is the smart water concept's operational formulation
- To develop a specific IS for water cycle management, a methodology for ident ifying priorities and strategic investments in the ICT domain is required. The r equested method must investigate all domains and provide a map of the vario us processes occurring in the various domains of the water use cycle. This for malization exercise, which focuses primarily on concepts and processes, is no w required to ensure the coherence of technical choices in a holistic approach

3.2 Smart Water

▪ Implementation priorities

- The water domain and water stakeholders are very broad and cover a large number of business processes, especially when all domains and activities are taken into account. This circumstance validates the mapping process and the prioritization of gaps that must be filled

Real-time monitoring
- Installation of leak detectors
- Sensors at all points of use
- Real-time information of cu stomers and stakeholders

Cities of tomorrow
- Improving water efficiency
- Generalized and standardized ICT
- Cascading usages of water, rainw ater harvesting, desalination, etc.

Energy efficiency
- Energy saving tools in treatment plant
- Monitoring and control of heat recovery in wastewater
- Smart metering / pricing tools (e.g. condition-based tariffs)

Asset and field work management
- Continuous performance, co ndition and risk assessment s ensing technologies
- Optimized network operation
- GIS/GPS information

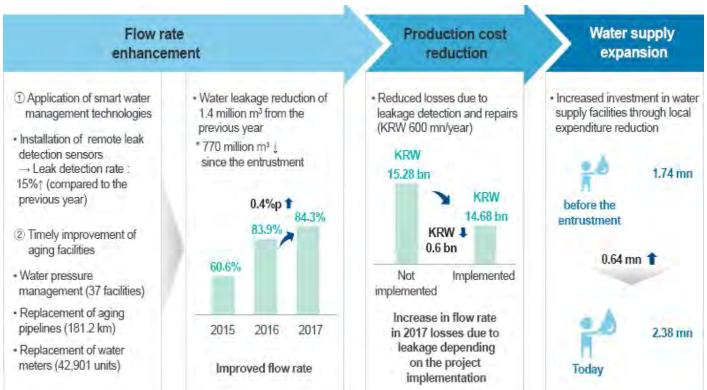
Water efficiency
- Improving water efficiency in cities
- Improving water efficiency in agr icultures; includes detection of ille gal abstraction
- Ecosystem and land-use man agement in perspective of pro ject scope and available reso urces

The implementation of smart water solutions in accordance with the five identified priorities will help to improve t he community's water security level

3.2 Smart Water

▪ Application of Smart Water

- "Smart water" is intended to collect meaningful and actionable data about a city's water flow and distribution. To sustain its growth, the water supply and management system must be sound and viable in the long run
- Energy is the largest controllable cost in water/wastewater operations. Water loss management is b ecoming increasingly important as supplies are stressed by population growth or water scarcity. A medium-sized city with 450,000 m³ per day of produced water that loses 25% incurring over US$13 million per year in non-recoverable labor, chemical and energy expenses



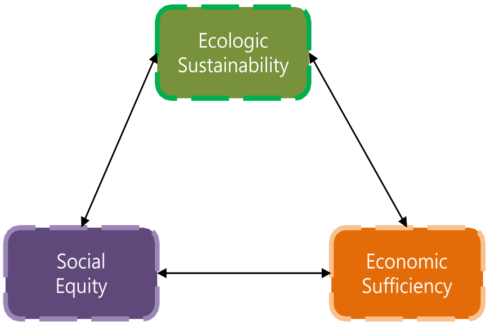
Source: K-water, https://www.kwater.or.kr/eng/busi/water02/smartWater02Page.do?s_mid=1186

[Performances and effects of smart water]

3.3 IWRM

▪ Definition of IWRM

▪ The Global Water Partnership (GWP) defines the integrated water resources m anagement (IWRM) as "a process that promotes the coordinated **developme nt** and **management** of water, land, and related resources in order to maximiz e the resultant economic and social welfare in an equitable manner without je opardizing the sustainability of vital ecosystems"



[Three principles of IWRM]

3.3 IWRM

▪ Main goals of IWRM

① To alleviate poverty, promote equitable access to water resources and the benefits that come with them

② Ensure that scarce water resources are used efficiently and to the greatest number of people's benefit

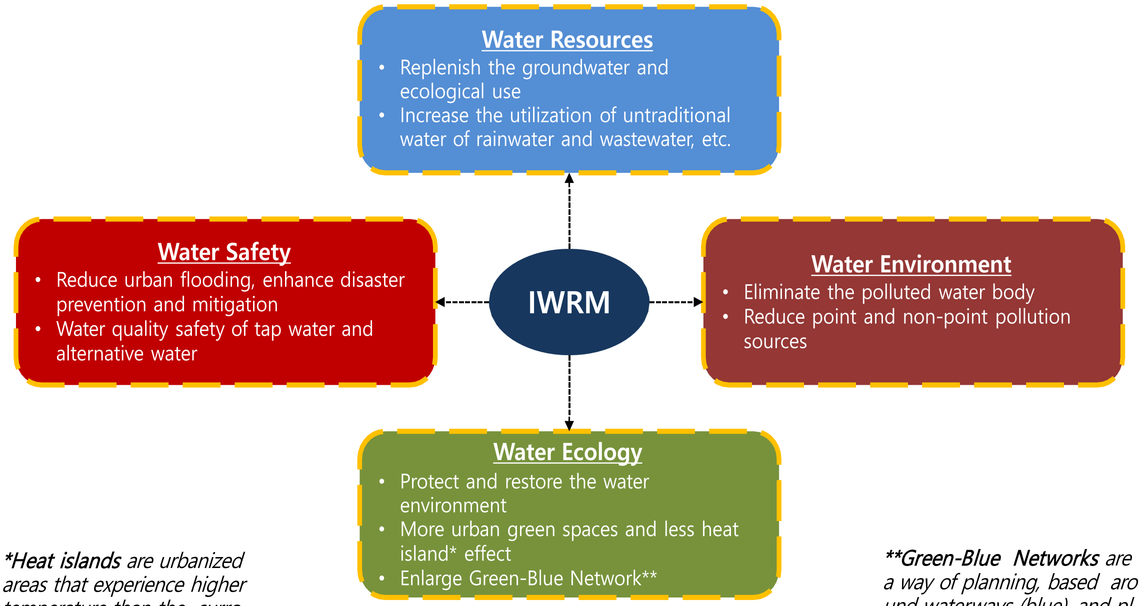
③ Coordination of projects and activities affecting water resources

④ Achieve more sustainable water use, including for environmental reasons

⑤ Bring new approaches in a new vision for water managers as "advocates" of sustainable resource use, and encourage changes in consumption behavior and modes of water su pply that account for social, economic, and environmental costs when assessing and pl anning water development options. The challenge remains in defining sustainable wate r resource management and what IWRM entails in policy options

3.3 IWRM

▪ Domain of IWRM



**Heat islands are urbanized areas that experience higher temperature than the surrounding areas.*

***Green-Blue Networks are a way of planning, based around waterways (blue), and planting and parks (green)*

3.3 IWRM

▪ Good practices

- Good practices, in the broadest sense, are a set of guidelines, ethics, or ideas that represent the most efficient or prudent course of action for achieving some goals. In the context of IWRM, good practices are a set of activities, practices, and tools designed to minimize negative effects on the environment and water resources, promote resource efficiency, improve consumer safety, and foster economic viability. The definition of what is good varies depending on the context and industry (IFSA, 2005)
- Good IWRM practices are methods, structures, and practices that are recommended to prevent or reduce water pollution, resource waste, promote efficient resource use, combat environmental deterioration, and enhance sustainability and social equity while maintaining economic efficiency and well-being (Botkosal, 2011)

A good IWRM practice can be identified by:

- Environmentally, economically, and socially sustainable
- Gender-sensitive
- Technically feasible
- Inherently participatory
- Scale
- Vertical and horizontal coordination
- Integration
- Replicable and adaptable
- Reducing disaster/crisis risks

4. Water Security and Resilience

1. Relation of Water Security and Resilience
2. Climate Resilience
3. Ecosystem Resilience
4. Urban Water Resilience

4.1 Relation of Water Security and Resilience

- **Water security and resilience go hand in hand**

- Resilience is the capability of a system to survive **disturbance events** and promptly recover to its initial performance state
- In the context of water security the **disturbance event** relates to events that can inhibit or disturb the access to acceptable quality and quantity of water
- Resilience to these disturbance events can be divided into:
  - Climate resilience
  - Ecosystem resilience
  - Urban water resilience

4.2 Climate Resilience

▪ Definition

- Climate resilience is the ability to **anticipate**, **prepare** for, and **respond** to potentially hazardous climate events, **trends**, or disturbances. Improving climate resilience entails determining how climate change will create new or alter existing climate-related risks, and then taking steps to better cope with these risks
- Climate resilience is frequently associated with **extreme events** – such as heavy rains, hurricanes, or droughts – that will become more frequent or intense as the climate changes. However, good resilience planning takes into account long-term issues such as rising sea levels, deteriorating air quality, and population migration
- The Intergovernmental Panel on Climate Change (IPCC) 5th Synthesis Report stated unequivocally that climate change over the 21st century is projected to significantly reduce renewable surface water and groundwater resources in most dry subtropical regions, intensifying competition for water among sectors. Changes in precipitation or melting perennial snow and ice are altering hydrological systems in many regions, affecting the quantity and quality of water resources

4.2 Climate Resilience

▪ Extreme hydrologic events

- Floods and droughts are natural occurrences in the hydrologic cycle. However, as the climate changes, **extreme events are becoming more common** in some places and at certain times. These occurrences have the potential to have a growing impact on water and global security
- Most rivers flood once every one to five years. During such events, river discharge is frequently 10 times the mean annual flow and 100 to 1000 times greater than the lowest flows. In that context, they might be considered extreme. When viewed in the context of all floods that occur over a century, floods that occur every one to five years are referred to as 'common floods’
- Labeling an event as 'extreme' necessitates some context regarding the timescales under consideration. Similarly, what is considered 'extreme' varies by location. A rainfall event with 50 mm of precipitation, for example, is quite rare in Utah but almost daily in parts of Hawaii. While there is no formal, universal definition of what hydrologists consider to be "extreme" events, there are numerous ways to assess precipitation and streamflow events within the appropriate context (timescale and location) to determine how they compare to "normal" conditions

4.2 Climate Resilience

▪ Extreme hydrologic events

- Drought is a **long period of dryness** in the natural climate cycle that can occur an ywhere on the planet. It is a slow-onset disaster caused by a lack of precipitation, w hich results in a water shortage. Drought has serious consequences for health, agri culture, economies, energy, and the environment
- Droughts affect an estimated 55 million people worldwide each year, and they are the most serious **threat to livestock and crops**. Drought endangers people's livelihoods, raises the risk of disease and death, and drives mass migration. Water scarcity affects 40% of the world's population, and up to 700 million people may be displaced as a r esult of drought by 2030 (WHO)
- Climate change is causing **rising temperatures** to make already dry regions drier and wet regions wetter. In dry regions, this means that as temperatures rise, **water evapor ates more quickly**, increasing the risk of drought or extending drought periods

4.3 Ecosystem Resilience

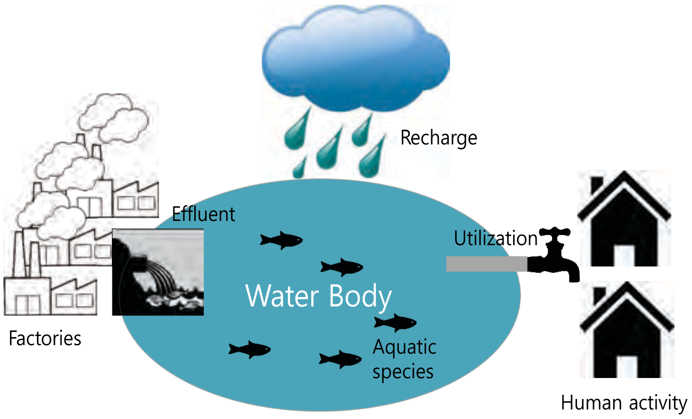
▪ Definition

- We live in an ecosystem; a complex of **living organisms** (plants, animals, microorganisms) and their **nonliving surroundings** (water, soil, minerals). These living and nonliving comp onents are linked as a **functional unit** by a complex series of interactions
- The primary goal of water resource management is to ensure the sustainable use of wat er resources. Water resources were initially regarded as a commodity to be used in the s ame way that oil, ore, or other extractable resources, with meeting human water needs being the primary concern of water resource managers. When existing supplies became fully allocated or utilized, the focus shifted to obtaining additional water sources
- Humans, ecosystems, and water resources are increas ingly **intertwined**. With the development of integrate d water resource management approaches in recent y ears, the concept of 'water for nature' is becoming m ore apparent. Water for nature is a frequently overloo ked human need

4.3 Ecosystem Resilience

▪ Relation of the elements

- The consequences of misusing water resources, as well as the resulting ecosyst em degradation and its effects on ecosystem services, demonstrate the negativ e consequences of non-sustainable water use. Water systems are extremely sen sitive to human activity in the drainage basins that surround them



Lakes/rivers act as sinks for water inputs as well as the materials and pollutants c arried in it, making them s ensitive barometers of hu man activity in their surro unding watersheds

4.3 Ecosystem Resilience

▪ Major ecosystem management options and goals

- **Maintaining environmental flows**
  - Ensuring minimum water flows, regulating the timing; maintain rivers and other aquatic ecosystem and their resources and diversity of existing potential services
- **Pollution control**
  - Reducing the load of contaminants emitted by point and nonpoint sources, as well as water reuse and recycling, and pollution reduction at the source
- **Ecohydrology and phytoremediation***
  - Using natural hydrology, or the ability of specific aquatic organisms, to reduce or reverse the negative effects of pollutants on aquatic ecosystems
- **Habitat rehabilitation**
  - Rebuilding and similar activities to rehabilitate aquatic ecosystems and related natural habitats

**Phytoremediation technologies use living plants to clean up soil, air, and water contaminated with hazardous contaminants*

4.3 Ecosystem Resilience

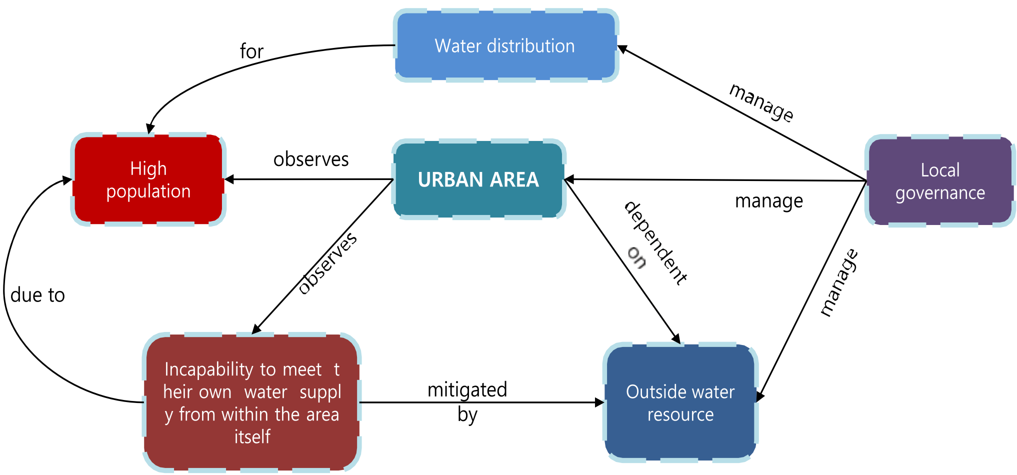
▪ Major ecosystem management options and goals

- **Conjunctive use of surface and groundwater**
  - Using a combination of surface and groundwater to meet human water demands in a way that maximizes the long-term viability of both water sources
- **Watershed management**
  - Using structural or nonstructural approaches within the context of IWRM or another management framework specifically designed to prevent or reduce degradation of aquatic ecosystems, or to rehabilitate already-degraded aquatic ecosystems
- **Water demand management**
  - Implementing policies to control consumer demand for water resources, specifically managing the distribution of, or access to, water on the basis of needs
- **Payment for ecosystem goods and services**
  - Employing economic instruments (incentives, penalties, user fees, licenses, etc) to compensate for excessive use or degradation of ecosystem services

4.4 Urban Water Resilience

▪ Definition

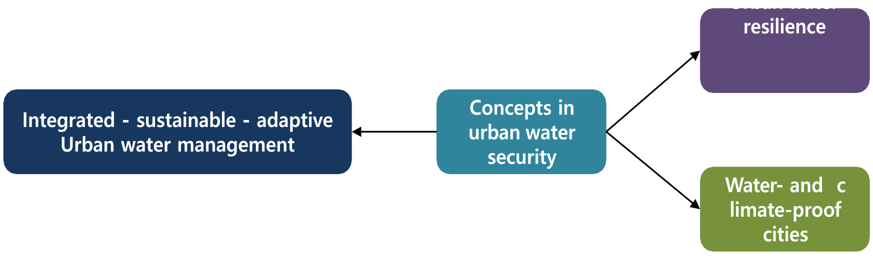
- The capacity of the urban water system, including its human, social, political, econo mic, physical, and natural assets, to anticipate and absorb, adapt and respond to, an d learn from shocks and stresses in order to protect public health and wellbeing, th e natural environment, and minimize economic disruption, is defined as urban wat er resilience



4.4 Urban Water Resilience

▪ Concepts

- Urban water is a common source of concern for water security in cities. Risks are con centrated in urban areas due to the high density of **population** and **economic activit y**. This necessitates relatively high security standards and, at times, different risk mana gement approaches
- In a typical governance setting, urban water security differs from water security at other l evels. Different departments are in charge of various water-related tasks or tasks that are **indirectly related** (such as spatial planning), with **municipal policies** but national regulat ions and other policy processes and **stakeholders** that are typical of the urban level



4.4 Urban Water Resilience

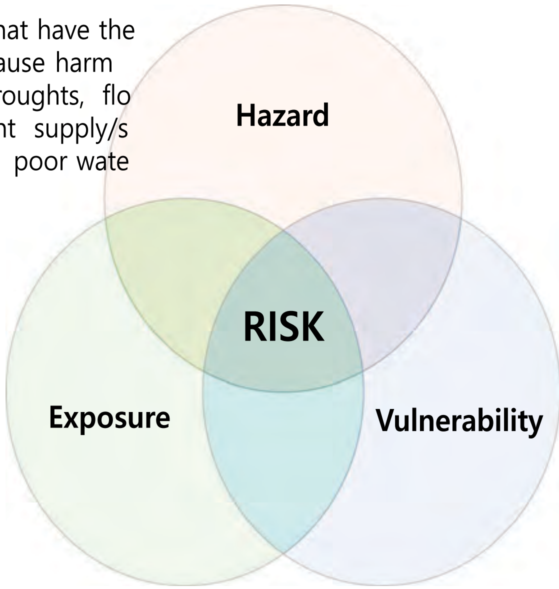
▪ Risk

- The term **risk** refers to the combination of **hazard**, **exposure**, and **vulnerability**. Because of the **concentration** of people and assets in urban areas, exposure is always relatively high. Cities with relatively low water hazard exposure may still be vulnerable due to inadequate water infrastructure
- Two cities may have a similar overall 'risk' or 'security' but differ in terms of the **underlying factors**. Low hazard-exposed city may come with high vulnerability due to bad infrastructure and bad governance, while high hazard-exposed city may be well-prepared for the risk
- In one case, natural conditions may be quite good, while risks increase as a result of **poor management**, such as water pollution and inadequate water supply. **Natural conditions**, on the other hand, can present a variety of chall enges, such as water shortages and flooding, while proper management red uces the risk

4.4 Urban Water Resilience

▪ Risk

Hazard:
Phenomena that have the potential to cause harm or damage: droughts, floods, insufficient supply/sanitation, and poor water quality



Exposure: People, livelihoods, infrastructure, and social-economic assets that may be harmed as a result of hazardous events

Vulnerability:
The tendency to suffer damage. Capacity to anticipate, deal with, and resist, and recover from adversity

[Combination of hazard, exposure, and vulnerability]

4.4 Urban Water Resilience

▪ Example of different levels of hazard-exposure and vulnerability

- **Low hazard-exposure and low vulnerability**
  Toronto has a moderate continental climate with **consistent monthly rainfall** throughout the year. Lake Ontario provides a significant freshwater buffer, but it also poses a storm surge hazard

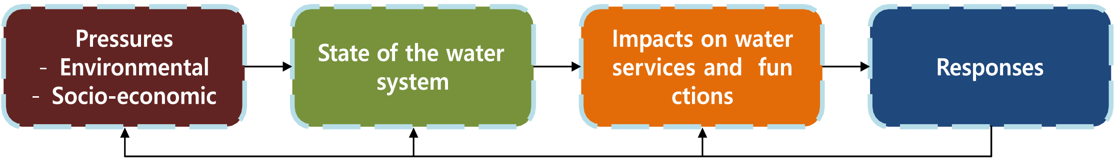
- **High hazard-exposure and low vulnerability**
  Dubai has a **hot desert climate**, **little rainfall**, and **few freshwater resources**. However, the city's vast **wealth** enables the government to meet the enormous freshwater demand through energy-intensive desalination **technologies**

- **Low hazard-exposure and high vulnerability**
  São Paulo, which receives a **large amount of rainfall** each year (1400 mm/year). The water demand in this metropolis is very high, but the surrounding basins theoretically provide enough water to supply the city; however, **poor infrastructure and management** result in regular water shortages, and water pollution in the city is significant

- **High hazard-exposure and high vulnerability**
  Jakarta is threatened by a significant **flood risk** due to its location in a low-lying, subsiding delta and its vulnerability to heavy monsoon rains. The city is vast, **impoverished**, and teeming with slums. Despite the area's abundance of water, groundwater resources are severely **overexploited**, and the quality of freshwater resources has deteriorated significantly. Every year, riverine and storm water flooding occurs

4.4 Urban Water Resilience

▪ Systemizing urban water security



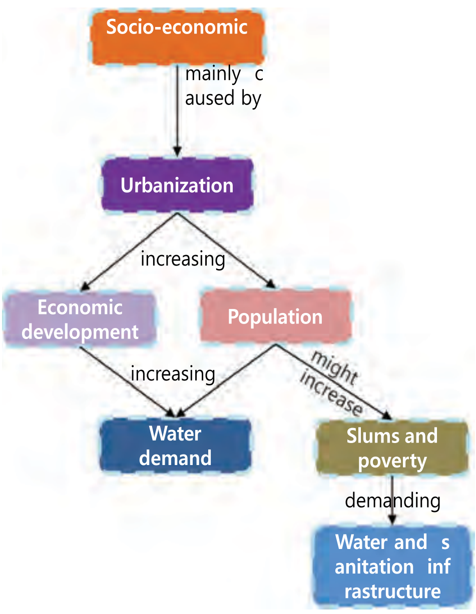
[Pressure-state-impact-response schematization] Source: Hoekstra, et al., 2018

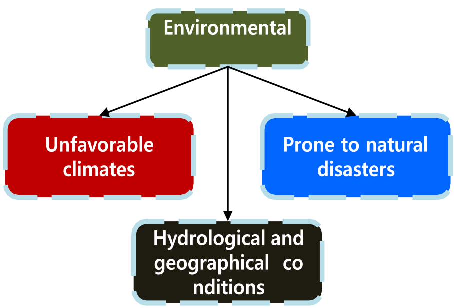
- Adopting a **system-dynamic perspective** to understand the complexity and time dimension of urban water secu rity can be beneficial, acknowledging many variables, causal mechanisms, and feedback processes play a role
- There are change-inducing mechanisms that put pressure on the system. Major pressures that change the water system in urban areas include both environmental and socio-economic pressures
- Water stocks and flows within the area, exchanges with surrounding areas, the occurrence of extreme events such as droughts and flooding, water quality, and available infrastructure can all be used to describe the state of the w ater system
- The effects of the water system's state on its functions or services can be expressed in terms of actual water supplied and the security of that supply, actual flood protection levels provided, and so on
- Institutional reform, new plans, plan implementation, and operation and maintenance are examples of responses. Effective responses will alleviate pressures (e.g., moderate continued urbanization, reduce water demand through water pricing or other measures), improve the state of the system (e.g., through improved infrastructure), or miti gate impacts (e.g., through spatial zoning and disaster planning)

4.4 Urban Water Resilience

▪ Pressures

- Cities face a slew of pressures that jeopardize water security. The pressures can be classified as socio-economic or environmental



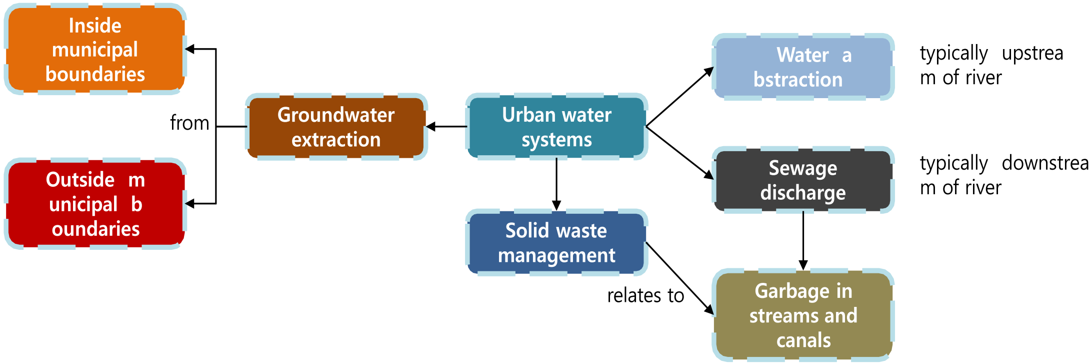


Note:
Further urbanization and climate change are li kely to increase water stress in cities, both in te rms of flooding and scarcity. McDonald et al. (2011) calculate how much water is physically a vailable near cities. They show that 150 million people currently live in cities with chronic water scarcity

4.4 Urban Water Resilience

▪ State of the water system

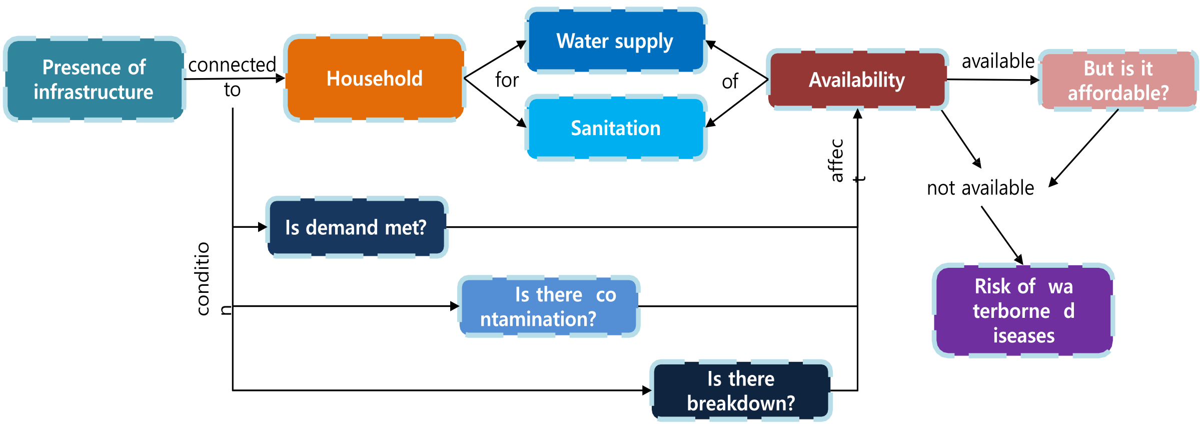
- The state of an urban water system refers to the **quantity** and **quality** of water, as well as the **infrastructure** used to manage it. Water stocks, flows, and exchanges with areas outside the municipal boundaries can all be used to describe the quantity of water in a city



- When assessing the state of urban water infrastructure, it is necessary to consider water supply infrastructure, sanitation infrastructure, and flood protection infrastructure. Because the investment horizon for this type of i nfrastructure is long, it should be compared to projections of climate change
- Water supply system coverage and drinking water quality standards are examples of relevant indicators

4.4 Urban Water Resilience

▪ Impacts on water services and functions



- The physical state of the water system is mostly described, but the impacts are centered on how well it provides water supply and sanitation, flood protection, recreational, environmental, and other services
- Rural water uses are typically sacrificed for urban uses, but any negative impacts on rural users must be compensated for. The effects of urban water extend beyond municipal boundaries. The water footprint of urban consumers is also dependent on external water resources for the production of food consumed wi thin the city

4.4 Urban Water Resilience

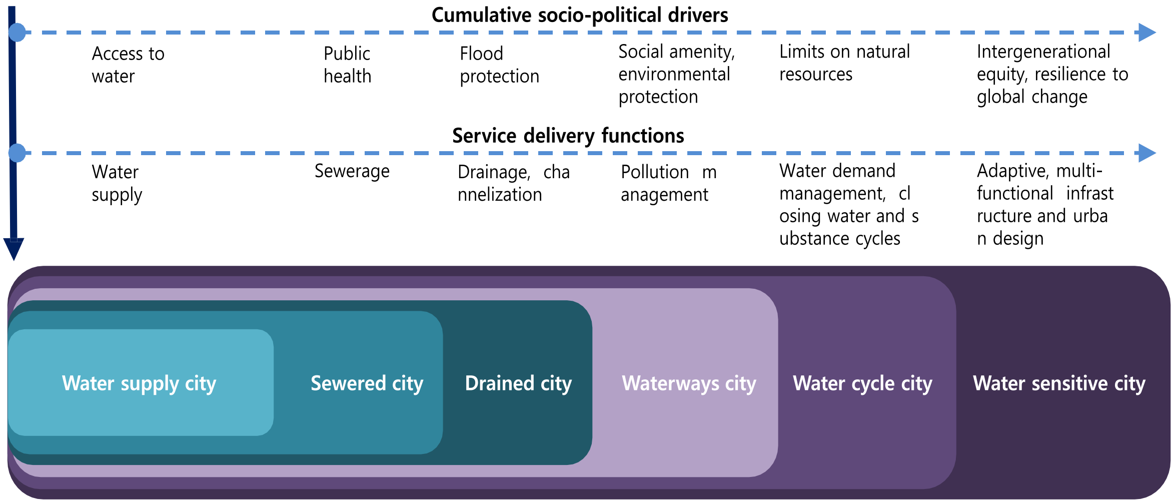
▪ Response

- A faulty water system is caused by a perceived mismatch between an actual a nd desired situation, or by an unfavorable future situation. Response aims to **r educe pressures**, **improve water system functionality**, and **reduce negative impacts** on services and functions in urban water system
- Many responses, such as policymaking for future climate change, necessitate dealing with uncertainty and ambiguity

4.4 Urban Water Resilience

▪ Transitions over time

- Brown et al. (2009) propose a framework for understanding how urban water man agement in cities transitions in general when moving toward sustainable urban wat er conditions. In the 'urban water management transitions framework,' they distin guish six stages



5. Water Governance

1. Importance of Water Governance
2. Green City
3. Green Growth

5.1 Importance of Water Governance

▪ A controlling body is important

- Water security is the result of **good water governance**, which can lead to improved access to water, sanitation, and the preservation of quantity and quality of water resources
- The goals are:
  - Reduce absolute poverty
  - Improve population health
  - Protect natural resources
  - Prevent water-related disasters
- It is necessary to implement policies and strategies that aid in the better management and use of water resources through the participation and interdependence of various actors and sectors that use water resources, including the environment itself

5.1 Importance of Water Governance

▪ A controlling body is important

- Thinking about water security in terms of governance can be a useful tool for developing policies and assisting decision-making on issues concerning private/public and individual /collective water use

- According to Kooiman (2003), governance is the structure that emerges in a socio-political system as a result of all the actors' interaction efforts, which conforms the rules of the game in a specific system

- Water security should be considered as a multidimensional element to be used as a **reference in decision making** and as a guide in the development of public management and governance policies, but it should be based on **technical and scientific knowledge**

- Water governance proposes methods for **strengthening communities** so that they can participate in local decision-making processes. Water governance emerges as an opportunity to create new models, or models of institutional articulation, for the management of the basin's territory in light of water-related priorities

5.2 Green City

▪ Green Cities Initiative

- The Initiative focuses on improving the urban environment, strengthening urban-rural linkages and the resilience of urban systems, services and populations to external shocks. Ensuring access to a healthy environment and healthy diets from sustainable agri-food systems, increasing availability of green spaces through urban and peri-urban forestry, it will also contribute to climate change mitigation and adaptation and sustainable resource management. A "Green Cities Network" will allow cities of all sizes - from megapolis to medium to small - to share experiences, best practices, successes and lessons learned, as well as build city-to-city cooperation opportunities

Focus areas:

Enabling Environment to support risk and vulnerability assessments, evidence-based and inclusive policies, planning and governance frameworks to foster investment and promote innovation for resilient green spaces and sustainable urban food systems.

Actions for metropolitan cities to enhance their contribution to sustainable growth and wealth at national level with a focus on innovation and green technologies for agri-food systems and green infrastructure, improved food distribution systems and food environments, and better food and water waste management through improved urban planning and rural urban linkages.

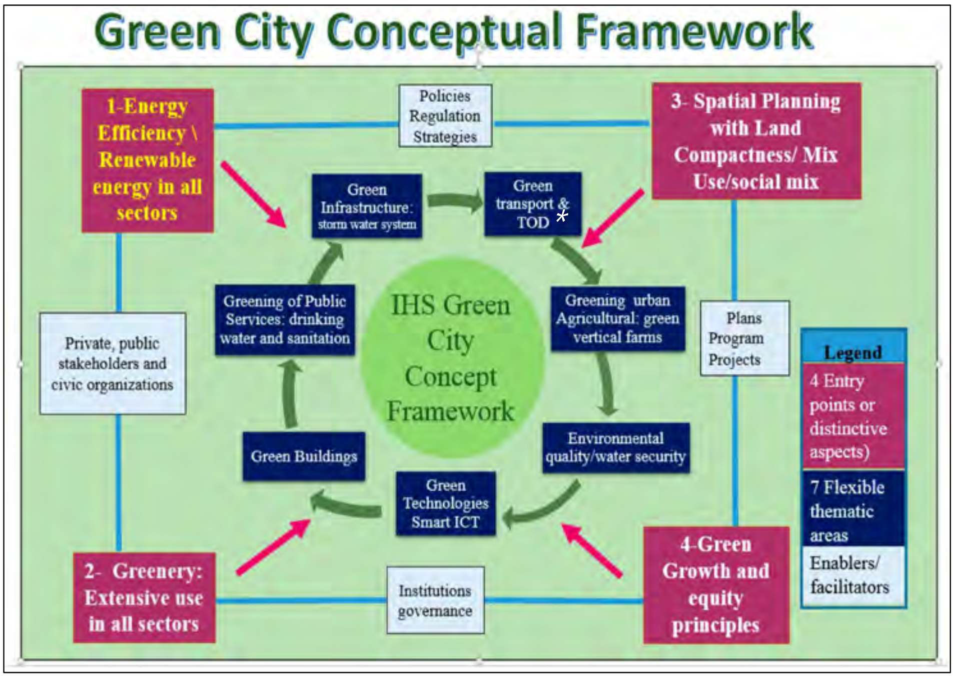
Actions for intermediary cities to enhance their role in connecting rural and urban areas to basic facilities and services with a focus on balancing green and healthy environments with productivity, producing local food, connecting producers and local markets, innovative agro-processing food hubs and green jobs, farmers markets and circular economy.

Actions for small cities to enhance nutrition, healthier diets and closer interactions to where food is produced with a focus on governance for functional territories, innovation and green technologies for green infrastructures and food systems, improved agro-processing hubs and urban-rural linkages, promoting off-farm job opportunities, reducing food loss and better food and water waste management.

Source: http://www.fao.org/green-cities-initiative/en/

5.2 Green City

▪ Conceptual framework



*TOD =transit oriented development

Source: Brilhante and Klaas (2018)

5.2 Green City

▪ Green City Accord

- The Green City Accord is a movement of European mayors committed to making cities cleaner and healthier. It aims to improve the quality of life for all Europeans and accelerate the implementation of relevant EU environmental laws. By signing the Accord, cities commit to addressing five areas of environmental management: air, water, nature and biodiversity, circular economy and waste, and noise (Source: https://ec.europa.eu/environment/green-city-accord_en)

Air
Significant improvement in air quality by moving closer to meeting WHO air quality guidelines and putting an end to EU air quality exceedances as soon as possible

Nature and biodiversity
Significant progress has been made in conserving and enhancing urban biodiversity, including an increase in the extent and quality of green space in cities, as well as halting and restoring urban ecosystem loss.

Circular economy and waste
Advance toward the circular economy by ensuring a significant improvement in household municipal waste management, a significant reduction in waste generation and landfilling, and a significant increase in re-use, repair, and recycling.

Water
Making significant progress in improving water body quality and water use efficiency

Noise
Reducing noise pollution in cities significantly and moving closer to WHO recommended levels

5.3 Green Growth

▪ Concept

- "Green Growth" is a concept that arose in response to the high environmental costs of rapid economic development and urbanization over the last several decades
- Green Growth, as defined by the United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP), is "environmentally sustainable economic progress to foster low-carbon, socially inclusive development"
- Green Growth, as a national policy emerged from the South Korea in 2008 as "a new national development paradigm for job creation and new growth through the use of green and clean technology"
- Water is an important **catalyst for Green Growth**. Water infrastructure and security pro mote economic growth while also promoting socially inclusive development. When count ries work together to protect the environment through water agreements, improve efficie ncy in water use, and conserve water, international cooperation around water issues plays a significant role in Green Growth.

5.3 Green Growth

▪ Key messages from case study

- Water is the medium by which Green Growth can occur
- Strong political leadership and commitment from the top, as well as from local governments and water basin levels, are required
- For the Water and Green Growth (WGG) strategies and policies to be implemented, a holistic approach that encompasses the three pillars of sustainable development (eco nomic, social, and environmental) is required
- Responsibilities among actors should be clearly defined for better coordination
- WGG projects benefit from a clear legal framework that provides support and continuity
- Water service financing that is secure and sustainable yields high economic, environmental, and social returns

5.3 Green Growth

- **Key messages from case study**

- Environmental awareness can be raised through educational programs and community capacity building, which can lead to participation in and promotion of WGG
- Water and data information systems that have been improved can provide critical decision support for effective water management
- Participation of the community in design and decision-making is valuable and required for reflecting the community's interests, building support, and conserving and protecting water resources
- Collaboration at all levels is essential for success. This means that government policies must be flexible enough to encourage innovation from a wide range of sectors, including public institutions, nongovernmental organizations (NGOs), civil society, academic institutions, and the private sector, at multiple levels
- There is no such thing as a one-size-fits-all strategy. WGG strategies must be context-specific at the start of the project

6. Closing Remarks

1. Emerging Solution to Urban Water Challenge
2. Challenges in Water Security Research
3. Conclusions

6.1 Emerging Solution to Urban Water Challenge

- Local water storage and stormwater drainage
  - ✓ Low impact development, water sensitive urban design, and sustainable urban drainage systems all attem pt to address the negative effects of urbanization on stormwater runoff while also increasing the use of ur ban catchment water as a resource in some cases. Green roofs, rainwater harvesting, and local water stora ge can help to reduce runoff and increase local water supply
- Increasing water productivity and non-conventional water sources
  - ✓ Water recycling and reuse are intended to boost water productivity. Several cities in water-stressed areas treat wastewater for irrigation and other purposes.
- Waste prevention and separation of waste and source
  - ✓ Reducing the use of potentially harmful chemicals and preventing them from ending up in wastewater can significantly reduce water pollution and the difficulty of wastewater treatment. Water recycling can be aide d by wastewater source separation
- Distributed or non-site treatments
  - ✓ As technology advances, the need for large centralized infrastructure may diminish in favor of distributed, on-site systems that can be implemented quickly and are especially suitable for cities with poor infrastru cture because they do not necessitate large-scale investments
- Institutional and organizational reforms
  - ✓ Water policy and management are complex, and new perspectives, concepts, and frameworks, such as a daptive and transformative change, social learning, self-organizing systems, informal networks, and poli-centricity, have emerged to understand this

6.1 Emerging Solution to Urban Water Challenge

▪ Urban water security indices

- Urban water security is a broad concept that can be approached from a variety of angles. Although the concept is frequently used qualitatively, there is value and interest in quanti fying urban water security

Urban water indices	
City Blueprint	van Leeuwen et al (2012), Koop and van Leeuwen (2015)
Sustainable City Water Index	Arcadis (2016)
Water Provision Resilience Index	Milman and Short (2008)
Sustainability Index for Integrated Urban Water Management	Carden and Armitage (2013)
Urban Water Security Indices and Indicators	Jensen and Wu (2018)

Urban sustainability indices	
Green City Index	Siemens (2012)
City Resilience Index	Arup (2014)
SDEWES Index	SDEWES Centre (2017)
National Water Security Index, including the aspect of urban water security	ADB (2013)

6.2 Challenges in Water Security Research

▪ Common obstacles in research field

- Academics and practitioners use a variety of, at times contradictory, definitions of water security
- Analyzing the socio-environmental implications of current changes in the global water cycle in support of science-informed policy necessitates interdisciplinary, collaborative research that transcends "broad" versus "narrow" and "academic" versus "applied" dis tinctions, in accordance with the integrative definition of water security
- Researchers from various disciplines tend to conduct water security research at different scales (e.g., whereas hydrologists focus on the watershed, political scientists focus on the nation-state), mirroring and possibly reinforcing the "scalar mismatch" that characterizes ground water governance

6.3 Conclusions

▪ Implementation of water security and resilience concept ensures sustainable development

- Water security is a global goal that needs to be implemented
  - Developing countries needs to enhance their water security in order to reach a sustainable development level
  - Developed countries needs to maintain their water security to protect them from system shocks
- There are many factors intertwined together that defines water security
  - Nature
  - People
  - Infrastructure
  - Governance
- Water security do not only concerned with present condition, but it is an ongoing goal that needs to be upkeep to maintain sustainability and resilience
- Water security and resilience is a concept that goes hand in hand. In order to improve water security, the system resilience must be considered
- The resilience of water systems infrastructure plays a big part in ensuring water security


Thank you very much

Water Related Resilience and Applications to Natural Hazards: Earthquakes

Water Security and System Resilience

3. Water Related Resilience and Applications to Natural Hazards: Earthquakes

UNESCO
United Nations Educational, Scientific and Cultural Organization
i-WSSM
International Centre for Water Security and Sustainable Management

Aims & Objectives

- The aims of the course are to:

  (1) Explain the basic understanding of “water related seismic resilience”
  (2) Introduce modeling frameworks of earthquake resilience for water supply infrastructures
  (3) Introduce applications for water related resilience assessment to earthquakes
  (4) Explain seismic resilient enhancement strategies for water supply systems

- The objectives are that trainees will understand:

  (1) Basic concept of “water related seismic resilience”
  (2) Modeling frameworks of earthquake resilience for water supply infrastructures
  (3) Some case studies to enhance seismic resilience of water infrastructure

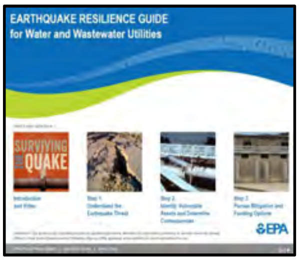
References

The BRIDGE (2019) Vol. 49, No. 2, Summer 2019

Water system service categ ories, post-earthquake inter action, and restoration stra tegies (Davis, 2014)

Seismic hazard assessment model for urban water supply networks (Yoo et al., 2016)

Enhancing resilience through risk-based design and benefit-cost analysis (Charles and Po rter, 2019)



Earthquake resilience guide for Water and Wastewater Utilities (US-EPA, 2018)

Recovery-based seismic resilience enhancement s trategies (Liu et al., 2020)

Contents

1. Water Related Seismic Resilience

1. Impact of Earthquake on Water Supply Systems
2. Definition of Resilience
3. General Types of Disruption
4. Types of Disruption Profile under Seismic Events
5. Enhancing Seismic Resilience Strategies

1.1 Impact of Earthquake on Water Supply Systems

- Impact of Natural Hazards on Water Supply Systems
- Earthquake, Flood, Drought...

Effect on Water Supply Systems	Earthquake	Volcanic Eruption	Landslide	Hurricane	Flood	Drought
Structural damage to system infrastructure	●	○	●	●	●	○
Rupture of mains and pipes	●	○	●	◐	●	○
Obstructions in intake points, intake screens, treatment plants and transmission pipes	○	●	◐	◐	●	○
Pathogenic contamination and chemical pollution of water supply	◐	●	○	●	●	○
Water shortages	◐	◐	○	○	○	●
Disruption of power, communications and road system	●	○	◐	●	◐	◐
Shortage of personnel	●	◐	◐	◐	◐	○
Lack of equipment, spare parts and materials	●	○	◐	●	●	○

* Symbols: ● Severe effect, ◐ Moderate effect, ○ Minimal effect
* Source: Pan American Health Organization (2002). Emergencies and Disaster in Drinking Water Supply and Sewerage Systems

1.1 Impact of Earthquake on Water Systems

- M 6.7 Northridge earthquake on Jan 17, 1994, in Los Angeles, USA.
- Trunk lines were severely damaged at 74 locations in LADWP water system.
- Distribution system required repairs at 1,013 locations.



< Seismic Hazard - Water Floods from Broken Water Pipes >

1.1 Impact of Earthquake on Water Systems

- M 7.2 Kobe earthquake on Jan. 17, 1995, in Hyogo, Japan.
- Trunk line (D=1.25m) was damaged at 23 locations.
- About 15 millions people move to other places because of water outage.


< Seismic Hazard - Broken Water Pipes >

1.1 Impact of Earthquake on Water Systems

▪ Earthquake-Resistant Rate of Local water Supply Systems in South Korea : 37% (2017)

Earthquake-Resistant Rate of Local water Supply Systems : 37% (2017)

Gyeongju Earthquake (2016.09.12.) Damage Status (Based on 2016.09.23)

Private facility	Building crack	Roof breakage	Fence damage	Water pipe leak/burst	Etc.	SUM
	2,064	2,653	996	71	718	6,502
Public facilities	Road crack	Educational Facilities	Reservoir	Cultural Heritage	Museums, etc.	SUM
	21	304	2	100	4	431

Pohang Earthquake (2017.11.15.) Damage Status (Based on 2017.11.27)

Private facility	Housing		Store		Factory		Etc.		SUM
	28,811		1,995		162		32		31,000
Public facilities	School	Governmental	Roads	Water Supply Systems	Harbor	Cultural Heritage	Defense Facilities	Etc.	SUM
	235	135	22	45	29	31	88	39	644

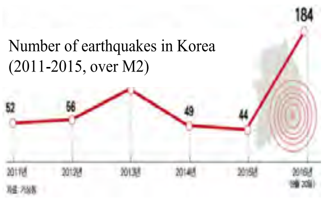
1.1 Impact of Earthquake on Water Systems

Risk

The age of water supply facilities are increasing

Underground buried with other facilities

There are high possibility of natural disasters under climate change



Crisis

Leakage/breakage of pipe, suspension of the pump facility, large scale water outage, sink hole, occurrence of earthquake, etc.

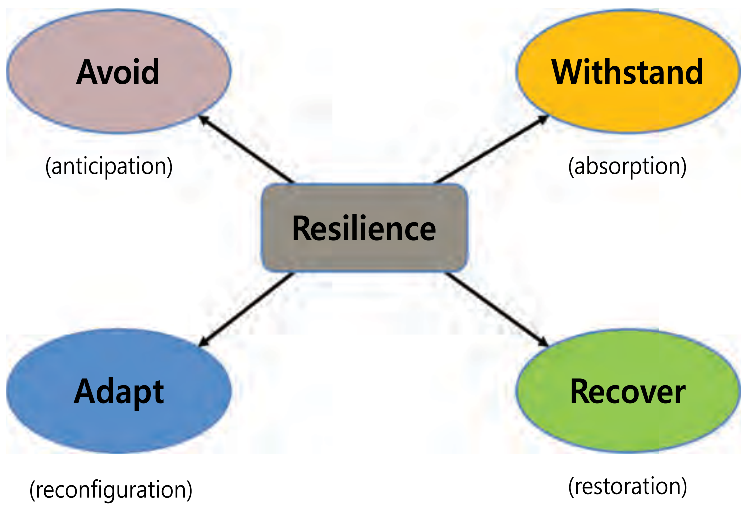
Direct /In Direct Damage

It cause huge amount of economic / social losses

Risk is the possibility of losing something of value.
A crisis is any event that is going (or is expected) to lead to an unstable and dangerous situation affecting an individual, group, community, or whole society.
* Source: EPA Office of Water (2018) EARTHQUAKE RESILIENCE GUIDE for Water and Wastewater Utilities, etc.

1.2 Definition of Resilience

- **Conceptually, resilience is the many-sided capabilities of a complex system that covers avoiding, absorbing, adapting to, and recovering from disrupti ons**

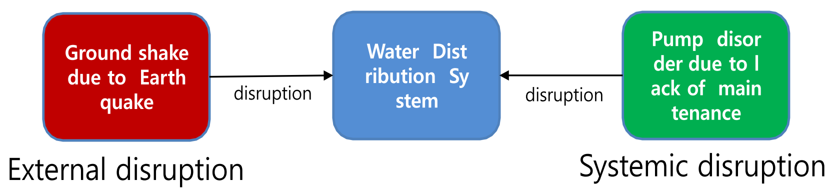


* Source from "Ch 1. Overview of Resilience"

1.3 General Types of Disruption

- **Disruption can be classified to external and systemic disruptions**

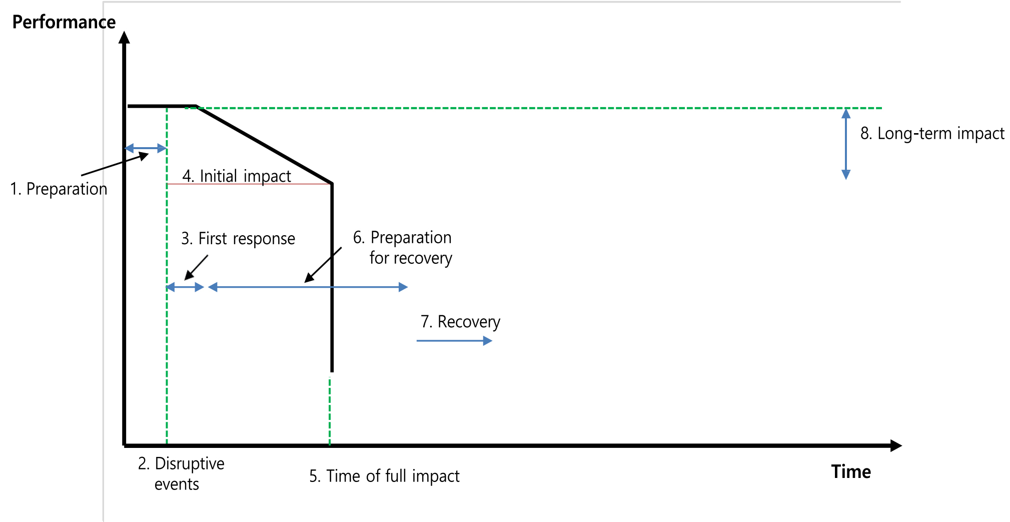
- Factors from outside of the system cause external disruptions
  - Examples include natural disasters
  - They have a high uncertainty / cannot be accurately predicted
  - Designing resilience against this kind of disruption needs a safety margin to account for the uncertainty
- Systemic disruptions are caused when a component in the system failed
  - It interrupts the function, capability, or capacity of the system
  - This type of failure typically results from inadequate reliability or safety measures and can be addressed by traditional analytical methods



* Source from "Ch 1. Overview of Resilience"

1.4 Types of Disruption Profile under Seismic Events

- When a disaster happens, a typical profile usually occurs and it can be categorized into 8 phases



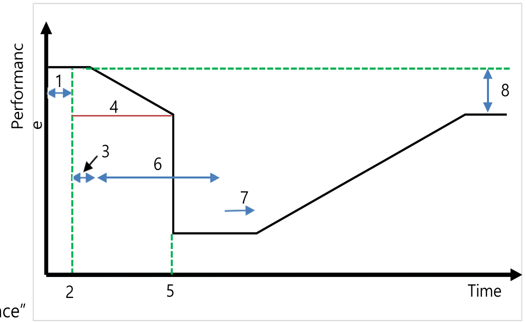
[Time to performance graph]

Source: Sheffi & Rice (2005)

* Source from "Ch 1. Overview of Resilience"

1.4 Types of Disruption Profile under Seismic Events

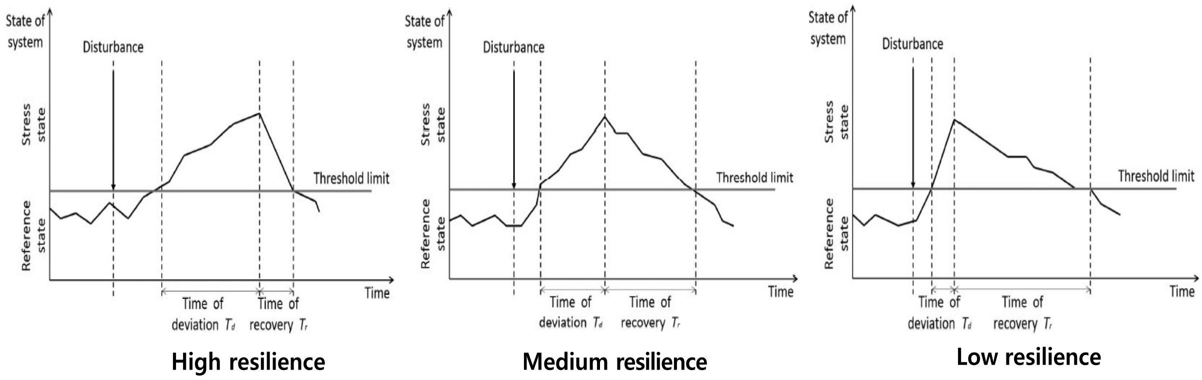
1. **Preparation**
   - In some cases, disruption can be foreseen and be prepared to minimize its effects
2. **Disruptive Event**
   - When a disruptive event happens, such as when a tornado hits or terrorists attack
3. **First Response**
   - First response is aimed at controlling the situation, saving and protecting lives, sh utting down affected systems, and prev enting further damage
4. **Initial Impact**
   - Depending on the scale of the disruption, the effect might not be felt instantaneously
5. **Full Impact**
   - The time when performance hits the lowest
6. **Recovery Preparations**
   - Typically done in parallel with the first re sponse. Preparing the needed resources t o recover from the disruptions
7. **Recovery**
   - Utilizing the available resource to try to return to acceptable performance
8. **Long-term Impact**
   - Sometimes, after a disruption, the performance will not return to the performance as before



* Source from "Ch 1. Overview of Resilience"

1.4 Types of Disruption Profile under Seismic Events

- High resilience of a system against a disturbance.
- Medium resilience of a system against a disturbance.
- Low resilience of a system against a disturbance.

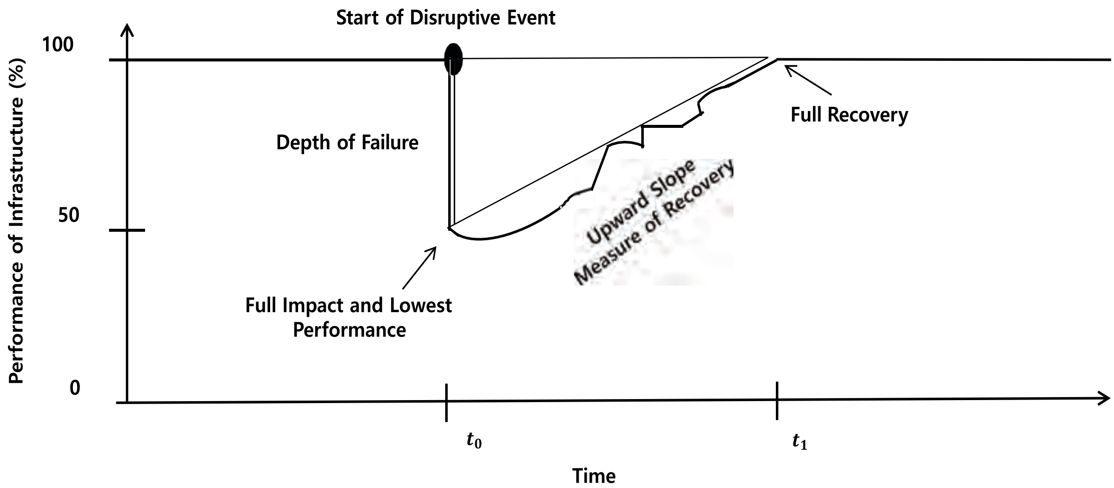


* Source: Attoh-Okine, N. O. (2016). *Resilience engineering: Models and analysis*. Cambridge University Press.

1.4 Types of Disruption Profile under Seismic Events

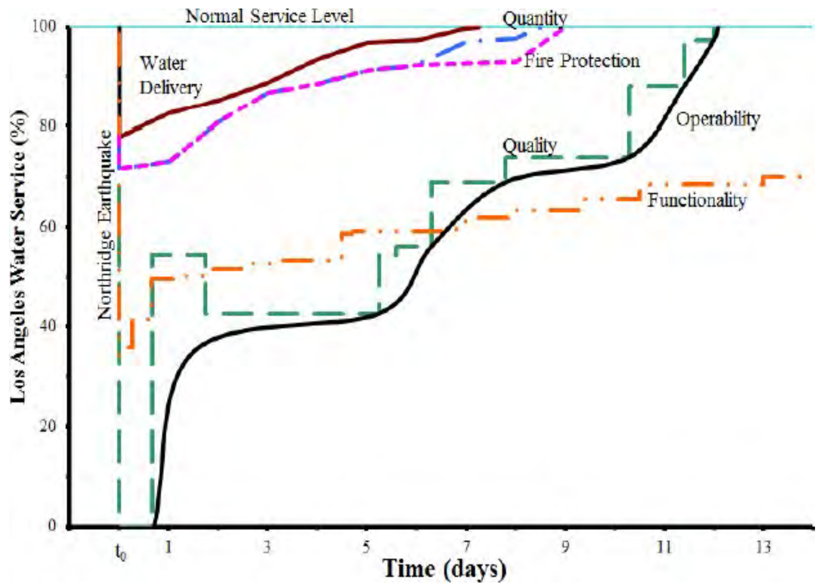
- General conceptualized resilience triangle for earthquake disaster

*1) Start of Disruptive Event, **2) Depth of failure,***
3) Full Impact and Lowest Performance,
4) Upward Slope Measure of Recovery, 5) Full Recovery



1.4 Types of Disruption Profile under Seismic Events

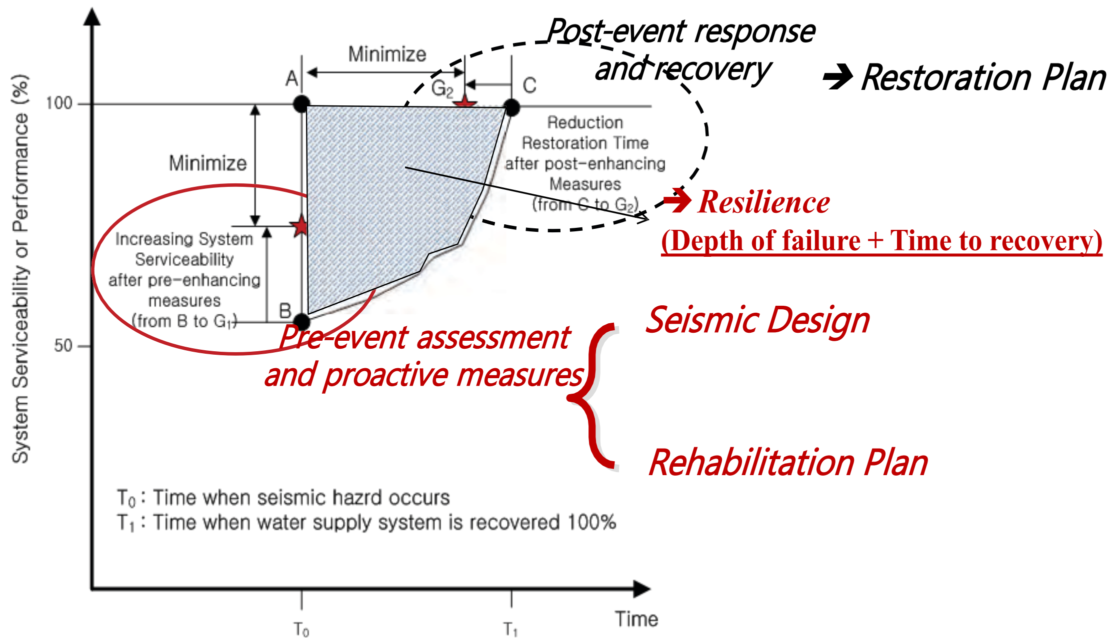
- **Real earthquakes - Los Angeles water system service restorations after the 1994 Northridge earthquake.**



* Source: Davis, C. A. (2014). Water system service categories, post-earthquake interaction, and restoration strategies. *Earthquake Spectra*, *30*(4), 1487-1509.

1.5 Enhancing Seismic Resilience Strategies

- **Pre-event assessment and proactive measures: Seismic design, rehabilitation plan**
- **Post-event response and recovery: Restoration plan**



< System Serviceability Function after Seismic Hazard >

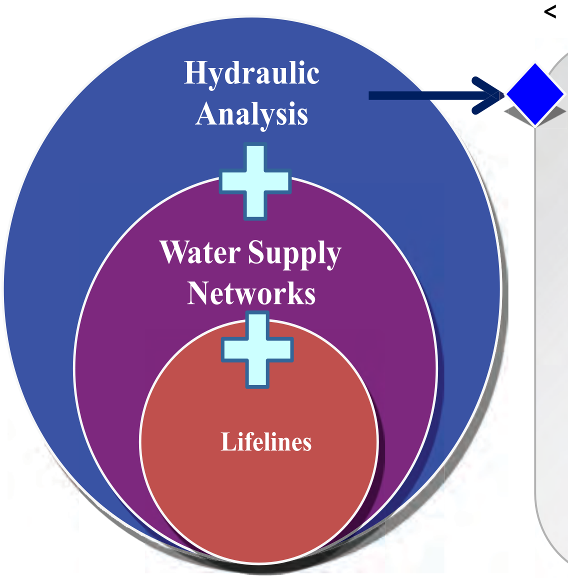
2. Modeling Frameworks of Earthquake Resilience

1. General Risk Assessment Framework
2. Seismic Resilience Assessment Model

2.1 General Risk Assessment Framework

▪ **Previous studies on seismic reliability assessment**

< Seismic Reliability Assessment of WSNs >



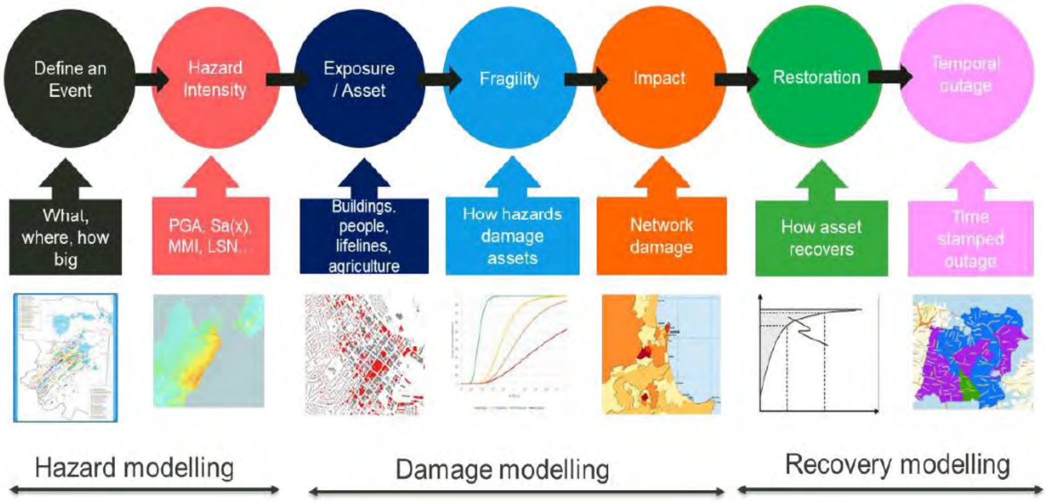
- Eguchi et al. (1983)
- Ballantyne et al. (1990)
- Shinozuka et al. (1981, 1992, 1998)
- Markov et al. (1994)
- Hwang et al. (1998)
- Shi (2006)
- Liu et al. (2010, 2011)

1. Hydraulic analysis is adopted for evaluating seismic reliability of water supply networks. (e.g. EP ANET, Kypipe)
2. Reflect detailed characteristic and hydraulic condition of water sup ply networks.

2.1 General Risk Assessment Framework

- **Stages involved in risk assessment framework**

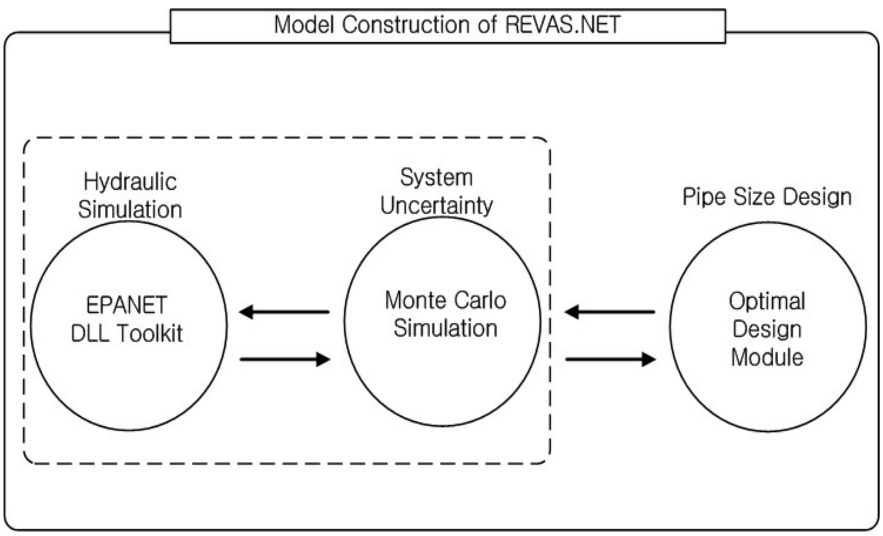
(i) earthquake hazard modelling;
(ii) developing network asset models and damage models; and
(iii) modelling recovery and estimating time-stamped outages for affected



* Source: Uma, S. R., Scheele, F., Abbott, E., & Moratalla, J. (2021). Planning for resilience of water networks under earthquake hazard. *Bulletin of the New Zealand Society for Earthquake Engineering*, *54*(2), 135-152.

2.2 Seismic Resilience Assessment Model

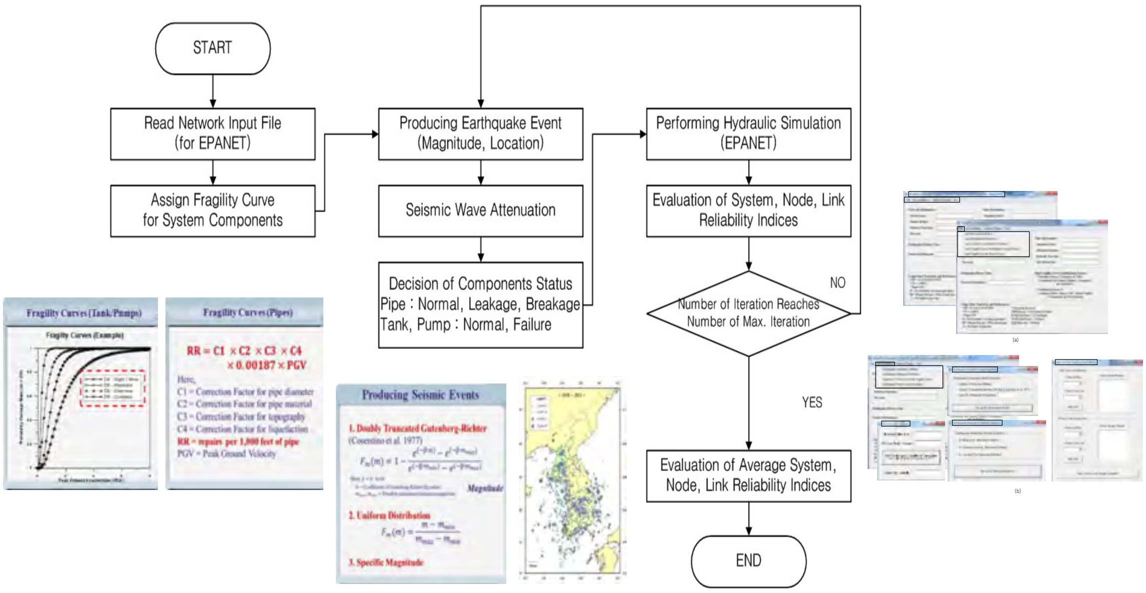
- **Reliability EVAluation model of Seismic hazard for water supply NETworks (REVAS.NET)**
- **Spatial Scope: Trunk/Main Pipes, Tanks, Pumps, and Distribution Pipes**
- **Temporal Scope: Steady State Analysis (Directly after Seismic Hazard)**



* Source: Yoo, D. G. et al. (2016). Seismic hazard assessment model for urban water supply networks. Journal of Water Resources Planning and Management, ASCE, 142(2).

2.2 Seismic Resilience Assessment Model

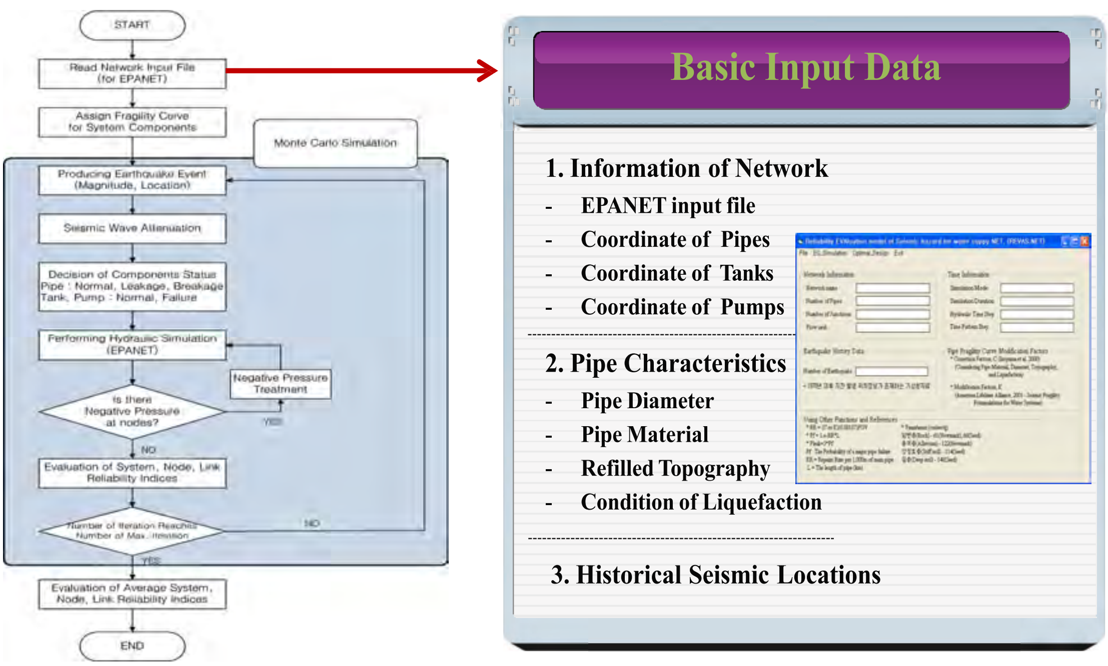
▪ Procedure of REVAS.NET



* Source: Yoo, D. G. et al. (2016). Seismic hazard assessment model for urban water supply networks. Journal of Water Resources Planning and Management, ASCE, 142(2).

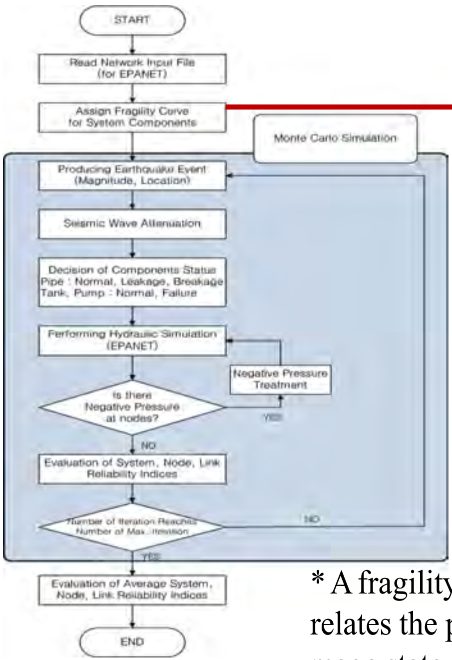
2.2 Seismic Resilience Assessment Model

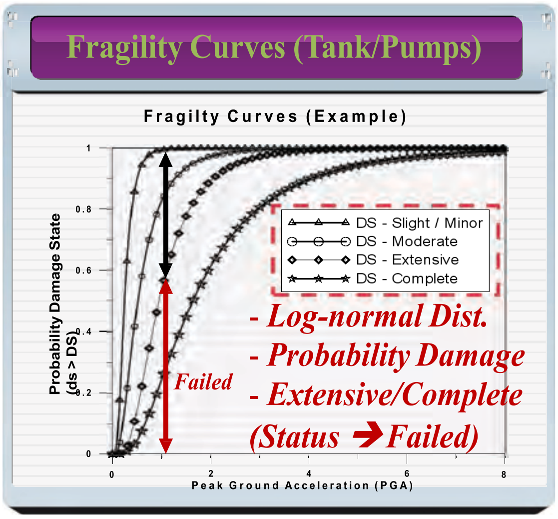
▪ Procedure of REVAS.NET



2.2 Seismic Resilience Assessment Model

▪ Procedure of REVAS.NET





* A fragility curve is defined as a mathematical expression that relates the probability of reaching or exceeding a particular da mage state, given a particular level of seismic hazard.

2.2 Seismic Resilience Assessment Model

▪ Procedure of REVAS.NET

Fragility Curves / Equations (Pipes)

$$RR = C1 \times C2 \times C3 \times C4 \times 0.00187 \times PGV$$

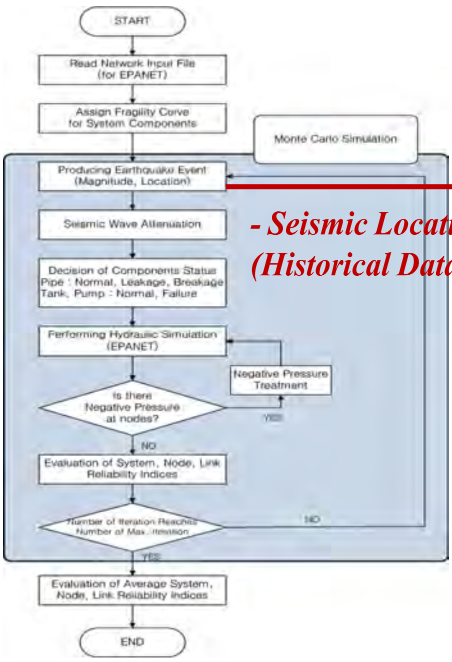
Here,
C1 = Correction Factor for pipe diameter
C2 = Correction Factor for pipe material
C3 = Correction Factor for topography
C4 = Correction Factor for liquefaction
RR = repairs per 1,000 feet of pipe
PGV = Peak Ground Velocity

The fragility of pipes is quantified based on the pipe Repair Rate

Category		Correction Factor
Pipe Diameter (mm) (C1)	$D < 100$	1.6
	$100 \le D < 200$	1.0
	$200 \le D < 500$	0.8
	$500 \le D$	0.5
Pipe Material (C2)	ACP	1.2
	VP, PVC*	1.0
	CIP	1.0
	PE, HI-3P*	0.8
	SP	0.3
	DCIP	0.3
Topography (C3)	Narrow Valley	3.2
	Terrace	1.5
	Disturbed Hill	1.1
	Alluvial	1.0
	Stiff Alluvial	0.4
Liquefaction (C4)	Total	2.4
	Partial	2.0
	None	1.0

2.2 Seismic Resilience Assessment Model

▪ Procedure of REVAS.NET



- Seismic Location (Historical Data)

Producing Seismic Events

1. Doubly Truncated Gutenberg-Richter
(Cosentino et al. 1977)

$$F_m(m) = 1 - \frac{e^{(-\beta \cdot m)} - e^{(-\beta \cdot m_{max})}}{e^{(-\beta \cdot m_{min})} - e^{(-\beta \cdot m_{max})}}$$

Here, $\beta = b \cdot \ln 10$
b = Coefficient of Gutenberg-Richter Equation
m_{max}, m_{min} = Possible maximum/minimum magnitude

Magnitude

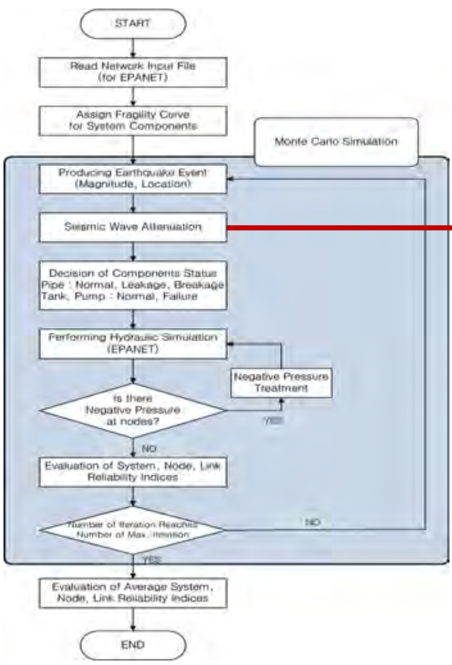
2. Uniform Distribution

$$F_m(m) = \frac{m - m_{min}}{m_{max} - m_{min}}$$

3. Specific Magnitude

2.2 Seismic Resilience Assessment Model

▪ Procedure of REVAS.NET



Seismic Wave Attenuation

1. Kawashima et al. (1984)

$$A = 403.8 \times 10^{0.265M} \times (R+30)^{-1.218} \ (\text{A: cm}/sec^2)$$

2. Baaget al. (1998)

$$\ln A = 0.40 + 1.2M - 0.76 ln\Delta - 0.0094\Delta$$
$(\text{A: cm}/sec^2)$

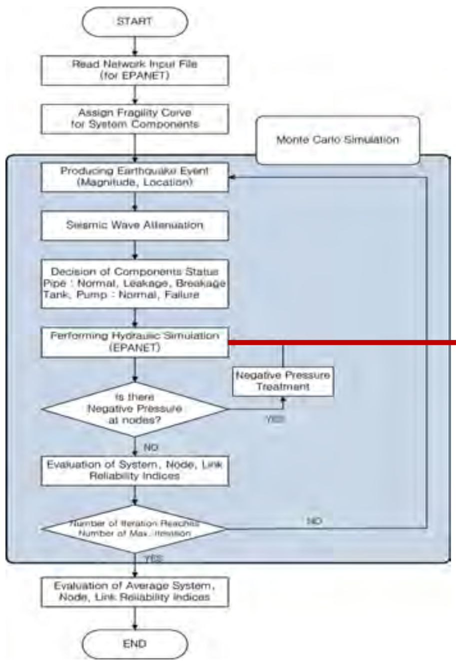
3. Lee and Cho (2002)

$$\log A = -1.83 + 0.386M - logR - 0.0015R$$
$(\text{A: g} = 981\text{cm}/sec^2)$

Here, A = Peak Ground Acceleration, R = Epicentral distance (km)
M = Magnitude of seismic hazard
Δ = Distance from seismic center assuming focal depth is 10km (km)

2.2 Seismic Resilience Assessment Model

▪ Procedure of REVAS.NET



Status of Components

1. Tanks / Pumps (Fail or Normal)

Tank Failed ➔ Connecting Pipes are Closed in simulation

Pump Failed ➔ Status of Pump is Closed in simulation

2. Pipes (Leakage, Breakage, or Normal)

$$C_D = (\frac{2g}{r_w})^{0.5} A$$

$$Q = C_D p^{0.5}$$

Q = Flow rate through the sprinkler

C_D = Discharge coefficient

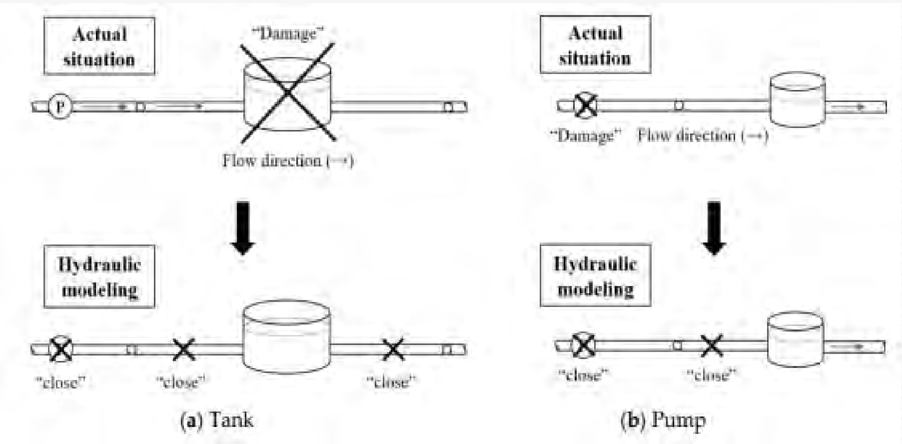
p = Sprinkler operational pressure

A = Total opening area

2.2 Seismic Resilience Assessment Model

▪ Procedure of REVAS.NET

Hydraulic Modeling of Damaged Tanks and Pumps

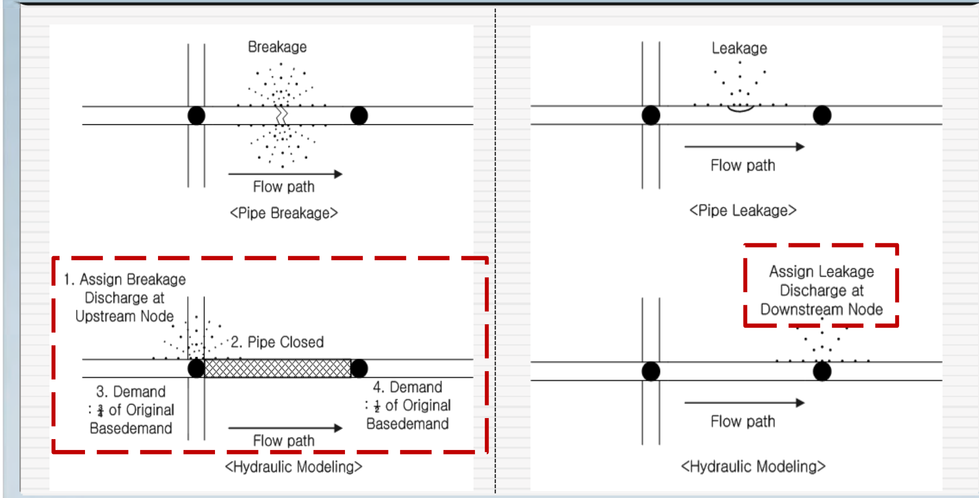


* Source: Choi, J., Yoo, D. G., & Kang, D. (2018). Post-earthquake restoration simulation model for water supply networks. *Sustainability*, *10*(10), 3618.

2.2 Seismic Resilience Assessment Model

▪ Procedure of REVAS.NET

Pipe Breakage / Leakage Modeling

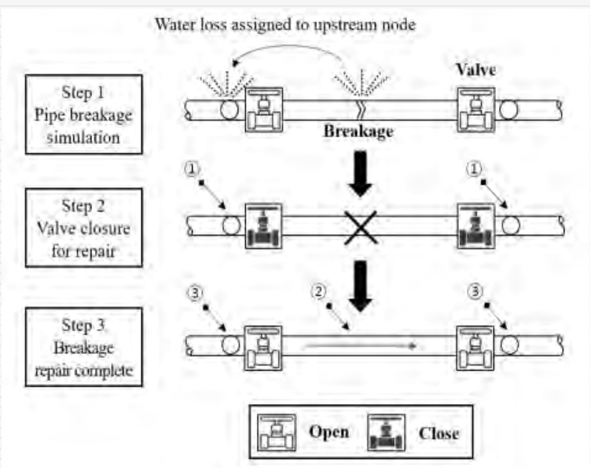


* Source: Choi, J., Yoo, D. G., & Kang, D. (2018). Post-earthquake restoration simulation model for water supply networks. *Sustainability*, *10*(10), 3618.

2.2 Seismic Resilience Assessment Model

▪ Procedure of REVAS.NET

Pipe Breakage Repair Simulation



2.2 Seismic Resilience Assessment Model

▪ Procedure of REVAS.NET

Resilience Indices

$$\text{System Serviceability } (S_S) = \frac{\sum Q_{avl,i}}{\sum Q_{ini,i}}$$

Here, $Q_{avl,i}$ = Available nodal demand at node i

$$Q_{avl,i} = \begin{cases} 0 & \text{when } P_i = 0 \\ Q_{new,i} \times \sqrt{\dfrac{P_i}{P_{min}}} & \text{when } P_i < P_{min} \\ Q_{new,i} & \text{when } P_i \geq P_{min} \end{cases}$$

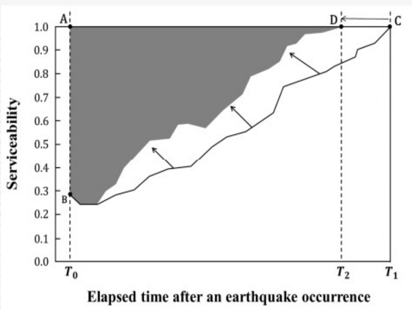
$Q_{new,i}$ = Updated nodal demand after pipe breakage modeling and negative pressure treatment at node i

$Q_{ini,i}$ = Required nodal demand at node i

2.2 Seismic Resilience Assessment Model

▪ Procedure of REVAS.NET

Resilience Indices



- The shaded area above the restoration curve reflects both the depth and duration of the water supply shortage and is quantified in time (hours).
- Smaller curve areas indicate more effective restorations
- **The serviceability index (Ss) and the area of the restoration curve can be utilized as indicators for quantitative comparison of different recovery strategies.**

3. Applications for Water Related Seismic Resilience Assessment

1. Quantification of the Serviceability Index
2. System Serviceability Over Time

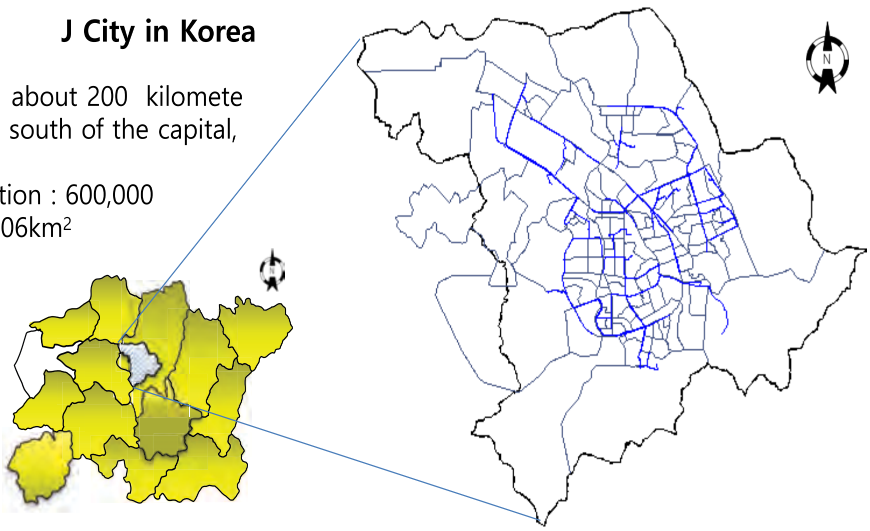
3.1 Quantification of the Serviceability Index

- J City in South Korea

i) Located about 200 kilometers to the south of the capital, Seoul.
ii) Population : 600,000
iii) Area: 206km^2

J City in Korea

-Located about 200 kilometers to the south of the capital, Seoul.
- Population : 600,000
- Area: 206km^2



3.1 Quantification of the Serviceability Index

▪ Adopted Scenarios and Parameters for J City

i)Number of Monte Carlo Simulations: 100,000 - Tanks & Pumps Fragility Curve: Type 1

ii) Minimum Required Pressure: 23m (Lowest pressure under normal condition)

Case	Seismic Hazard	
	Historical Location Data (Number of Data)	Magnitude
Scenario 1	South Korea (373)	Doubly Truncated Gutenberg-Richter (3≤M≤7)
Scenario 2	South Korea (373)	Specific Magnitude (M=7)
Scenario 3	J Do (29)	Specific Magnitude (M=6)
Scenario 4	J Do (29)	Specific Magnitude (M=7)
Scenario 5	J City (3)	Specific Magnitude (M=6)
Scenario 6	J City (3)	Specific Magnitude (M=7)
Scenario 7	J City (1, Closest Data)	Specific Magnitude (M=7)

Normal Case

Seismic Design Criteria, Korea (M 5.7 ~ 6.4)

Worst Case

3.1 Quantification of the Serviceability Index

▪ Ss Results of Scenarios for J city (Main Pipeline)

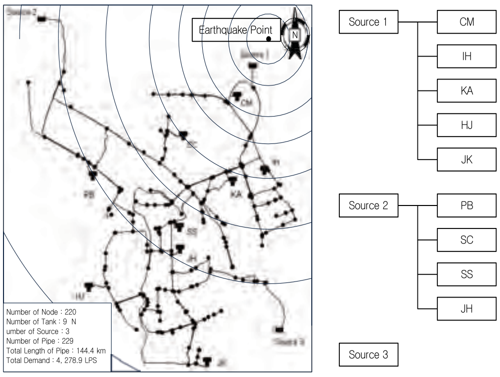
Case	Reliability Indices					
	System Serviceability (S_S)	Nodal Serviceability (N_S)			Normal Status Rate of Link (NSR_L)	Normal Status Rate of Tank (NSR_T)
		Min.	Max.	Stdv.		
Scenario 1	0.995	0.979	1.000	0.004	0.997	1.000
Scenario 2	0.922	0.742	0.993	0.057	0.956	0.994
Scenario 3	0.913	0.693	0.998	0.069	0.951	0.998
Scenario 4	0.783	0.380	0.977	0.139	0.884	0.971
Scenario 5	0.795	0.367	0.982	0.146	0.889	0.979
Scenario 6	0.538	0.148	0.921	0.176	0.755	0.812
Scenario 7	0.305	0.000	0.816	0.212	0.626	0.596

3.1 Quantification of the Serviceability Index

- Ss Results of Scenario 7

Case	Reliability Indices					
	System Serviceability (S_S)	Nodal Serviceability (N_S)			Normal Status Rate of Link (NSR_L)	Normal Status Rate of Tank (NSR_T)
		Min.	Max.	Stdv.		
Scenario 7	0.305	0.000	0.816	0.212	0.626	0.596

Water Supply Main Pipeline of J city in Korea and Earthquake Scenario



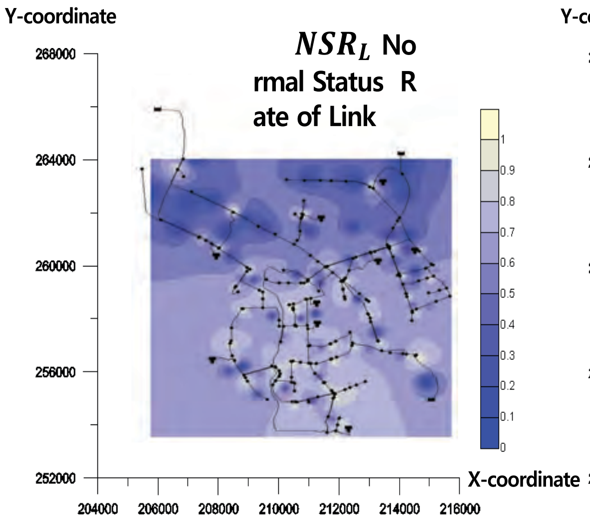
- Occurred 2.3 km northeast of CM distributing reservoir.

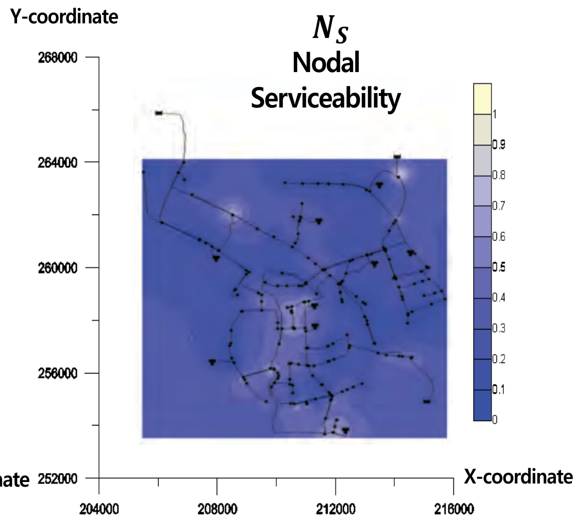
1) 420,000 (70% of entire people) persons cannot be served the water.
2) 37% of pipes are leaked or broken.
3) About half of tanks are failed.

➔The seismic hazard caused total paralysis in the city.

3.1 Quantification of the Serviceability Index

- NSR_L : Relatively long and connecting with reservoir pipes have low reliability.
- N_S: Regardless of the distance from the epicenter, single path nodes from source have low serviceability





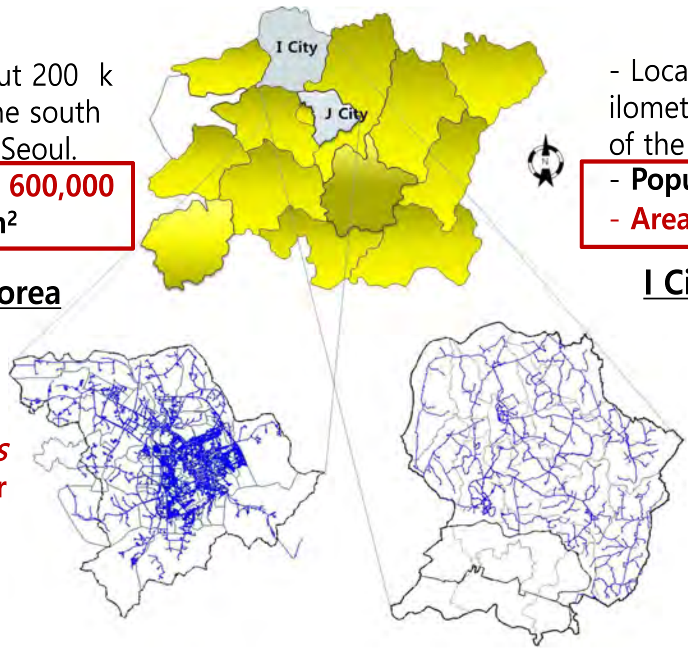
3.1 Quantification of the Serviceability Index

- **Application example results for adjacent cities**

- Located about 200 k ilometers to the south of the capital, Seoul.
- **Population : 600,000**
- **Area: 206km²**

J City in Korea

Population is 2 times **larger** *than* **I City**



- Located about 180 k ilometers to the south of the capital, Seoul.
- **Population : 300,000**
- **Area: 507km²**

I City in Korea

Area is 2.5 times **larger** *than* **J City**

3.1 Quantification of the Serviceability Index

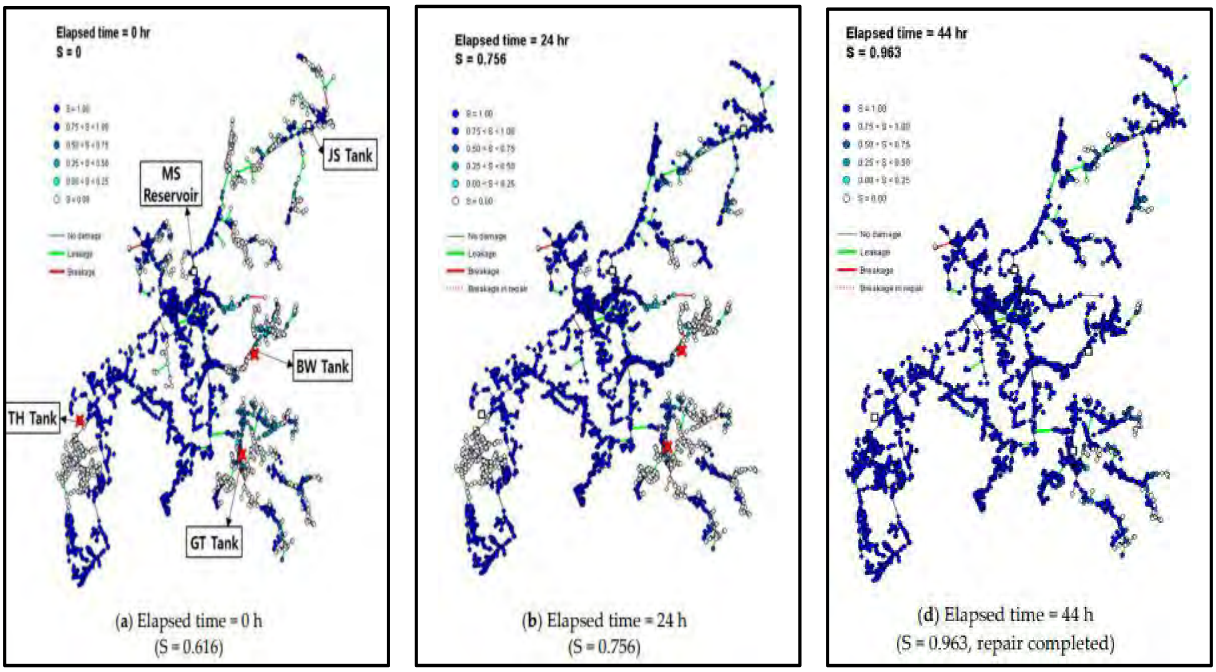
- **Application example results for adjacent cities**

City	Reliability Indices				
	System Serviceability (S_S)	Nodal Serviceability (AVG.) (N_S)	Normal Status Rate of Link (NSR_L)	Normal Status Rate of Tank (NSR_T)	Normal Status Rate of Pump (NSR_P)
I City	0.370	0.399	0.897	0.988	0.999
J City	0.469	0.555	0.959	0.970	0.933

1. *Different Service Areas and Number of Tanks*
- **I city: 304 km², J city: 206.3 km²**
- **I city: 4 tanks , J city: 11 tanks**
2. *Different Service Areas per Tank*
- **J city: 18.75 km²/tank, I city: 76.04 km²/tank**
3. *Different Fragility of Pipes*
- **Distribution rate of medium size pipes (I city > J city)**

3.2 System serviceability over time

▪ Spatiotemporal distribution of system serviceability over time



(a) Elapsed time = 0 h (S = 0.616)

(b) Elapsed time = 24 h (S = 0.756)

(d) Elapsed time = 44 h (S = 0.963, repair completed)

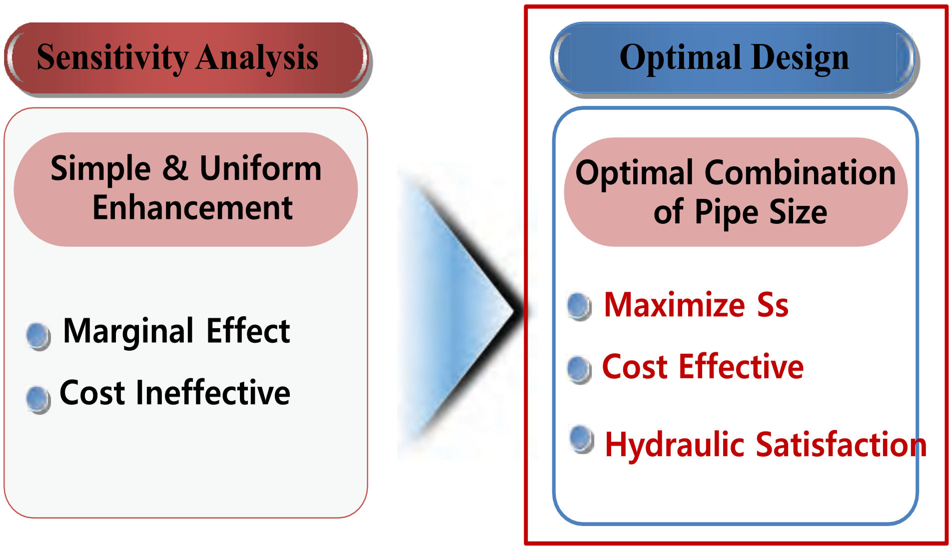
* Source: Choi, J., Yoo, D. G., & Kang, D. (2018). Post-earthquake restoration simulation model for water supply networks. *Sustainability*, *10*(10), 3618.

4.Strategies for Enhancing Seismic Resilience of Water Supply System

1. Optimal Seismic Design
2. Prioritized Rehabilitation Model
3. Strategic Restoration Model

4.1 Optimal Seismic Design

- Simple durability enhancement of components has a marginal effect.
- Optimal pipe size design for enhancing seismic resilience.



4.1 Optimal Seismic Design

- Simple durability enhancement of components has a marginal effect.
- Optimal pipe size design for enhancing seismic resilience.

Objective Function

$$\textbf{Maximize}\ \text{System Serviceability}\ (S_S) = \frac{\sum Q_{avl,i}}{\sum Qini,i}$$

Subject to,

$$P_{i,n} \geq P_{min}$$

$$C \leq C_{limit}$$

Here,

$Q_{avl,i}$ = Available nodal demand at node i

$$Q_{avl,i} = \begin{cases} 0 & when\ P_i = 0 \\ Q_{new,i} \times \sqrt{\frac{P_i}{P_{min}}} & when\ P_i < P_{min} \\ Q_{new,i} & when\ P_i \geq P_{min} \end{cases}$$

$Q_{new,i}$ = Updated nodal demand after pipe breakage modeling and negative pressure treatment at node i

P_i = Nodal pressure at node i, P_{min} = Allowable minimum nodal pressure

$Q_{in\,i,i}$ = Required nodal demand at node i

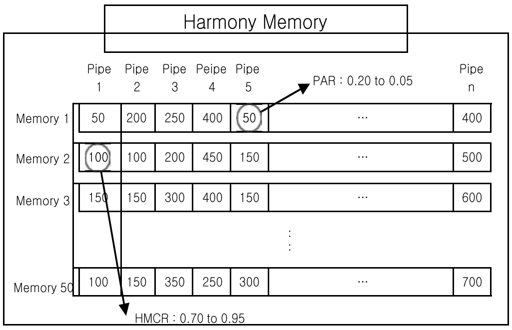
$P_{i,n}$ = Nodal pressure under normal condition at node i

C = Pipe construction cost, C_{limit} = Pipe construction cost limit

Category		Correction Factor
Pipe Diameter (mm) (C1)	D < 100	1.6
	100 ≤ D < 200	1.0
	200 ≤ D < 500	0.8
	500 ≤ D	0.5

4.1 Optimal Seismic Design

▪ Optimization technique: Harmony Search Algorithm



< Revised HS >

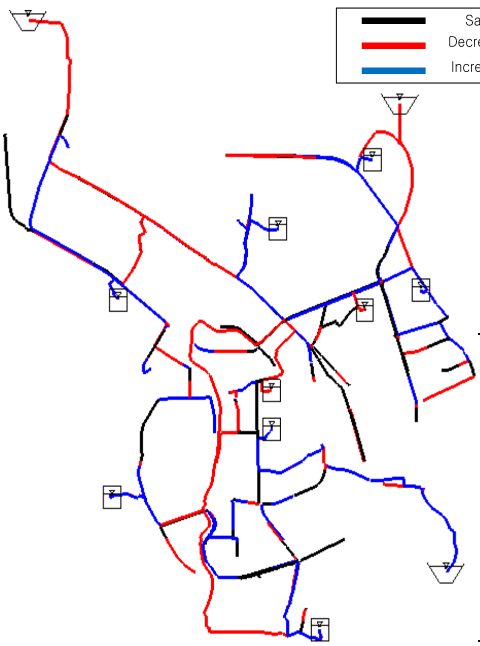
HMCR : Increase from 0.70 to 0.95

PAR : Decreased from 0.20 to 0.05

- Harmony Memory
  : Stores a group of good harmonies throughout the practices
- HMCR(Harmony Memory Considering Rate)
  : The ratio indicating whether a new harmony is formed from
  1) In HM
  2) Randomly generated
- PAR(Pitch Adjusting Rate)
  : Improving solution by searching adjacent region

4.1 Optimal Seismic Design

▪ Case Study: J City Main Pipeline – Results (Optimal Diameter)

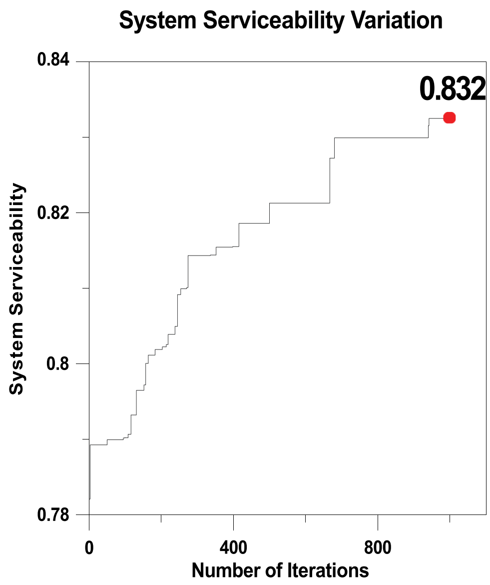


Diameter Change	Number of Pipes	Distribution Rate (%)	Total Length (km)	Distribution Rate (%)
Increased	84	36.7	51.8	35.9
Same	83	36.2	39.3	27.2
Decreased	62	27.1	53.3	36.9
Sum	229	100.0	144.4	100.0

Pipe Diameter (mm)		Number of Pipe	Rate (%)	Total Length (km)	Rate (%)
Increased	200 ≤ D < 500	40	47.6	19.2	37.1
	500 ≤ D	44	52.4	32.6	62.9
	Sum	84	100.0	51.8	100.0
Decreased	200 ≤ D < 500	26	41.9	10.3	19.3
	500 ≤ D	36	58.1	43.0	80.7
	Sum	62	100.0	53.3	100.0

4.1 Optimal Seismic Design

▪ Case Study: J City Main Pipeline – Results (Objective Function)



Comparison Results	Reliability Indices	
	System Serviceability (S_S)	Nodal Serviceability (AVG.) (N_S)
Original Network	0.783	0.786
Optimal Design Network	0.832	0.836
Differences (%)	4.9 (↑)	5.0 (↑)
Simple Design (One Size Lager)	0.798	0.797
Differences (%)	1.5 (↑)	1.1 (↑)

4.1 Optimal Seismic Design

▪ Case Study: J City Main Pipeline – Results (Cost Effectiveness)

Comparison Results	System Serviceability (S_S)	Construction Cost (Billion Won)
Original Network	0.783	104
Optimal Design Network	0.832	99
Differences (%)	4.9% (↑)	3.6% (↓)
Simple Design (One Size Lager)	0.798	112
Differences (%)	1.5% (↑)	7.6% (↑)

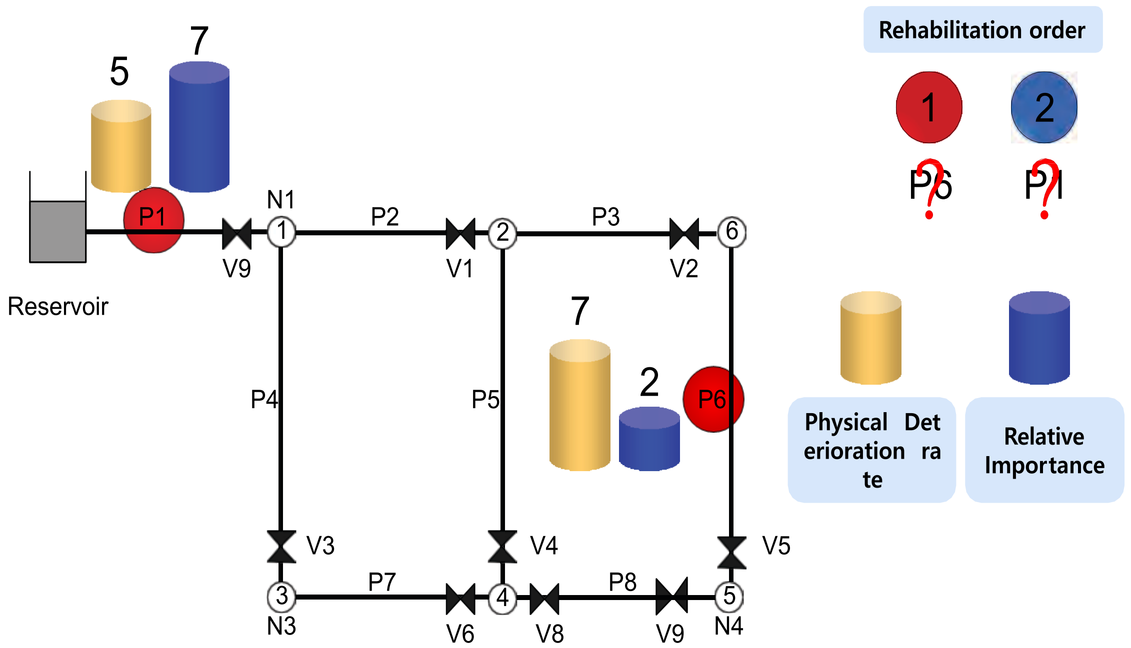
1. *Two factors are simultaneously achieved.*

- More Reliable (4.9% ↑)
- Cost Effective Design (3.6% ↓)

2. *Optimal pipe design for seismic damage is needed.*

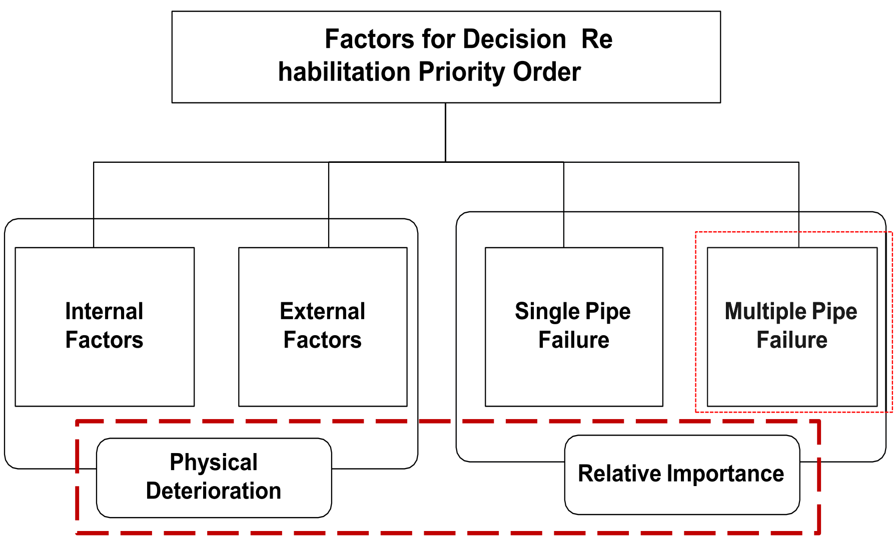
4.2 Prioritized Rehabilitation Model

- Priority of rehabilitation order of each pipe
- Concept of relative importance



4.2 Prioritized Rehabilitation Model

- Determination of reasonable and realistic priority orders for pipe rehabilitation



4.2 Prioritized Rehabilitation Model

▪ Physical deterioration
i) External factors, ii) Internal factors

External Factors

- Pipe outside corrosion
- Refilled soil
- Road wide
- Installed district

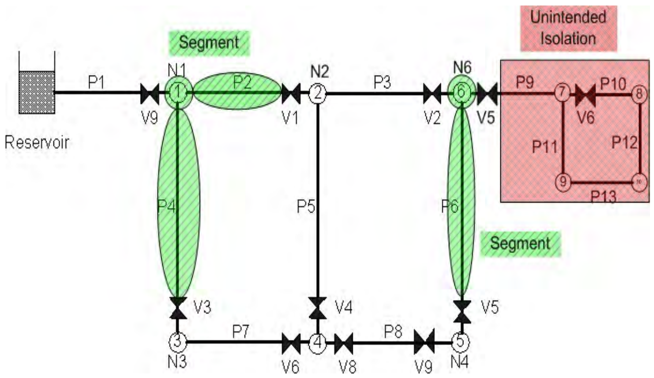
Considering Factors

Internal Factors

- Pipe material
- Diameter of pipe
- Inside corrosion
- Elapsed time from installation
- Type of joint
- Record of leakage and breakage
- Record of a civil appeal
- Maximum pressure

4.2 Prioritized Rehabilitation Model

▪ Relative importance (Single pipe failure)
i) Segments, ii) Unintended isolation



Effect of Single Pipe Failure

Segment & Unintended Isolation

$$ISPF_i = \frac{Q_{i,S} + Q_{i,UI}}{Q}$$

Here, $\mathrm{ISPF_i}$ = Importance by single pipe failure when pipe i is failed

Q = Total pipe flow under normal condition

$Q_{i,S}$ = Segment pipe flow when pipe i is failed

$Q_{i,S}$ = Unintended isoltation pipe flow when pipe i is failed

4.2 Prioritized Rehabilitation Model

- **Relative Importance (Multiple pipe failure)**

i) System serviceability under earthquake

< One of Reliability Indices >

$$\text{Nodal Serviceability } (N_S,i) = \begin{cases} \dfrac{Q_{avl,i}}{Q_{in\,i,i}} & when\ Q_{in\,i,i} \neq 0 \\ \sqrt{\dfrac{Min(P_i, P_{min})}{P_{min}}} & when\ Q_{in\,i,i} = 0 \end{cases}$$

Here, P_i = Nodal pressure at node i, P_{min} = Allowable minimum nodal pressure

Effect of Multiple Pipe Failure

REVAS.NET

$$IMPF_i = 1 - \frac{UN_{S,i} + DN_{S,i}}{2}$$

Here, $ISPF_i$ = Importance of pipe i by multi pipe failure

$UN_{S,i}$ = Upstream nodal serviceability of pipe i

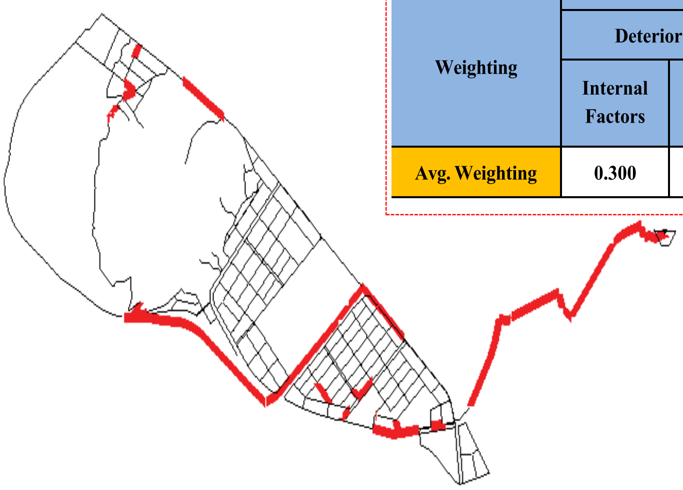
$DN_{S,i}$ = Downstream nodal serviceability of pipe i

4.2 Prioritized Rehabilitation Model

- **Case Study: Results - Rehabilitation priority order**

< Top 20 pipes have to be rehabilitated >

Weighting	Weighting Factor			
	Deterioration		Relative Importance	
	Internal Factors	External Factors	Single Pipe Failure	Multiple Pipe Failure
Avg. Weighting	0.300	0.263	0.283	0.154

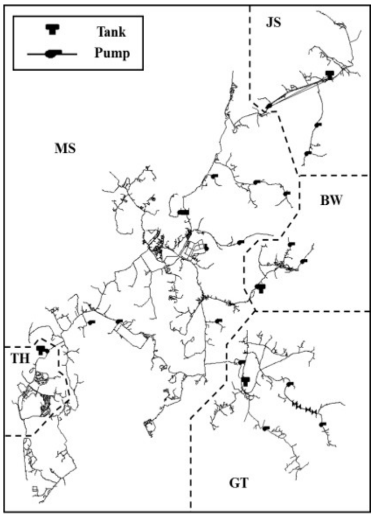


Weighting Factor is most important

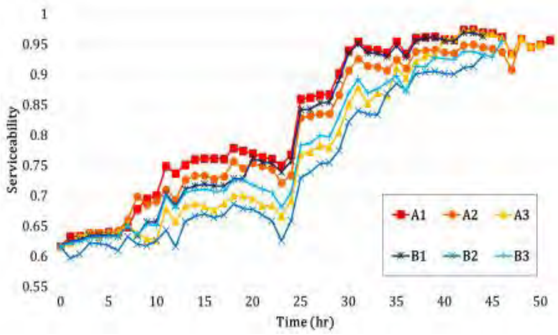
1. Major Effect
→ Deterioration by Internal Factors
2. Marginal Effect
→ Multiple Pipe Failure

4.3 Strategic Restoration Model

- System restoration strategies
- Restoration curve area and repair completion time
- Restoration total rank



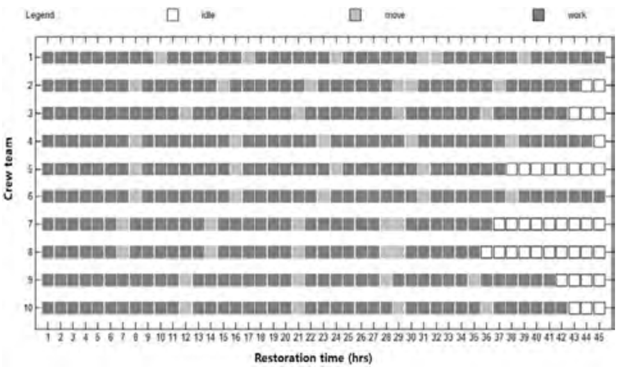
Case	Zoning	Rule	Description
A1	No	1	Pipes carrying higher water flow get higher repair priority
A2	No	2	Pipes closer to water sources get higher repair priority
A3	No	3	Pipes nearest to a current repair point get priority
B1	Yes	1	Pipes carrying higher water flow get higher priority within a zone
B2	Yes	2	Pipes closer to water sources get higher priority within a zone
B3	Yes	3	Pipes nearest to a current repair point get priority within a zone



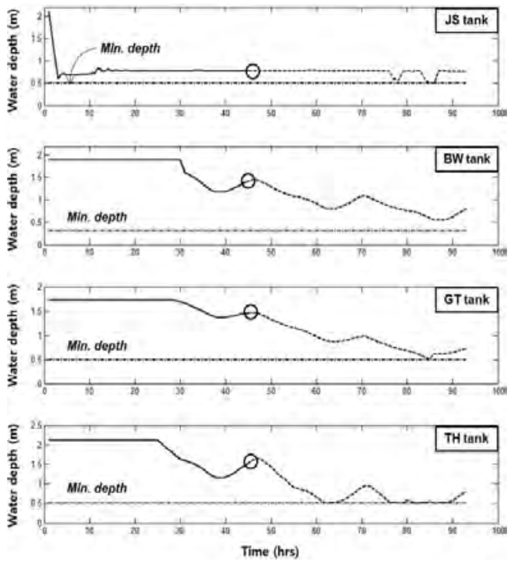
* Source: Choi, J., Yoo, D. G., & Kang, D. (2018). Post-earthquake restoration simulation model for water supply networks. *Sustainability*, *10*(10), 3618.

4.3 Strategic Restoration Model

- Spatiotemporal restoration pattern: Repair crew activity
- Impact on tank water level



Case	Average Time for Repair (h)	Average Time for Travel (h)	Average Time for Wait (h)
A1	41.3	7.7	4.0
A2	41.3	6.5	5.1
A3	41.4	7.1	4.5
B1	36.2	4.8	4.0
B2	36.2	5.2	4.6
B3	37.0	5.3	5.7



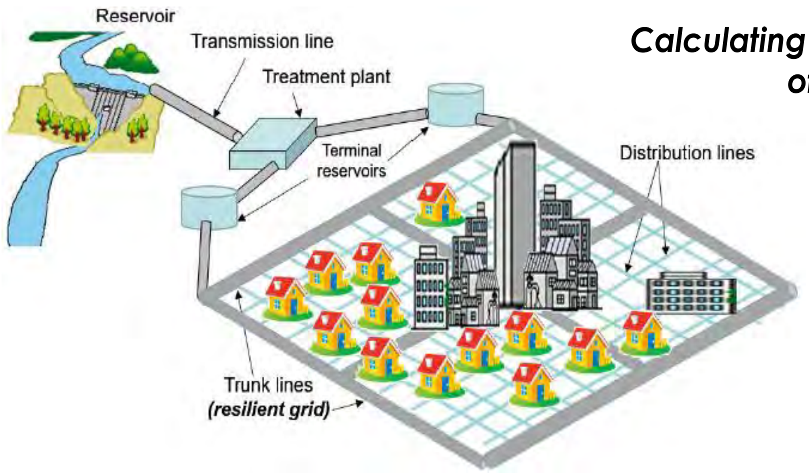
* Source: Choi, J., Yoo, D. G., & Kang, D. (2018). Post-earthquake restoration simulation model for water supply networks. *Sustainability*, *10*(10), 3618.

5. Other Related Applications

5.1 Calculating the Financial Benefits of Resilience

5.1 Calculating the Financial Benefits of Resilience

- Schematic of “as-is” water supply network: transmission line brings raw wat er from source (reservoir) to treatment plant; treated water is conveyed via trunk lines to terminal reservoirs and then to distribution network. Some or all trunk lines can form the resilient grid.



Calculating the Financial Benefits of Resilience

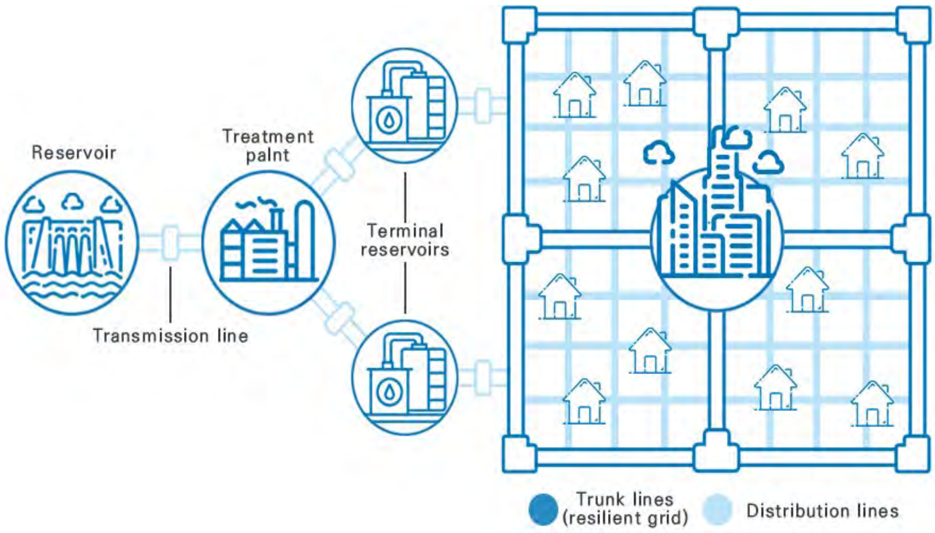
* Source: MMC [Multihazard Mitigation Council]. 2018. Natural Hazard Mitigation Saves: 2018 Interim Report. Washington: National Institute of Building Sciences.

Davis CA. 2017. Developing a seismic resilient pipe network using performance-based seismic design procedures. Proceedings of the 10th JWWA/WRF/CTWWA Water System Seismic Conference, Oct 18–19, Tainan, Taiwan. Taipei: National Center for Research on Earthquake Engineering.

5.1 Calculating the Financial Benefits of Resilience

- **Schematic of "as-is" water supply network: transmission line brings raw water from source (reservoir) to treatment plant; treated water is conveyed via trunk lines to terminal reservoirs and then to distribution network. Some or all trunk lines can form the resilient grid.**

Calculating the Financial Benefits of Resilience



5.1 Calculating the Financial Benefits of Resilience

- **Calculating the financial benefits of resilience**

- These benefits include reduced losses in

(a) water system repair costs,
(b) fire-related property losses,
(c)direct business interruption(BI) associated with lack of water service and fire damage,
(d)indirect BI losses for the rest of the economy that does business with customers who lose water service or suffer fire damage, and
(e)deaths, injuries, and instances of posttraumatic stress disorder(PTSD) resulting from fire after the earthquake.

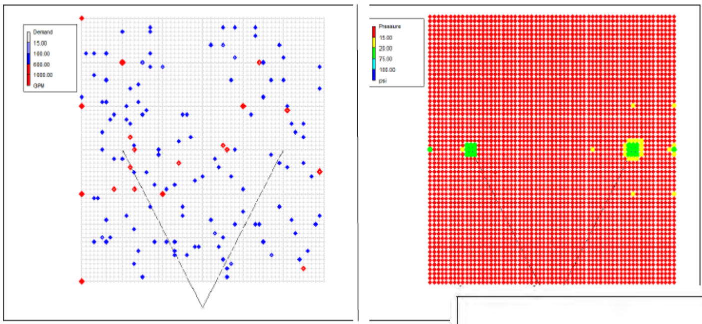
These benefits were then converted to equivalent dollar amounts per year by integrating benefits with hazard frequency.

* Source: MMC [Multihazard Mitigation Council]. 2018. Natural Hazard Mitigation Saves: 2018 Interim Report. Washington: National Institute of Building Sciences.

Davis CA. 2017. Developing a seismic resilient pipe network using performance-based seismic design procedures. Proceedings of the 10th JWWA/WRF/CTWWA Water System Seismic Conference, Oct 18–19, Tainan, Taiwan. Taipei: National Center for Research on Earthquake Engineering.

5.1 Calculating the Financial Benefits of Resilience

- **Under an MMI 8 earthquake the as-is design (left) sustains 111 distribution and 9 trunk line repairs (blue diamonds) and 21 ignitions (red diamonds, not all shown at this scale), changing the pressure distribution (right): red indicates nodes with inadequate pressure for firefighting, yellow barely adequate, and green adequate.**



($ millions)

	Modified Mercalli intensity (MMI)				
	VI	VII	VIII	IX	X
Losses without resilient grid	none	$138	$19,007	$53,224	$152,774
Losses with resilient grid	none	$119	$8,667	$33,517	$132,993
Benefit of resilient grid	none	$19	$10,341	$19,707	$19,782
Cost of resilient grid	$403	$403	$403	$403	$403
Benefit-cost ratio	0	0.05	25.7	48.9	49.1

* Source: MMC [Multihazard Mitigation Council]. 2018. Natural Hazard Mitigation Saves: 2018 Interim Report. Washington: National Institute of Building Sciences.

Davis CA. 2017. Developing a seismic resilient pipe network using performance-based seismic design procedures. Proceedings of the 10th JWWA/WRF/CTWWA Water System Seismic Conference, Oct 18–19, Tainan, Taiwan. Taipei: National Center for Research on Earthquake Engineering.

5.1 Calculating the Financial Benefits of Resilience

- **Observations**

- The major benefit of the resilient grid was due to improved supply of firefighting water.
- The benefit of the resilient grid was due to the lack of fire service capacity. If the fire service increased its capacity—for example, by moving water via tanker trucks or portable water supply systems—the resilient grid was less beneficial.
- The observation above reinforced the point that the resilient grid concept cannot be solely a water department initiative but needs to be pursued in close cooperation with the fire service.

* Source: MMC [Multihazard Mitigation Council]. 2018. Natural Hazard Mitigation Saves: 2018 Interim Report. Washington: National Institute of Building Sciences.

Davis CA. 2017. Developing a seismic resilient pipe network using performance-based seismic design procedures. Proceedings of the 10th JWWA/WRF/CTWWA Water System Seismic Conference, Oct 18–19, Tainan, Taiwan. Taipei: National Center for Research on Earthquake Engineering.

5.1 Calculating the Financial Benefits of Resilience

▪ Observations

- The resilient grid was quite likely to significantly reduce restoration time of the water supply to customers.
- Closer spacing of the resilient grid (e.g., trunk lines at every fifth or sixth distribution line rather than every tenth) may not significantly increase the BCR: although it increased benefits, it also increased costs.
- The findings on BCRs were based on the overly conservative assumption that the resilient grid required the replacement of 100 percent of the trunk lines. If only a portion of the resilient grid required replacement (e.g., 50 percent of the existing trunk lines were considered of low vulnerability and therefore did not require replacement), the BCRs would have been doubled.

* Source: MMC [Multihazard Mitigation Council]. 2018. Natural Hazard Mitigation Saves: 2018 Interim Report. Washington: National Institute of Building Sciences.

Davis CA. 2017. Developing a seismic resilient pipe network using performance-based seismic design procedures. Proceedings of the 10th JWWA/WRF/CTWWA Water System Seismic Conference, Oct 18–19, Tainan, Taiwan. Taipei: National Center for Research on Earthquake Engineering.

6. Conclusions

6. Conclusions

- From, 1980s resilience concept is widely used in seismic risk management policies. But, there are rare studies to reflect det ailed characteristic and hydraulic and structural condition of wa ter supply networks under earthquake.
- Different frameworks and models of resilience will be briefly compared and their application in influence on seismic risk management were discussed.
- Some real applications were presented to illustrate their pra ctical relevance in the developing and developed country.
- An integrated, insightful approaches to community-based, s ystem-based, and infrastructure-based seismic resilience are required.

Water Related Resilience and Applications to Natural Hazards:

Drought and floods

Water Security and System Resilience

4. Water Related Resilience and Applications to Natural Hazards: Drought and floods

UNESCO
United Nations Educational, Scientific and Cultural Organization
i-WSSM
International Centre for Water Security and Sustainable Management

Aims & Objectives

- The aims of the course are to:

(1) Explain the basic understanding of “drought and flood resilience”
(2) Introduce for quantifying of drought and flood resilience for water systems
(3) Introduce applications for water related resilience assessment to drought and flood

- The objectives are that trainees will understand:

(1) Basic concept of “drought and flood resilience”
(2) Analysis frameworks of drought and flood resilience for water systems
(3) Some applications to investigate drought and flood resilience

References

Regional drought resiliency and vulnerability (Karamouz et al., 2016)

A systems approach to natural disaster resilience (Harrison and Williams, 2016)

RESILIENCE STRATEGIES FOR DROUGHT (Center for Climate and Energy Solutions, 2018)

Evaluation of Drought Resilience Reflecting Regional (Lee and Yoo, 2021)

Drought response and recovery (US-EPA, 2018)

References

Flood resilience (Zevenbergen et al., 2020)

Flood resilience: a systematic review (McClymont et al., 2020)

Assessing urban pluvial flood resilience (Chen et al., 2021)

Relation between flood risk management and flood resilience (Disse et al., 2020)

FLOOD RESILIENCE (US-EPA, 2014)

Contents

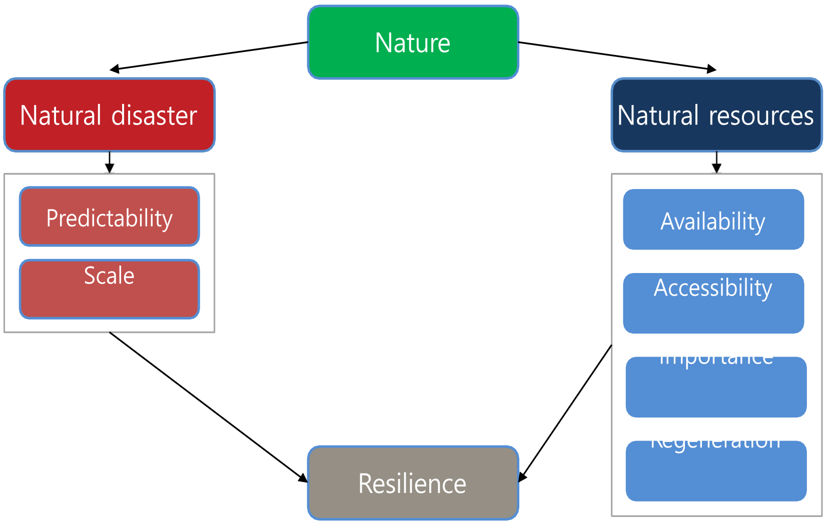
1. Drought and flood resilience
2. Resilience quantification for drought and flood
3. Case studies for drought resilience assessment
4. Case studies for flood resilience assessment
5. Drought and flood resilient utilities
6. Conclusions

1. Drought and flood resilience

1. Defining Resilience to Natural Disasters
2. Drought Resilience
3. Flood Resilience

1.1 Defining Resilience to Natural Disasters

- Nature should always be considered for resilience
- Natural disasters are often unpredictable
- Climate change is affected by many factors



* Source from "Ch 1. Overview of Resilience"

1.1 Defining Resilience to Natural Disasters

- Systems-based approaches

"City Resilience describes the capacity of individuals, communities, institutions, busin ess, and systems within a city to survive, adapt, and grow no matter what kinds of ch ronic stresses and acute shocks they experience." (Rockefeller Foundation)

Emphasis on,

People and institutions rather than infrastructure and the built environment

Systems-based approaches have been applied to resilience,

"they mostly examine the resilience of individual sub-systems rather than attempting to consider the resilience of the city as a system itself"

* Rockefeller Foundation, 100 Resilient Cities, Available [Online]: https://www.rockefellerfoundation.org/our- work/initiatives/100- resilient- cities/
Harrison, C. G., & Williams, P. R. (2016). A systems approach to natural disaster resilience. Simulation Modelling Practice and Theory, 65, 11-31.

1.1 Defining Resilience to Natural Disasters

- **Resilience to natural disasters**

"The ability of a system, community or society exposed to hazards to resist, absorb, ac commodate to and recover from the effects of a hazard in a timely and efficient mann er, including through the preservation and restoration of its essential basic structures and functions." (UN International Strategy for Disaster Reduction, UN ISDR)

Resilience vs sustainability (often interact…)

Sustainability takes the view that a community must live cautiously so as not to impair its natural environment, social balance, and economic viability under the assumption that all externalities remain constant.

Resilience deals with the fact that things do not remain constant. Climate change may slowly bring drought, new technologies may lead to the decline of old industries, and revolutions may change social and political structures.

* UN ISDR, Available [Online]: http://www.unisdr.org/ (accessed 20.08.15).
Harrison, C. G., & Williams, P. R. (2016). A systems approach to natural disaster resilience. Simulation Modelling Practice and Theory, 65, 11-31.

1.2 Drought Resilience

- **The world experienced prolonged periods of abnormally dry or unusually hot weather that threaten the availability of water.**
- **Unlike other hazards, such as flooding and earthquakes, droughts develop gradually over months or years.**

1.2 Drought Resilience

- **Droughts can result in significant economic, social, environmental and water utility operational impacts, including:**

• Loss of water supply.
• Poor source water quality that may affect treatment and the ability to meet drinking water standards.
• Stressed alternative and supplementary water sources due to high demand by other drought-affected users.
• Increased demand from customers.
• Increased costs and reduced revenues related to drought response.

* US-EPA (2018) Drought response and recovery.

1.2 Drought Resilience

- **Drought resilience is the ability to respond to immediate water supply threats, withstand drought impacts and recover quickly. (US-EPA, 2018)**

Drought-resilient utilities:
• Take action to protect human health and the environment, while maintaining a minimum level of service for customers during drought.
• Manage decreases in water supply, increases in water demand and changes in water quality.
• Plan for future changes in weather and climate patterns that can reduce water supply.

1.3 Flood Resilience

- **Flooding is one of the most common hazards in the world, causing more damage than any other severe weather-related event.**

•• Can occur from tropical storms, hurricanes, swollen rivers, heavy rains, tidal surges, spring snowmelt, levee or dam failure, local drainage issues and water distribution main breaks.

• Impacts to drinking water and wastewater utilities can include loss of power, damage to assets
• dangerous conditions for personnel.

1.3 Flood Resilience

- **The ability of water and wastewater utilities to withstand a flooding event, minimize damage and rapidly recover from disruptions to service.**

A mitigation measure can be an emergency planning activity, equipment modification/upgrade or new capital investment/construction project. Examples of mitigation measures include:

• Emergency response plan • Barriers around key assets
• Elevated electrical equipment • Emergency generators
• Bolted down chemical tanks

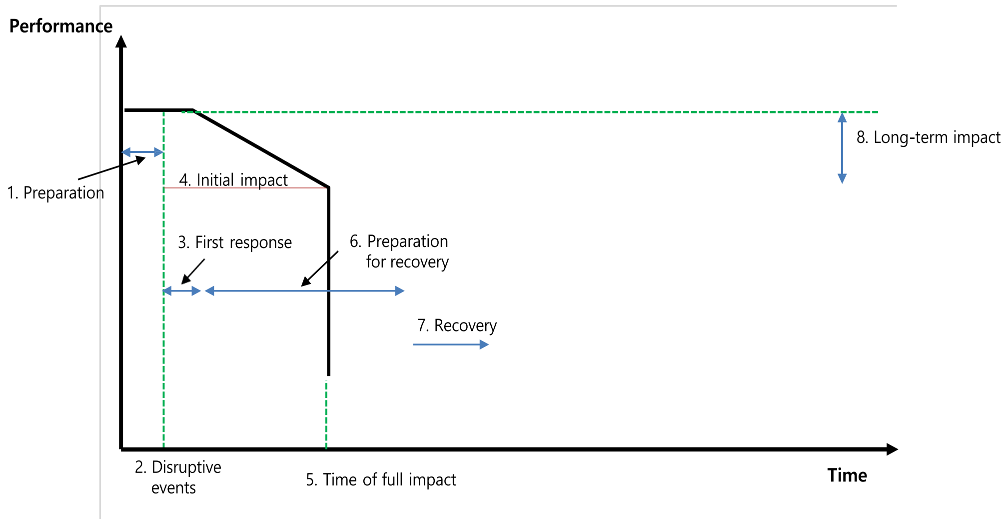
* US-EPA (2014) Flood resilience. A Basic Guide for Water and Wastewater Utilities.

2. Resilience quantification for drought and flood

1. System Performance Curve to Natural Disasters
2. Resilience Quantification for Drought
3. Resilience Quantification for Flood

2.1 System Performance Curve to Natural Disaster

- When a disaster happens, a typical profile usually occurs and it can be categorized into 8 phases



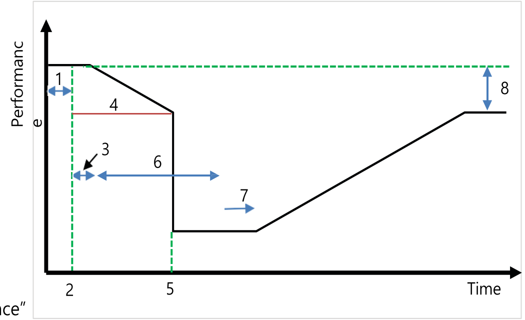
[Time to performance graph]

Source: Sheffi & Rice (2005)

* Source from "Ch 1. Overview of Resilience"

2.1 System Performance Curve to Natural Disaster

1. **Preparation**
   - In some cases, disruption can be foreseen and be prepared to minimize its effects
2. **Disruptive Event**
   - When a disruptive event happens, such as when a tornado hits or terrorists attack
3. **First Response**
   - First response is aimed at controlling the situation, saving and protecting lives, sh utting down affected systems, and prev enting further damage
4. **Initial Impact**
   - Depending on the scale of the disruption, the effect might not be felt instantaneously
5. **Full Impact**
   - The time when performance hits the lowest
6. **Recovery Preparations**
   - Typically done in parallel with the first re sponse. Preparing the needed resources t o recover from the disruptions
7. **Recovery**
   - Utilizing the available resource to try to return to acceptable performance
8. **Long-term Impact**
   - Sometimes, after a disruption, the performance will not return to the performance as before

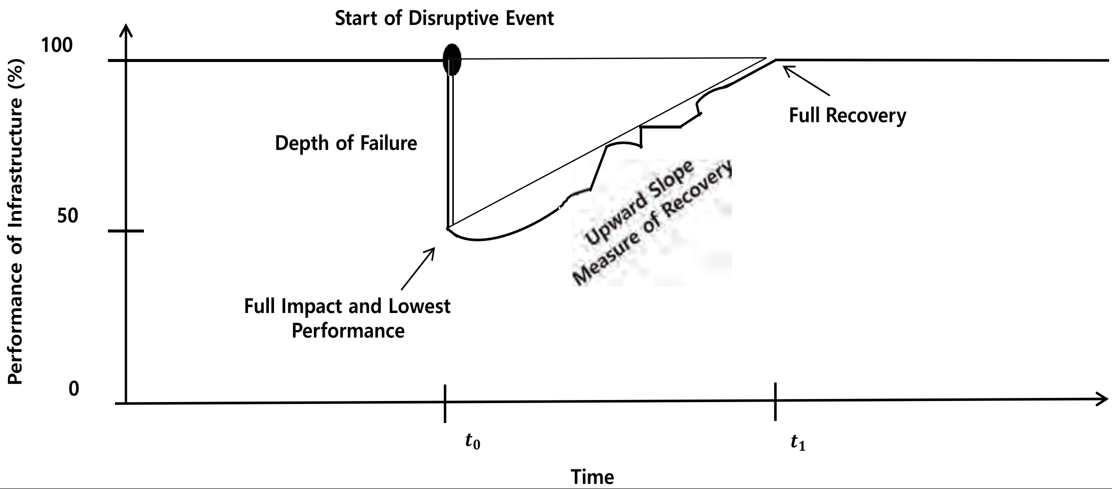


* Source from "Ch 1. Overview of Resilience"

2.1 System Performance Curve to Natural Disaster

- **General conceptualized resilience triangle for such as earthquake disaster**

*1) Start of Disruptive Event, **2) Depth of failure,***
3) Full Impact and Lowest Performance,
4) Upward Slope Measure of Recovery, 5) Full Recovery

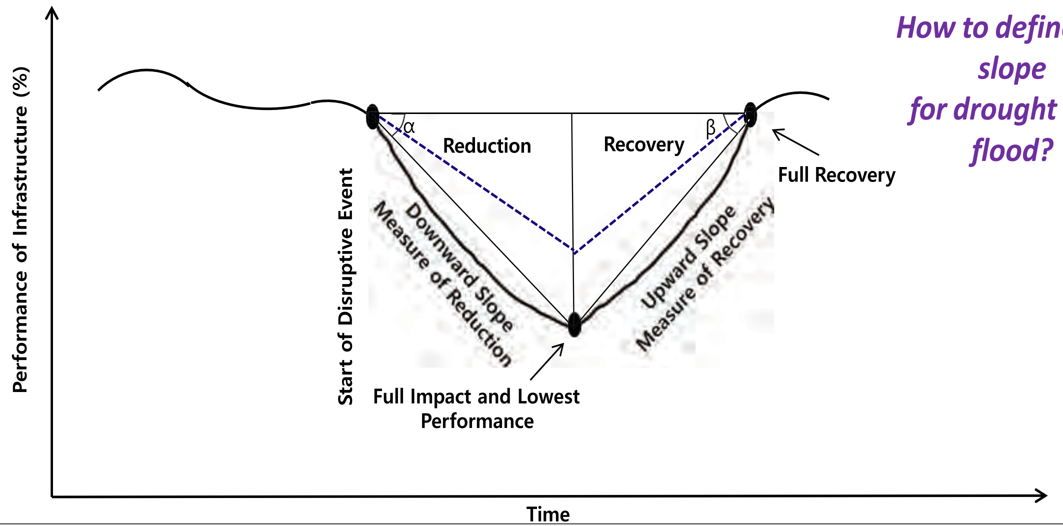


2.1 System Performance Curve to Natural Disaster

▪ **Conceptualized resilience triangle for a major weather events such as drought and flooding**

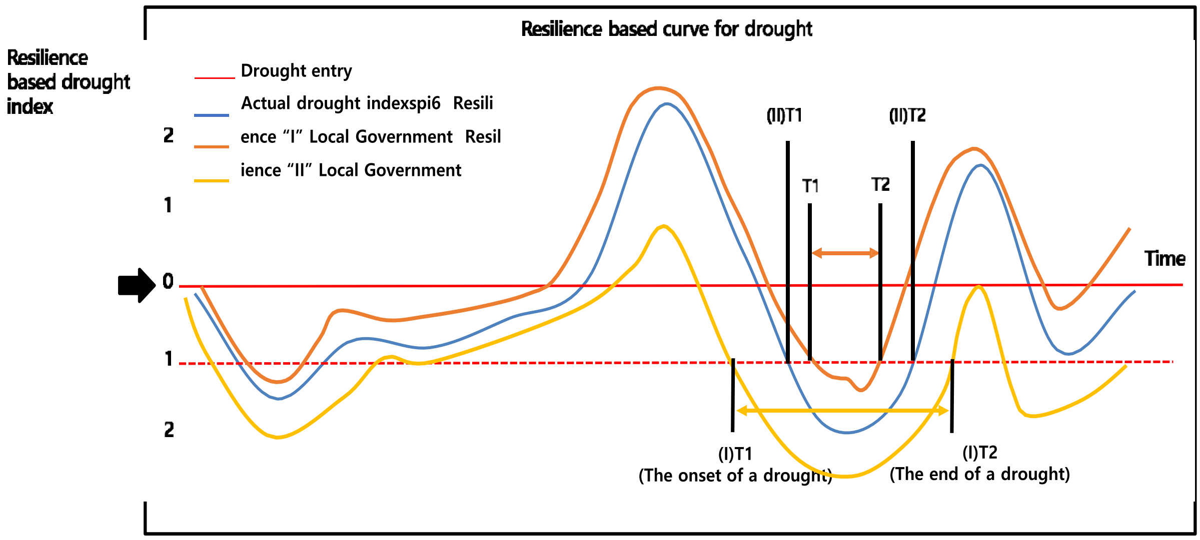
1) Start of Disruptive Event, ***2) Downward Slope Measure of Reduction,***
3) Full Impact and Lowest Performance,
4) Upward Slope Measure of Recovery, 5) Full Recovery

How to define the slope for drought and flood?



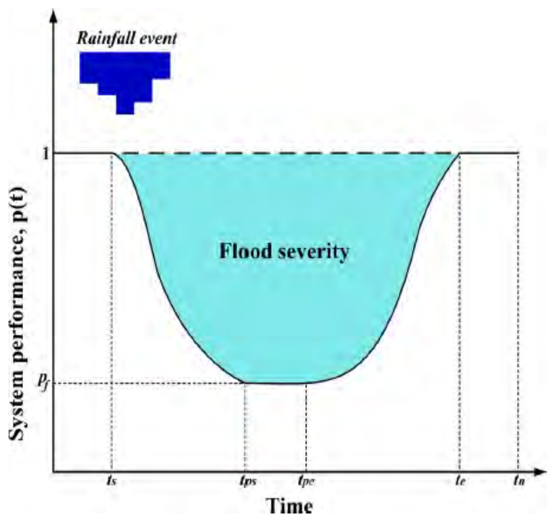
2.2 Resilience Quantification for Drought

▪ **Evaluation of drought resilience reflecting regional characteristics and drought resilience curve based on drought index**



2.2 Resilience Quantification for Flood

- **Flood severity is an aggregated representation of the level of system damage during the entire process**



$$Sev = \frac{1}{t_n}\int_0^{t_n}[1 - p(t)]dt$$

$$Sev = \frac{V_{TF}}{V_{TI}} \times \frac{t_f}{t_n} \qquad Res_0 = 1 - Sev = 1 - \frac{V_{TF}}{V_{TI}} \times \frac{t_f}{t_n}$$

- "S_{ev}" is flood severity,
- "t_n" is the total simulation time
- "Res_0" is simplified metric by approximating the flood severity "S_{ev}"
- "V_{TF}" is the total flood volume,
- "V_{TI}" is total inflow into adrainage system,
- "t_f" is the mean duration offlooding across the entire network

* Wang, Y., Meng, F., Liu, H., Zhang, C., & Fu, G. (2019). Assessing catchment scale flood resilience of urban areas using a grid cell based metric. Water research, 163, 114852.
Chen, J., Chen, W., & Huang, G. (2021). Assessing urban pluvial flood resilience based on a novel grid-based quantification method that considers human risk perceptions. Journal of Hydrology, 601, 126601.

3. Case Studies for Drought Resilience Assessment

1. Attributes of Resilience
2. Applications for Drought Resilience Assessment
3. Applications for Flood Resilience Assessment

3.1 Attributes of Resilience

- **Resilience has become an important concept concerning response to various natural disasters and the establishment of countermeasures as well as rece nt droughts**

- *Drought is one of the natural disasters with not only environmental and economic but also social impact in various and complex ways and is cla ssified into meteorological, hydrological, agricultural, and socioeconom ic drought (relate to drought index) due to the various paths and effect s of drought.*

- *Recently, not only monitoring of a drought index but the concept of resil ience is being introduced to evaluate the performance of the system aga inst emergency accidents, natural and social disasters and to establish c ountermeasures against possible accidents and disasters in the future.*

3.1 Attributes of Resilience

- **Safety resilience is divided into three areas**
  1) Human resilience focused on human,
  2) Community resilience focused on recovery, and
  3) System resilience focused on preparation to function normally in unpredictable and constantly changing situations.

- *Human resilience refers to the process of overcoming or recovering from tragedy, trauma, and stress.*

- *Community resilience is a field that studies factors that can recover from natural disas ters such as typhoons and heavy rains, or social infrastructure, disaster management systems, human and material resources, etc., and applies the concept of prevention-pr eparation-response-recovery.*

- *Human resilience and community resilience share a basic concept that prevention is possible if removing the cause of an accident or event with resilience, which recovers to its original state.*

3.1 Attributes of Resilience

▪ Safety resilience is divided into three areas
1) Human resilience focused on human,
2) Community resilience focused on recovery, and
3) System resilience focused on preparation to function normally in unpredictable and constantly changing situations.

- *System resilience has a more advanced perspective and goal than the common concept of human and community resilience and requires coordination and performance capabilities to bring out the intended results.*
- *System resilience refers to the ability of an organization, hardware and software system to mitigate the severity and possibility of failure or loss, adapt to changing conditions, and respond appropriately afterward.*

3.1 Attributes of Resilience

▪ Safety resilience is divided into three areas
1) Human resilience focused on human,
2) Community resilience focused on recovery, and
3) System resilience focused on preparation to function normally in unpredictable and constantly changing situations.

- *Various researchers have conducted researches that applied the concept of resilience to drought disasters since 2010.*
- *Most of the studies have researched a framework to evaluate and strengthen community resilience from national, government, and regional perspectives on drought.*
- *The resilience researches for drought disaster so far has been aimed at presenting the communication between stakeholders and policy improvement directions by calculating community resilience.*

3.1 Attributes of Resilience

- Resilience can be defined by the following 4 attributes (Bruneau and Reinhorn, 2007):
  - Robustness (RO)
  - Redundancy (RD)
  - Resourcefulness (RS)
  - Rapidity (RA)

Robustness:
The ability of the system to withs tand a level of stress without suff ering degradation or loss of func tion

Redundancy:
The ability to substitute parts in the system that is affected to maintain functionality

Resourcefulness:
The ability to identify, prioritize pr oblems, and allocate resources to r ecover from stress

Rapidity:
The capacity to recover and achieve goals quickly in order to limit loss and prevent future disruptions

* Source from "Ch 1. Overview of Resilience"

3.2 Applications for Drought Resilience Assessment

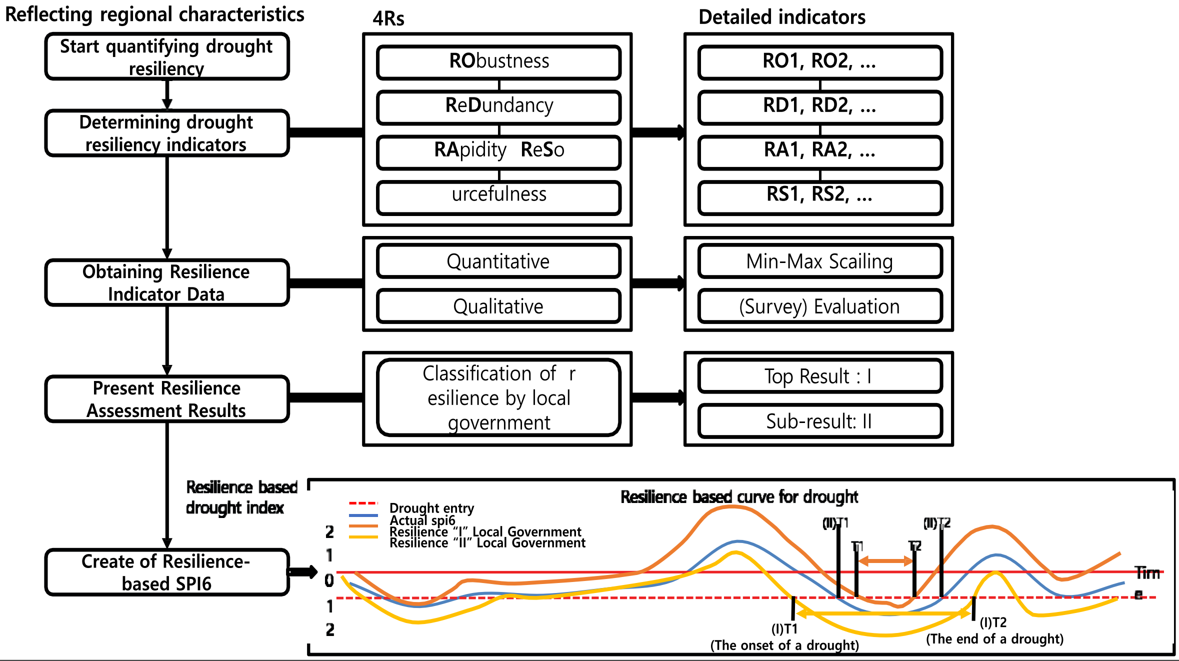
- Standardized Precipitation Index(SPI) range by drought stage
- The SPI is a widely used index to characterize meteorological drought on a range of timescales.

Drought Category	SPI Values	Ref.
Mild drought	0 ~ -0.99	Mckee et al. (1993)
Moderate drought	-1.00 ~ -1.49	
Severe drought	1.50 ~ -1.99	
Extreme drought	-2.00 SPI	

* Source from "Ch 1. Overview of Resilience"

3.2 Applications for Drought Resilience Assessment

▪ Evaluation of drought resilience reflecting regional characteristics - Focused on 160 local governments in South Korea



3.2 Applications for Drought Resilience Assessment

▪ Indicators for quantifying drought resilience in South Korea

Robustness(RO)	Redundancy(RD)	Resourcefulness(RS)	Rapidity(RA)
RO1 : Available Regional Water Resources	RD1: Availability of Water Resources in Surrounding Areas	RS1: Specificity of Drought Comprehensive Measures	RA1: A Local Population
RO2 : Regional Economic Vulnerability	RD2: Groundwater Resource Availability	RS2: Degree of budgeting for water resource (drought) disasters	RA2: Virtual Drought Training Status and Specificity
RO3: Average Annual Precipitation and Variability in the Region	RD3: The Way to Use Agricultural Water	RS3: Drought Prediction and Alarm System Availability and Utilization	RA3: Public Awareness and Understanding of the Concept of Drought
RO4: Historical Drought Experience and Regional Adaptation Levels for Drought	RD4: Presence of Water Allocation Priorities for Drought)	RS4: Drought Vulnerability Map Existence and Utilization	-
RO5 : Regional Average Water Consumption	RD5: Presence of Reservoir Operation Policy During Drought	RS5: Specificity of Organizational Management in Drought	-

3.2 Applications for Drought Resilience Assessment

▪ Quantitative robustness indicators for quantifying drought resiliency in local governments

Item	Indicator	Sub-indicator	Calculation data
Robustness, RO	[RO1] Available Regional Water Resources	Water supply rate (representing the percentage of the total population receiving tap water)	Utilize water supply (%) data
		Regional reservoir capacity (total reservoir capacity in the region)	Utilize local reservoir capacity ( ) data
		Total amount of local tube-well information (use of groundwater irrigation in the region)	Use the total amount of local government information data (annual usage)
	[R02] Regional Economic Vulnerability	Financial self-reliance (tax analysis indicators indicating the ability to self-provision financial income)	Use fiscal self-reliance (%) data
		Gross regional product (GRDP, production by unit, consumption, prices, etc.)	Use Gross regional product (GRDP)
	[R03] Average Annual Precipitation and Variability of the Region (Coefficient of Variation)	The average annual precipitation in the region	Utilization of annual precipitation data (local distribution based on observatory)
		Variation of regional annual precipitation (coefficient of variation)	Coefficient of variation based on annual average precipitation data
	[R04] Historical drought experience and local adaptation to drought levels	Meteorological: SPI6 standard (number of days) the number of past severe drought anomalies	Calculation and utilization of the number of SPI6 drought standards (SPI6<2.0) that lasted more than 30 days
		Agricultural: Number of occurrences of severe drought in the past based on SMI	Calculation and utilization of the number of heavy SMI droughts (15% or less) occurred
		Water for living: Past number of water-outage, intermittent water supply	Utilization of past number of water-outage, intermittent water supply
	[R05] Regional average water consumption	the amount of water used per person	Leverage annual usage data
		Amount of industrial water used per person	
		Amount of agricultural water used per person	

3.2 Applications for Drought Resilience Assessment

▪ Quantitative redundancy, resourcefulness, rapidity indicators for quantifying drought resiliency in local governments

Item	Indicator	Sub-indicator	Calculation data
Redundancy, RD	[RD2] Groundwater resource availability	Total amount of local tube well – use of groundwater irrigation in the region	The amount of planned tube well water intake
	[RD3] Agricultural water use method (irrigation status, etc.: ratio of field irrigation)	The ratio of irrigated paddy - paddies supplied with water by irrigation facilities such as reservoirs, waterworks, reservoirs, and groundwater pipes	The ratio of irrigated paddy
		Percentage of field irrigation - fields supplied by agricultural water supply facilities	Percentage of field irrigation
Resourcefulness, RS	[RS2] Degree of budgeting for water resource (drought) disasters	Ratio of local taxes among past disaster management-related expenditures	Use local tax rate (%) data
		Percentage of self-recovery expenses in case of natural disasters	Utilize recovery cost ratio (%)
Rapidity, RA	[RA1] A local population	Population count by administrative district (city)	Use the population by city and county
		Percentage of vulnerable class by administrative district (city)	Ratio of 63 years of age or older by city and county

3.2 Applications for Drought Resilience Assessment

▪ Qualitative indicators for quantifying drought resilience in local governments

Item	Indicator
Redundancy, RD	RD1 : Availability of water resources in surrounding areas
	RD4 : Presence of water allocation priorities for drought
	RD5 : Presence of reservoir operation policy during drought
Resourcefulness, RS	RS1 : Specified degree of drought comprehensive measures
	RS3 : Drought prediction and alarm system availability and utilization
	RS4 : Drought vulnerability map existence and utilization
	RS5 : Specified degree of organizational management in drought
Rapidity, RA	RA2 : Virtual drought training status and specificity
	RA3 : Public awareness and understanding of the concept of drought

3.2 Applications for Drought Resilience Assessment

▪ Sources of drought resilience by indicators

Indicator	Sub-indicator	Reference data source
RO1 : Available Regional Water Resources	Water supply rate (representing the percentage of the total population receiving tap water)	Ministry of Environment (Water supply statistics)
	Regional reservoir capacity (total reservoir capacity in the region)	Water Resources Management Information System (Regional reservoir capacity)
	Total amount of local tube-well information (use of groundwater irrigation in the region)	K-water (tube-well management information)
RO2 : Regional Economic Vulnerability	Financial self-reliance (tax analysis indicators indicating the ability to self-provision financial income)	Statistics Korea (General Regional Statistics Department)
	Gross regional product (GRDP, production by unit, consumption, prices, etc.)	
RO3 : Average Annual Precipitation and Variability in the Region	The average annual precipitation in the region	Korea Meteorological Administration (average annual precipitation)
	Variation of regional annual precipitation (coefficient of variation)	
RO4 : Historical Drought Experience and Regional Adaptation Levels for Drought	SPI6	Hydrologic Weather, Drought Information Analysis System (Drought Index)
	SMI	Agricultural Drought Management System (Drought Index)
	Water for living: Past number of water-outage, intermittent water supply	National Drought Information Portal (Emergency water supply status)

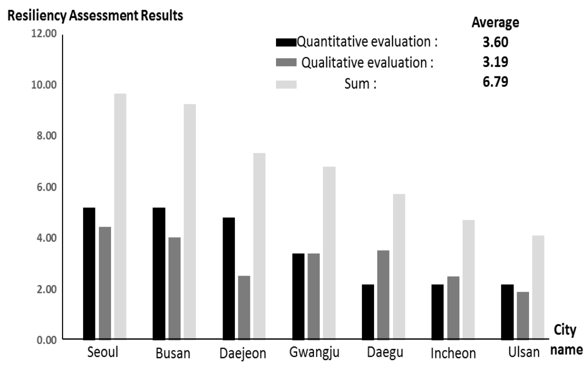
3.2 Applications for Drought Resilience Assessment

▪ Sources of drought resilience by indicators

Indicator	Sub-indicator	Reference data source
RO5 : Regional Average Water Consumption	Amount of living, agricultural and industrial water used	Water Resources Management Information System (Usage of living, agricultural and industrial water)
RD2 : Groundwater Resource Availability	Total amount of local tube well – use of groundwater irrigation in the region	K-water (Annual water intake plan)
RD3 : The Way to Use Agricultural Water	The ratio of irrigated paddy	Water Resources Management Information System (Cultivated Acreage)
	Percentage of field irrigation	
RS2 : Degree of budgeting for water resource (drought) disasters	Ratio of local taxes among past disaster management-related expenditures	The Ministry of the Interior and Safety (MOIS) (Statistical Yearbook of Local Taxes)
	Percentage of self-recovery expenses in case of natural disasters	e-Country Indicators: Public Data Request Required (Natural Disaster Recovery Expenses)
RA1 : A Local Population	Population count by administrative district (city)	The Ministry of the Interior and Safety (MOIS) (Resident registered population status)
	Percentage of vulnerable class by administrative district (city)	The Ministry of the Interior and Safety (MOIS) (Resident registered population status)

3.2 Applications for Drought Resilience Assessment

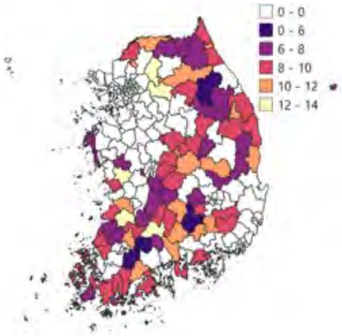
▪ Drought resilience results for metropolitan cities



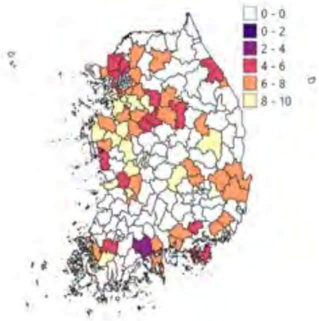
Special Metropolitan City				
Area name	Quantitative Indicators(A)	Qualitative indicators(B)	(A)+(B)	Resilience Separation
Seoul	5.20	4.45	9.65	I
Busan	5.20	4.04	9.24	
Daejeon	4.80	2.53	7.33	
Gwangju	3.40	3.40	6.80	
Daegu	2.20	3.52	5.72	II
Incheon	2.20	2.51	4.71	
Ulsan	2.20	1.90	4.10	
Average	3.60	3.19	6.79	
Stdev	1.44	0.91	2.13	
CV	0.40	0.29	0.31	

3.2 Applications for Drought Resilience Assessment

▪ Drought resilience evaluation results (county unit; 153 locations)



(a) Resilience I

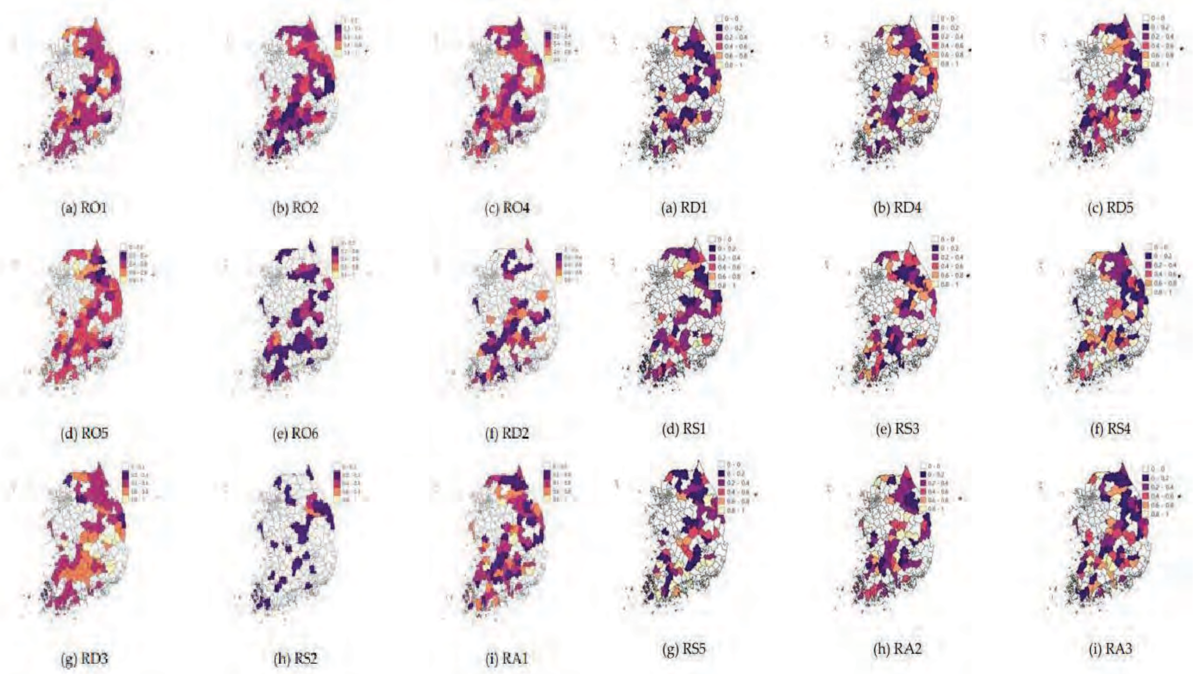


(b) Resilience II

	Evaluation Results						
	Quantitative Indicators(A)		Qualitative indicators(B)		(A)+(B)		
Resilience Separation	I	II	I	II	I	II	I+II
average	5.06	2.79	2.70	2.49	7.76	5.28	6.45
stdev	0.82	0.81	0.47	0.36	0.76	0.81	1.47
cv	0.16	0.29	0.17	0.15	0.10	0.15	0.23

3.2 Applications for Drought Resilience Assessment

▪ Quantitative and qualitative indicator assessment results for "Resilience I" Group



(a) RO1 (b) RO2 (c) RO4 (a) RD1 (b) RD4 (c) RD5

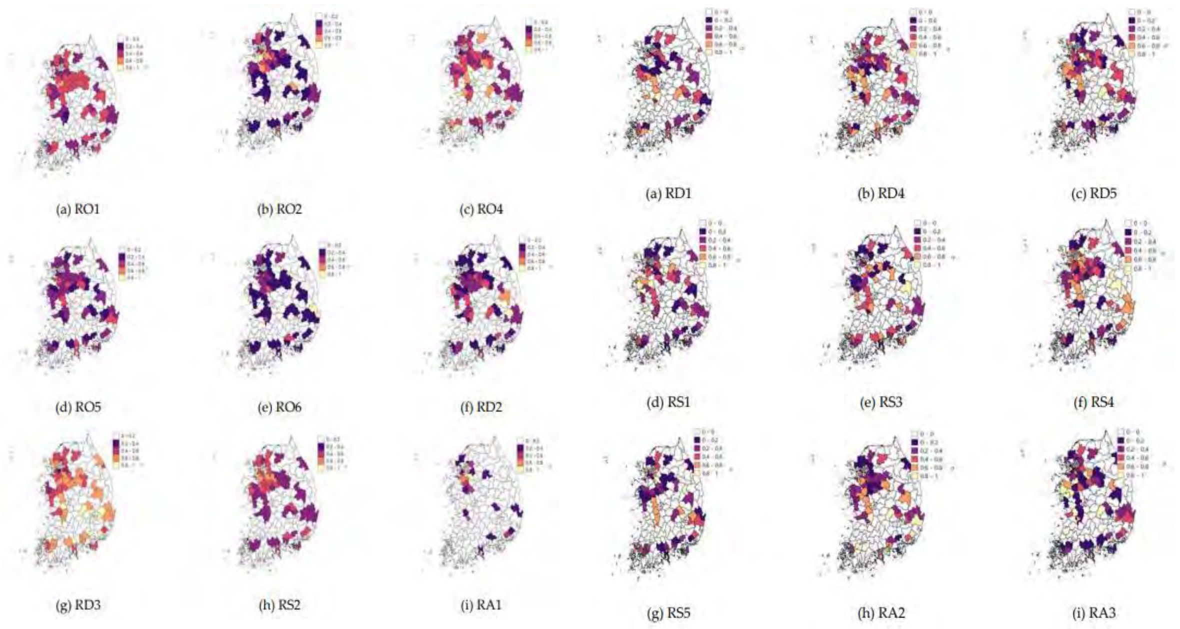
(d) RO5 (e) RO6 (f) RD2 (d) RS1 (e) RS3 (f) RS4

(g) RD3 (h) RS2 (i) RA1 (g) RS5 (h) RA2 (i) RA3

Quantitative Indicator **Qualitative Indicator**

3.2 Applications for Drought Resilience Assessment

- Quantitative and qualitative indicator assessment results for “Resilience II” Group

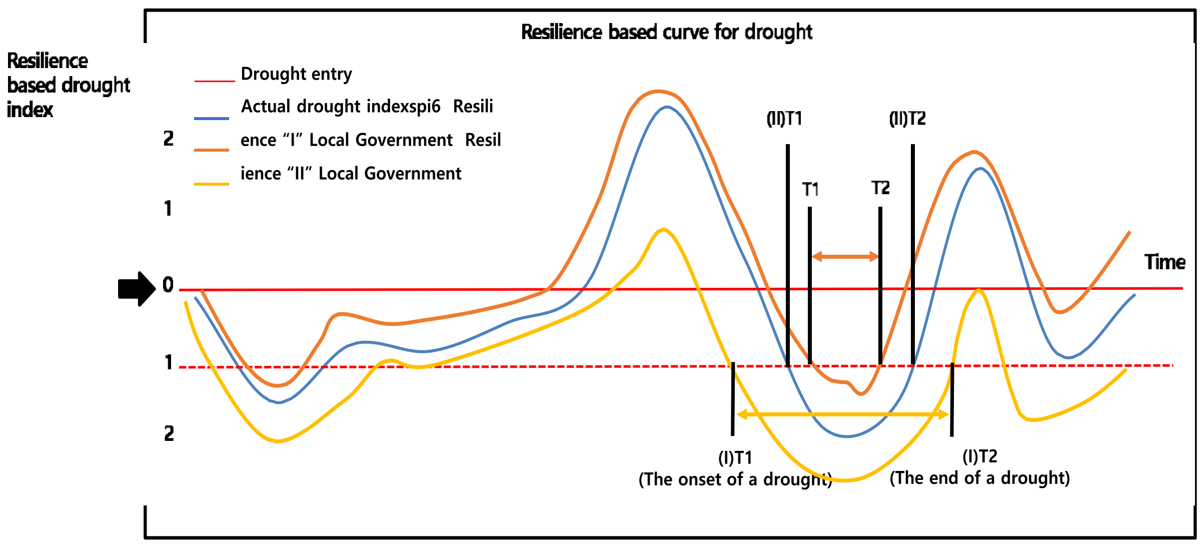


Quantitative Indicator

Qualitative Indicator

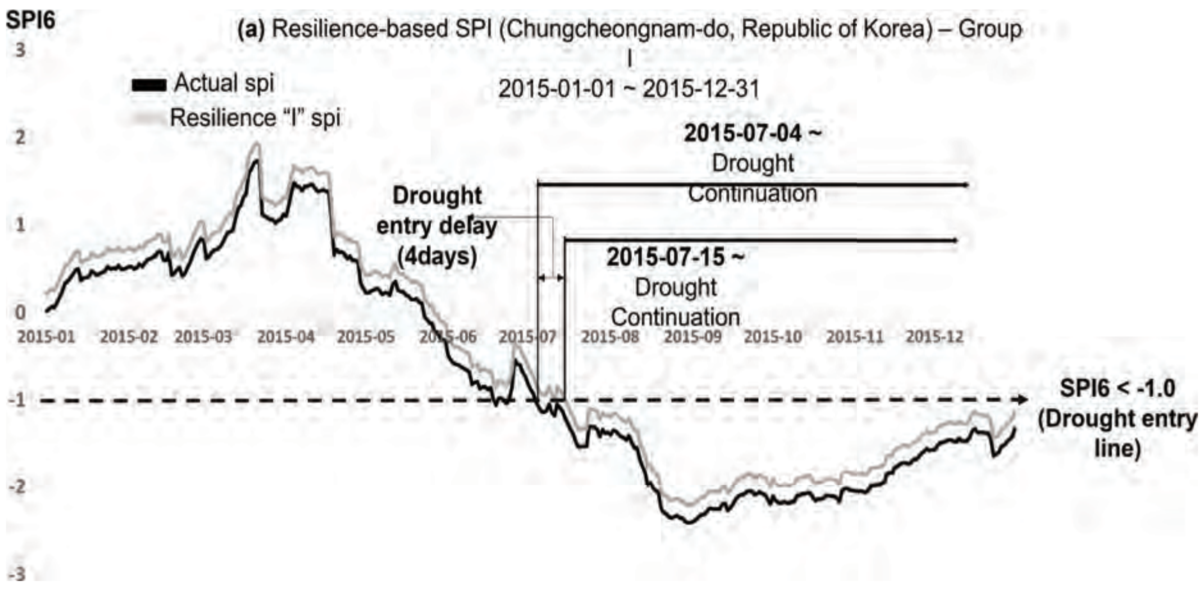
3.2 Applications for Drought Resilience Assessment

- Resilience-based curve for drought



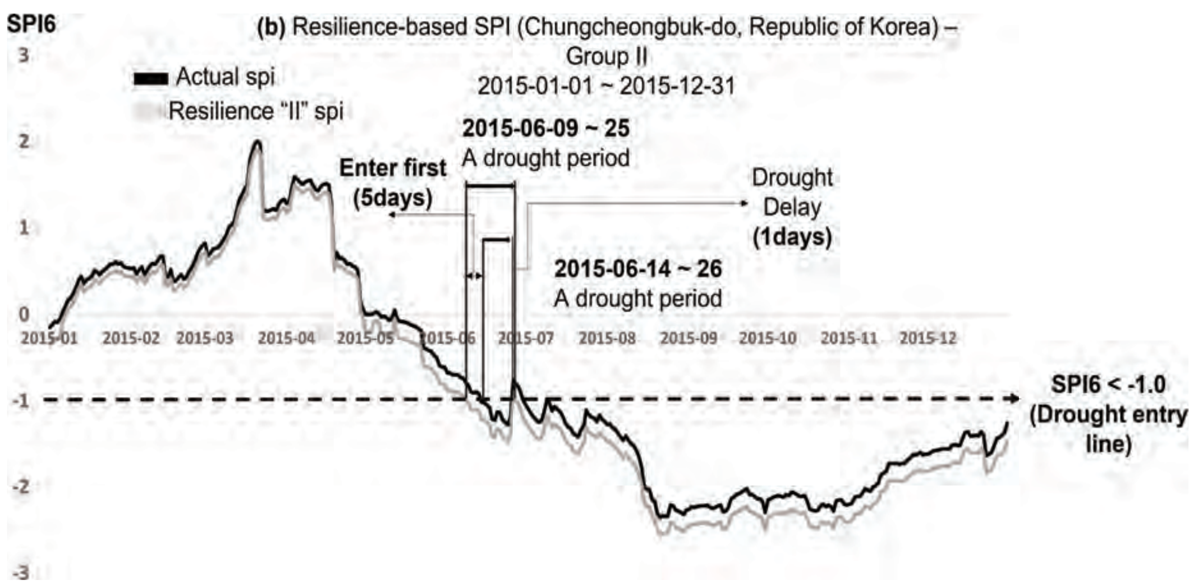
3.2 Applications for Drought Resilience Assessment

▪ **Resilience-based curve for drought**



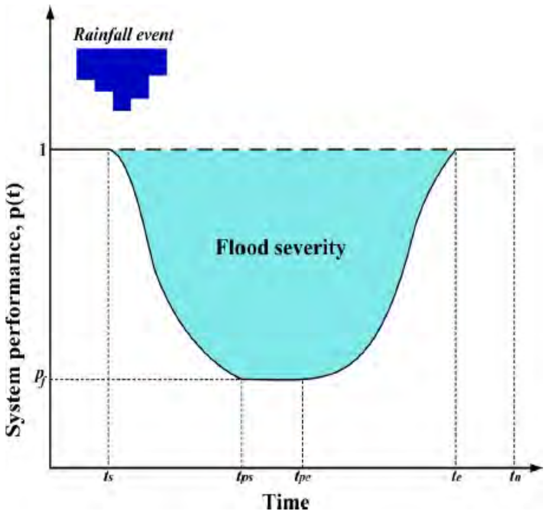
3.2 Applications for Drought Resilience Assessment

▪ **Resilience-based curve for drought**



3.3 Applications for Flood Resilience Assessment

- **Flood severity is an aggregated representation of the level of system damage during the entire process**



$$Sev = \frac{1}{t_n}\int_0^{t_n}[1 - p(t)]dt$$

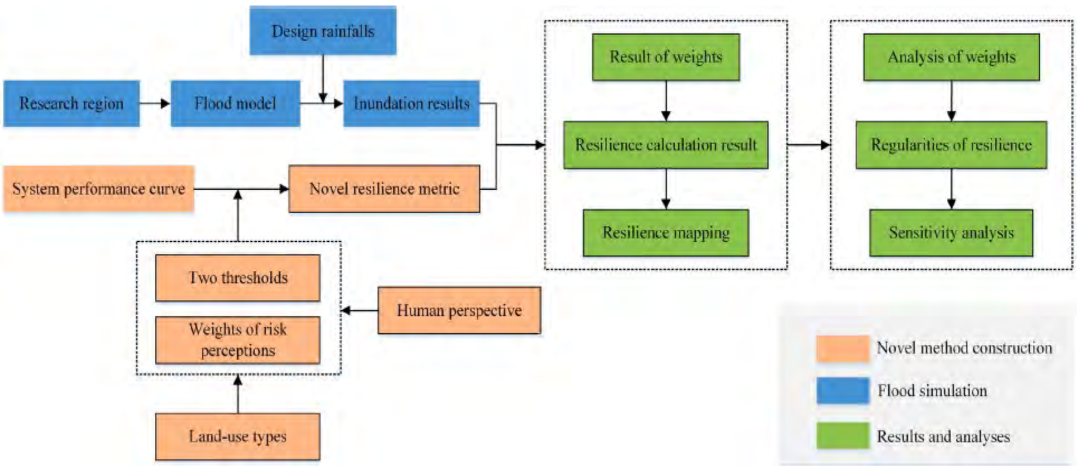
$$Sev = \frac{V_{TF}}{V_{TI}} \times \frac{t_f}{t_n} \qquad Res_0 = 1 - Sev = 1 - \frac{V_{TF}}{V_{TI}} \times \frac{t_f}{t_n}$$

- "Sev" is flood severity,
- "tn" is the total simulation time
- "Res0" is simplified metric by approximating the flood severity "Sev"
- "VTF" is the total flood volume,
- "VTI" is total inflow into adrainage system,
- "tf" is the mean duration offlooding across the entire network

* Wang, Y., Meng, F., Liu, H., Zhang, C., & Fu, G. (2019). Assessing catchment scale flood resilience of urban areas using a grid cell based metric. Water research, 163, 114852.
Chen, J., Chen, W., & Huang, G. (2021). Assessing urban pluvial flood resilience based on a novel grid-based quantification method that considers human risk perceptions. Journal of Hydrology, 601, 126601.

3.3 Applications for Flood Resilience Assessment

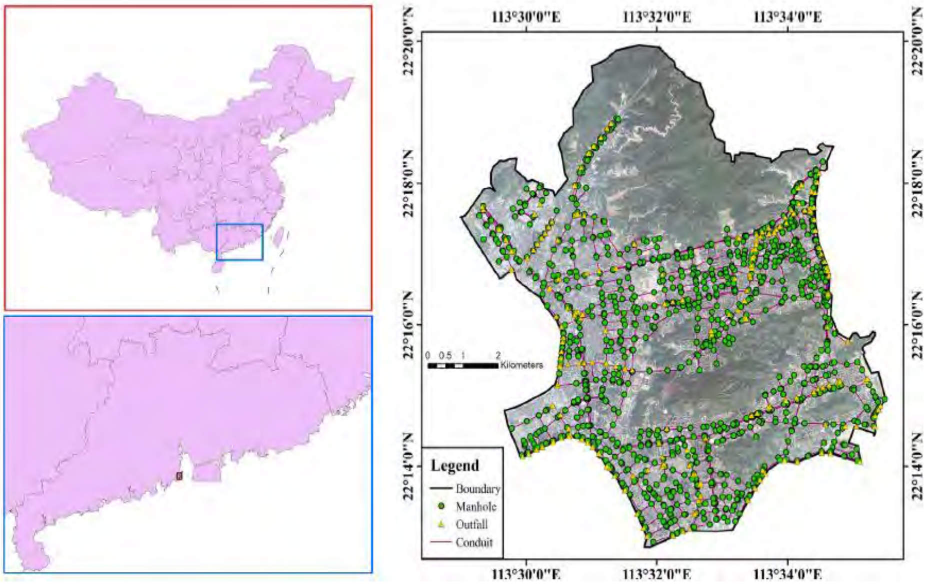
- **(Case Study -1) Flowchart of the urban flood resilience assessment**



* Chen, J., Chen, W., & Huang, G. (2021). Assessing urban pluvial flood resilience based on a novel grid-based quantification method that considers human risk perceptions. Journal of Hydrology, 601, 126601.

3.3 Applications for Flood Resilience Assessment

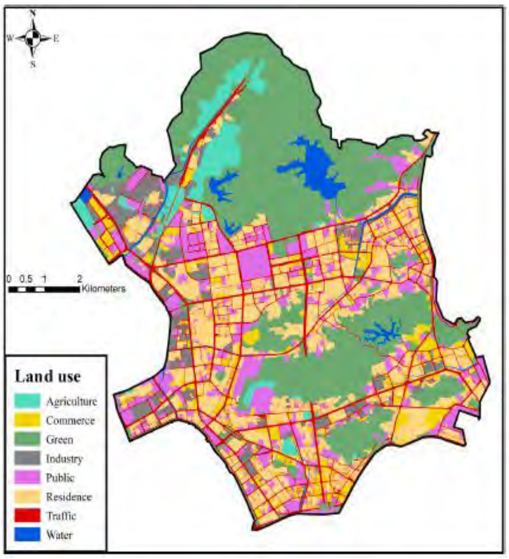
▪ (Case Study -1) Research region and sewer system

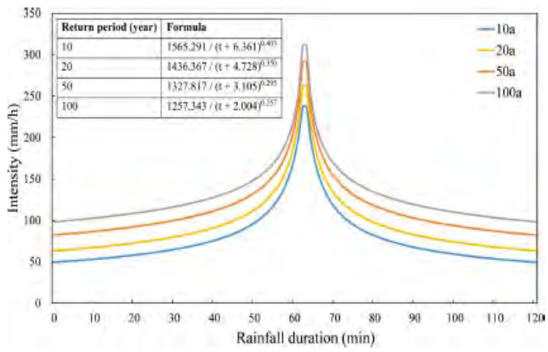


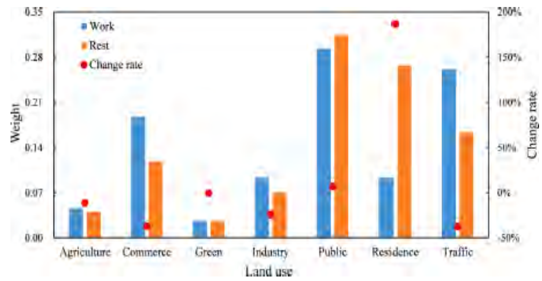
* Chen, J., Chen, W., & Huang, G. (2021). Assessing urban pluvial flood resilience based on a novel grid-based quantification method that considers human risk perceptions. Journal of Hydrology, 601, 126601.

3.3 Applications for Flood Resilience Assessment

▪ (Case Study -1) Research region and sewer system



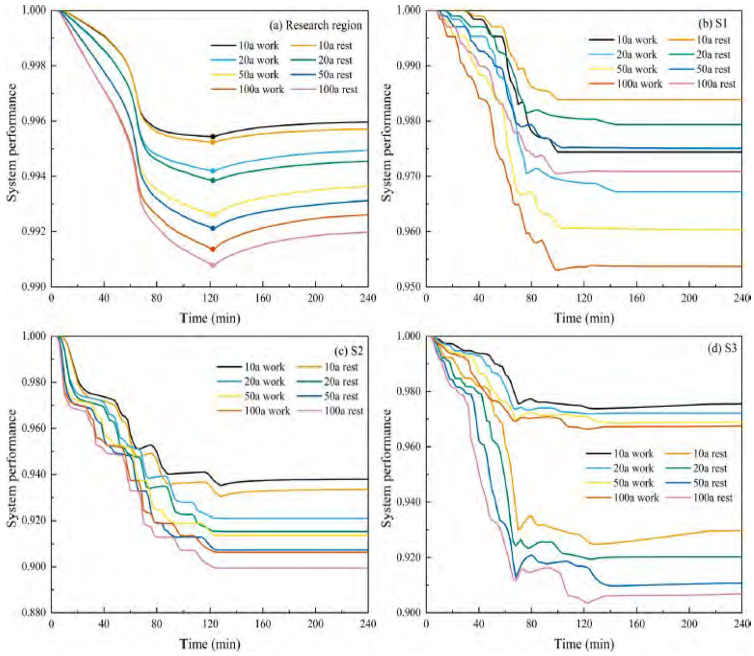




* Chen, J., Chen, W., & Huang, G. (2021). Assessing urban pluvial flood resilience based on a novel grid-based quantification method that considers human risk perceptions. Journal of Hydrology, 601, 126601.

3.3 Applications for Flood Resilience Assessment

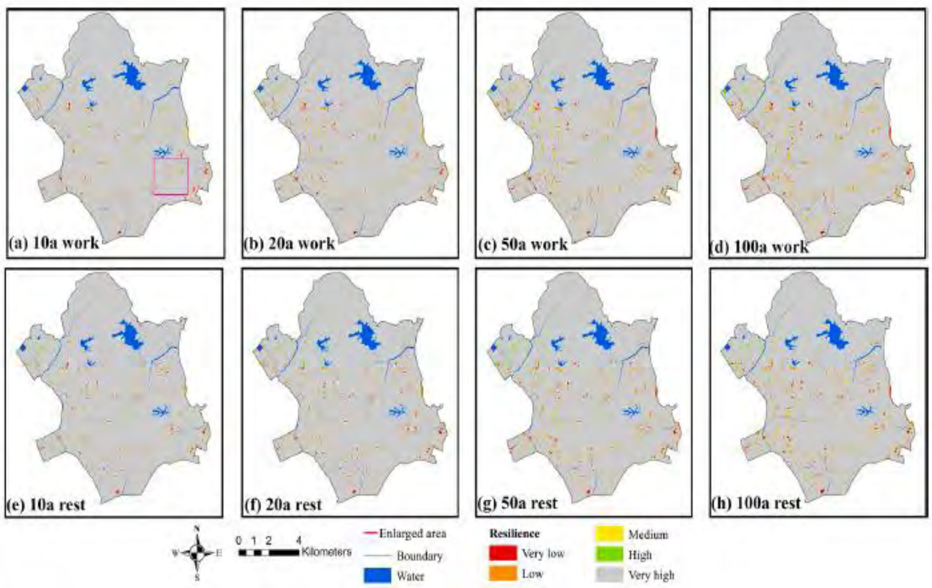
- **(Case Study -1) Performances of the research region and three sites for the eight scenarios**



* Chen, J., Chen, W., & Huang, G. (2021). Assessing urban pluvial flood resilience based on a novel grid-based quantification method that considers human risk perceptions. Journal of Hydrology, 601, 126601.

3.3 Applications for Flood Resilience Assessment

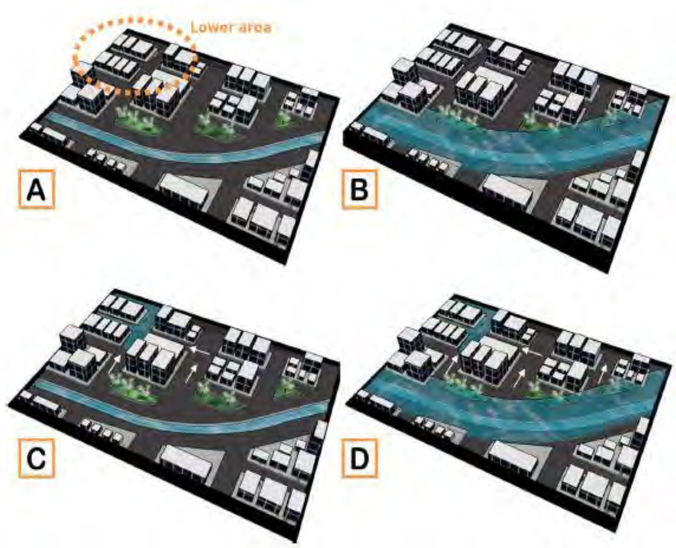
- **(Case Study -1) Spatial distributions of five resilience levels**



* Chen, J., Chen, W., & Huang, G. (2021). Assessing urban pluvial flood resilience based on a novel grid-based quantification method that considers human risk perceptions. Journal of Hydrology, 601, 126601.

3.3 Applications for Flood Resilience Assessment

▪ (Case Study -2) Types of urban landscape



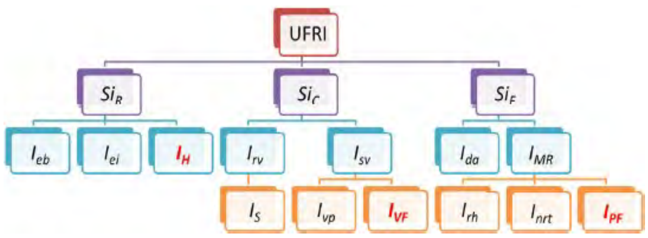
- *Urban landscape*

A.representing three flooding e vents.
B. represents a river overflow, that impacts only the fluvial path.
C.represents a drainage failure i n a lower area of the watershed, that depends on urban minor dr ainage network.
D.represents both phenomena. T he white arrows represent the s urface slope on the streets, indic ating the preferred direction of w ater flows.

* Rezende, O. M., de Oliveira, A. K. B., Jacob, A. C. P., & Miguez, M. G. (2019). A framework to introduce urban flood resilience into the design of flood control alternatives. Journal of Hydrology, 576, 478-493.

3.3 Applications for Flood Resilience Assessment

▪ (Case Study -2) Hierarchical arrangement of Urban Flood Resilience Index



Composition of the Urban Flood Resilience Index – UFRI.

Sub-index	Indicator	Sub-indicator
Si_R Sub-index of Risk to Resistance Capacity	I_{eb} – Building Exposure I_{ei} – Urban Infrastructure Exposure I_H – Flood Depth	
Si_C Sub-index of Risk to Material Recovery Capacity	I_{rv} – Relative Value I_{sv} – Social Vulnerability	I_S – Building Susceptibility I_{vp} – Vulnerability of People I_{VF} – Velocity Factor
Si_F Sub-index of Risk to System Maintenance Capacity	I_{da} – Aid Access Difficulty I_{MR} – Mobility Risk	I_{rh}- Road Hierarchy I_{nrt}- Non-Rail Transport Service I_{PF} – Permanence Factor

$$UFRI = a\bullet(1 - Si_R) + b\bullet(1 - Si_C) + c\bullet(1 - Si_F)$$

with, $Si_R \rightarrow$ *Risk to Resistance Capacity Sub-index*
$Si_C \rightarrow$ Risk to Material Recovery Capacity Sub-index
$Si_F \rightarrow$ Risk to System Functional Capacity Sub-index
a, b e $c \rightarrow$ weights of each term

- *Urban flood resilience index – UFRI*

(i)"absorptive capacity – the ability of the system to absorb the disruptive event", re presented by the Sub-index of Risk to Resi stance Capacity (SiR).

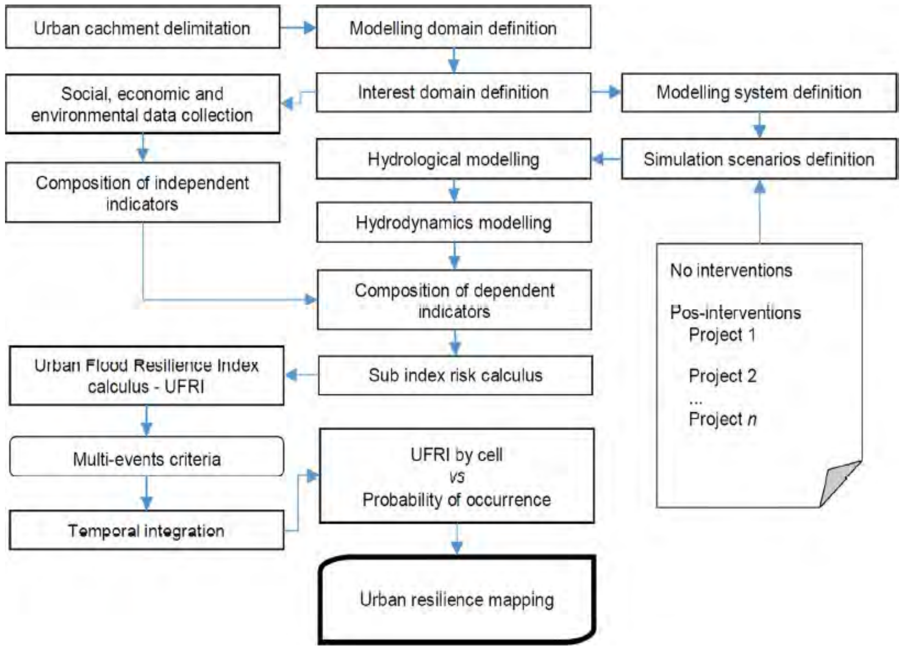
(ii)"adaptive capacity – the ability to ad apt to the event", represented by the Su b-index of Risk to System Functional Ca pacity (SiF).

(iii)"restorative capacity – the ability of th e system to recover", represented by the S ub-index of Risk to Material Recovery Cap acity (SiC)

* Rezende, O. M., de Oliveira, A. K. B., Jacob, A. C. P., & Miguez, M. G. (2019). A framework to introduce urban flood resilience into the design of flood control alternatives. Journal of Hydrology, 576, 478-493.

3.3 Applications for Flood Resilience Assessment

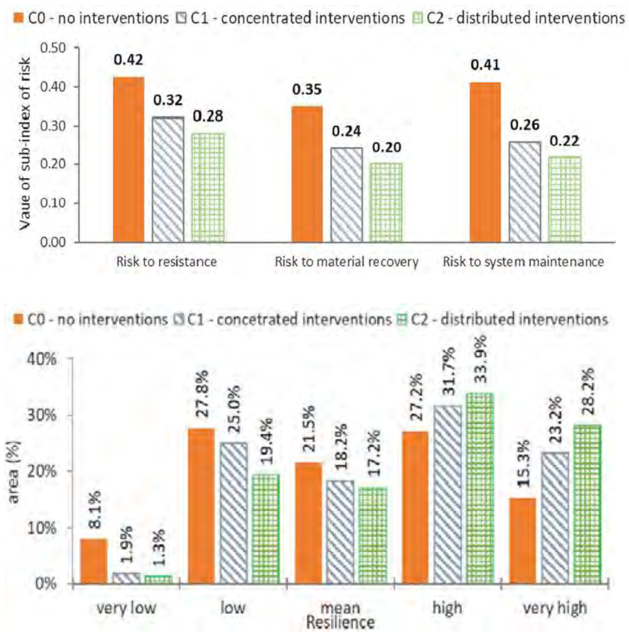
▪ (Case Study -2) Methodological framework to map urban flood resilience



* Rezende, O. M., de Oliveira, A. K. B., Jacob, A. C. P., & Miguez, M. G. (2019). A framework to introduce urban flood resilience into the design of flood control alternatives. Journal of Hydrology, 576, 478-493.

3.3 Applications for Flood Resilience Assessment

▪ (Case Study -2) Urban Flood Resilience for the three drainage system conditions



- *Three conditions of the drainage infrastructure system*

C0 – without interventions, reflecting the actual state of flooding in the urban catc hment.

C1 – with concentrated large interventions, based on a set of solutions proposed by the Drainage Master Plan of Rio de Janeiro City, published in 2010.

C2 – with distributed interventions over the watershed, based on the Canal do Mangue Flood Control Project, presented in 2000 (but not implemented).

* Rezende, O. M., de Oliveira, A. K. B., Jacob, A. C. P., & Miguez, M. G. (2019). A framework to introduce urban flood resilience into the design of flood control alternatives. Journal of Hydrology, 576, 478-493.

4. Resilient Drought and Flood Utilities

1. Resilience Strategies for Drought
2. Resilience Strategies for Flood

4.1 Resilience Strategies for Drought

▪ **Co-benefits of resilience strategies for drought**

	BENEFITS									
	AVOIDED INDIVIDUAL COSTS	AVOIDED COMMUNITY COSTS	AFFORDABILITY	LESS LANDSCAPE MAINTENANCE	ENERGY SAVINGS	ECOLOGICAL	SOCIAL AND HEALTH	ADAPTABLE IMPLEMENTATION	AGRICULTURAL	INCREASED AWARENESS
Indoor Conservation	●	●	●		▲	▲	▲	●		▲
Outdoor Conservation	●	●	●		▲	▲	▲	●		▲
City Planning	▲	▲	▲	▲	▲	▲	▲			
Conservation Ordinances	●	▲	▲	▲	●	▲				▲
Water Pricing	▲	●	▲		▲	▲	▲	●		▲
Landscape Rebates	●	▲	●	▲	▲	●	▲	●		▲
Plumbing Retrofit Rebates	●	▲	●		▲	▲	▲	●		▲
Community Leak Detection and Repair	▲	●	▲		▲	▲	▲	●	▲	
Public Education	▲	▲	▲	▲	▲	▲	●	●		●
Water Reuse/Recycling	▲	▲	▲		▲	▲	▲			
Desalination		▲				▲				
Urban-Rural Partnerships	▲	●	▲		●	●		●	▲	
Watershed Management	▲	▲	▲		▲	●	▲		▲	
Emergency Planning		▲					●			●

* US-EPA (2014) Flood resilience. A Basic Guide for Water and Wastewater Utilities.

- *The benefits of the strategies overviewed in the factsheet are summarized above, with g reen dots indicating a benefit that could be expected from each of the strategies.*
- *The yellow triangles indicate benefits and c osts that could apply in certain areas or circ umstances, especially if the strategy was de signed or implemented to that purpose.*
- *When weighing different strategies for use in a community, consider the greatest local vuln erabilities, which benefits would address the m and choose strategies that offer these ben efits. Be aware of gaps in benefits offered by the strategies prioritized.*

4.2 Resilience Strategies for Flood

- **Mitigation options for flood in water and wastewater utilities (example)**

- Practical mitigation measures

- Mitigation options for specific assets/operations

- *Practical Mitigation Measures*

- PREVENT INTRUSION OF FLOOD WATER
-PROTECT ASSETS AND OPERATIONS
- ENSURE POWER RELIABILITY

* Center for Climate and Energy Solutions (2018) RESILIENCE STRATEGIES FOR DROUGHT

4.2 Resilience Strategies for Flood

- **Mitigation options for flood in water and wastewater utilities (example)**

- Practical mitigation measures

- Mitigation options for specific assets/operations

BOOSTER STATIONS AND OTHER PUMPS (page 1 of 2)

✓ Drinking water

Flood waters can severely damage pumps, thereby impacting the entire drinking water system from intake through distribution. Similarly, loss of facility power could render pumps inoperable without adequate backup power. Vulnerable water facility control systems include pump controls, variable frequency drives, electrical panels, motor control centers and Supervisory Control and Data Acquisition (SCADA) systems.

See the following checklist for potential flood mitigation options for your utility booster station/pumps.

✓	Mitigation Options for Booster Stations and Other Pumps	Cost
1. Prevent booster stations from flooding.		
	a. Procure temporary flood barriers (e.g., sandbags) for use in minor floods.	$
	b. Install permanent physical barriers (e.g., flood walls, levees, sealed doors).	$$
2. Protect critical components if booster stations do flood.		
	a. During upgrades or design of new equipment, develop capability to temporarily remove and safely store vulnerable components in advance of a flood.	$-$$$
	b. Waterproof, relocate or elevate motor controls, variable frequency drives, computers and electrical panels to a higher elevation by constructing platforms or integrating controls into existing buildings or infrastructure on-site.	$$
	c. De-energize systems prior to flooding to mitigate damage to electrical components.	$
	d. Replace non-submersible pumps with submersible pumps, if cost effective.	$$-$$$
	e. Replace standard electrical conduits with sealed, waterproof conduits. Replace electrical panels with submersion rated enclosures.	$$$
	f. Install sump pumps for below-ground facilities. Although not typically used to protect against flooding events, sump pumps may provide additional time to take other mitigation measures.	$
	g. Replace a below-grade booster station with an above-grade station elevated higher than the flood stage.	$$$

- *Mitigation Options for Specific Assets/Operations*

- BUILDINGS
- CHEMICAL AND OTHER STORAGE
-INSTRUMENTATION AND ELECTRICAL CONTROLS
- POWER SUPPLY
-WATER INTAKE, DISTRIBUTION AND STORAGE
- BOOSTER STATIONS AND OTHER PUMPS
-DRINKING WATER TREATMENT PLANT

* Center for Climate and Energy Solutions (2018) RESILIENCE STRATEGIES FOR DROUGHT

4.2 Resilience Strategies for Flood

- **Mitigation options for flood in water and wastewater utilities (example)**

- Practical mitigation measures

- Mitigation options for specific assets/operations

DRINKING WATER TREATMENT PLANT (page 1 of 2)

Drinking water

Flood waters may inundate a treatment facility and wash out open tanks and filter beds, damage mechanical equipment, render electrical power and controls useless, spoil finished water storage, deposit debris on-site or wash contaminants into the treatment process. Flood waters may also alter source water chemistry and turbidity, posing treatment challenges to utilities that continue to operate during a flood. For example, residence times may need to be significantly longer following a flood to attain safe drinking water standards due to high turbidity and the potential influence of contaminants in the flood waters.

See the following checklist for potential flood mitigation options for your utility treatment plant.

✓	Mitigation Options for Drinking Water Treatment Plant	Cost
	1. Prevent structures from flooding.	
	a. Install physical barriers to protect the entire facility from flooding (e.g., flood walls, levees) or be able to deploy temporary systems that achieve the required protection.	$$-$$$
	b. Install green infrastructure within or beyond the boundaries of the treatment plant to attenuate, divert or retain flood water and storm surges.	$$-$$$
	c. Install flood water pumping systems and/or channel/culvert systems to collect and divert flood water away from treatment processes.	$$
	2. Protect critical components if the treatment plant does flood.	
	a. During upgrades or design of new equipment, develop capability to temporarily remove and safely store vulnerable components before a flood when there is enough advanced notice to do so.	$-$$$
	b. Install saltwater-resistant equipment and storage tanks (e.g., for chemicals and fuel).	$$
	c. Waterproof electrical components (e.g., pump motors, monitoring equipment) and circuitry.	$$
	d. Elevate, relocate or cap individual assets to prevent damage from flood waters; vertically extend the walls of a treatment structure (e.g., basin, tank, filter) above flood stage; and/or flood-proof/seal structures to prevent seepage of flood water into the treatment train.	$$$

- *Mitigation Options for Specific Assets/Operations*

- BUILDINGS

- CHEMICAL AND OTHER STORAGE

-INSTRUMENTATION AND ELECTRICAL CONTROLS

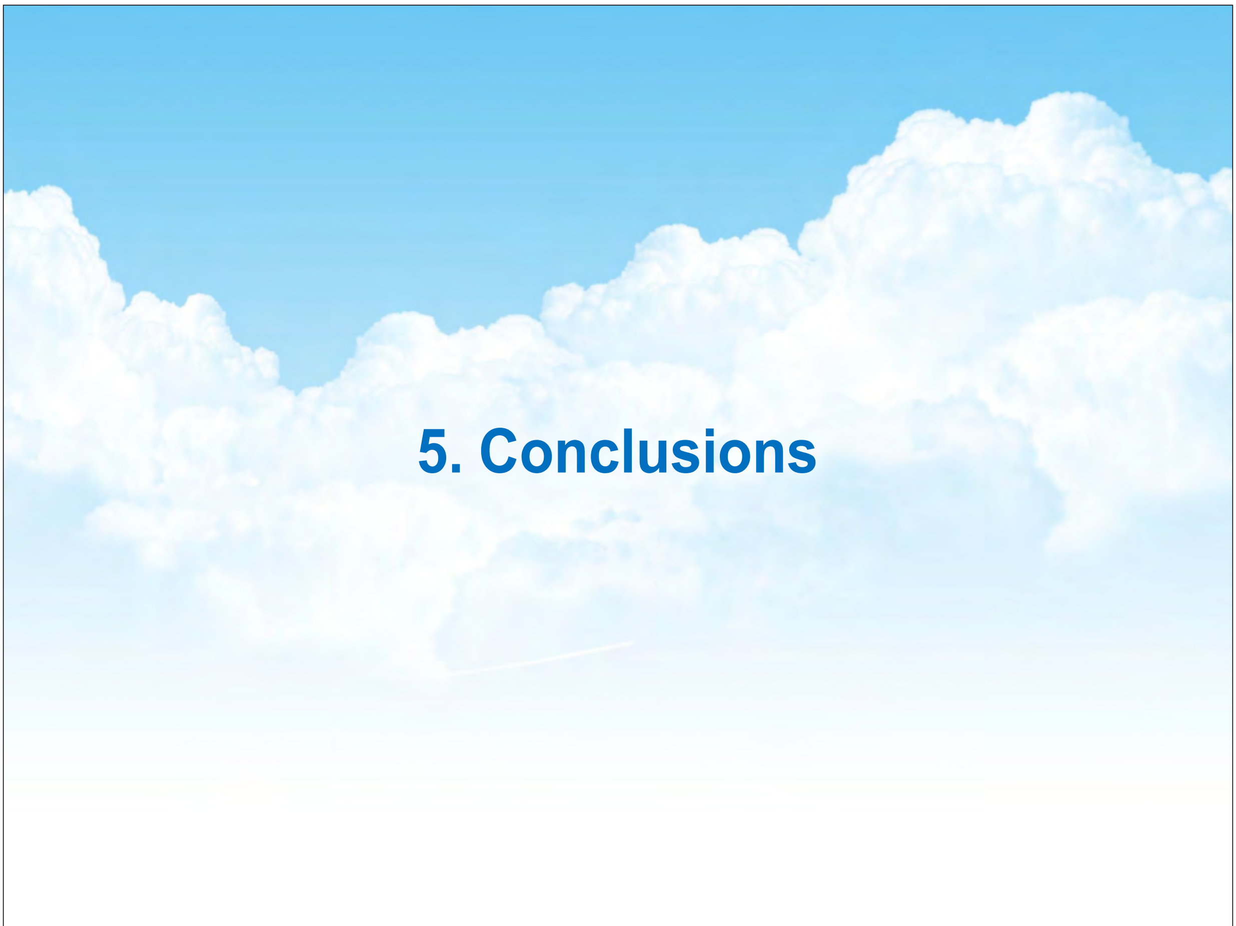
- POWER SUPPLY

-WATER INTAKE, DISTRIBUTION AND STORAGE

- BOOSTER STATIONS AND OTHER PUMPS

-DRINKING WATER TREATMENT PLANT

* Center for Climate and Energy Solutions (2018) RESILIENCE STRATEGIES FOR DROUGHT



5. Conclusions

8. Conclusions

- The emergence of resilience in multiple disciplines presents a challenge and opportunity in drought and flood risk management.
- Resilience is widely used in drought and flood risk management policies, but is still largely conceptual. But, research and applications in the last d ecade have focused on quantifying drought and flood resilience.
- Different frameworks of resilience will be briefly compared and their application in influence on drought and flood risk management were discussed.
- Some case studies were presented to illustrate their practical relevance in the developing and developed country.
- In order to understand the quantification method for resilience to drought and flood, it is necessary to understand in detail the quantification process of the cause of each disaster, damage, and extent of impact.

Thank you very much

Resilience of Drinking Water Infrastructure: Background

Water Security and System Resilience

5. Resilience of Drinking Water Infrastructure : Background

UNESCO | i-WSSM

United Nations Educational, Scientific and Cultural Organization | International Centre for Water Security and Sustainable Management

Aims & Objectives

- The aims of the course are to:

  (1) Explain the basic understanding drinking water infrastructure resilience
  (2) Explain threats to the drinking water infrastructure
  (3) Explain direct/indirect impact of drinking water infrastructure failure

- The objectives are that trainees will understand:

  (1) Mechanism of threats to water distribution system failure
  (2) Interdependency of water distribution system to other critical infrastructures

References

Drinking water distribution systems: assessing and reducing risks. (NAC, 2007)

Public Water Supply Distribution Systems: Assessing and Reducing Risks: First Report (NAC, 2005)

System Measures of Water Distribution System Resilience (USEPA, 2015)

Water sector resilience: Final Report and Recommendations (Baylis et al., 2016)

Contents

1. Understanding Resilience of Drinking Water Infrastructure
2. Characterizing Assets of Drinking Water Infrastructure
3. Characterizing Threats of Drinking Water Infrastructure
4. Direct Impacts of Water Distribution System
5. Cascading Impact of Water Distribution System
6. Closing Remarks

1. Understanding Resilience of Drinking Water Infrastructure

1. Drinking Water Infrastructure
2. Role of Water Distribution System
3. Problems of Drinking Water Infrastructure
4. Examples of Drinking Water Infrastructure Failure/Restoration
5. Review Concept of Resilience
6. Attribute of Resilience
7. Resilience Assessment

1.1 Drinking Water Infrastructure

- Historical Urban Water Advances

“. . . The greatest advances in improving h
uman health were the development of cle
an drinking water and sewage systems. S
o, we owe our health as much to civil engi
neering as we do biology.”

- Lewis Thomas, Former Dean of Yale Medical School &
Director of Memorial Sloan-Kettering Cancer Center

1.1 Drinking Water Infrastructure

- **Drinking Water Infrastructure and urban water keywords and associated modeling highlights**

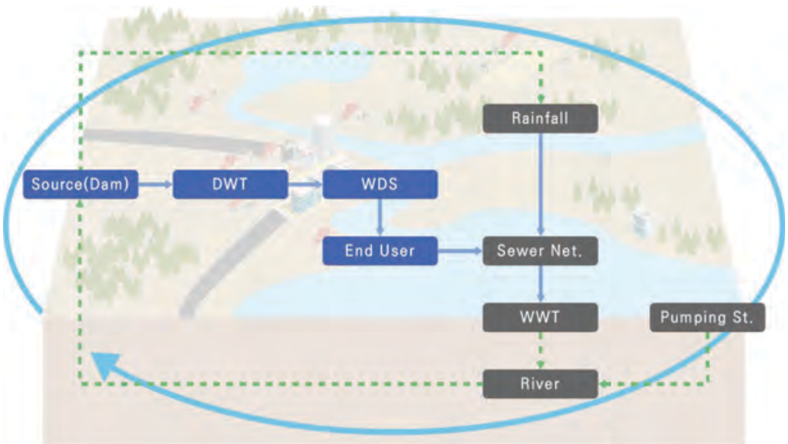
1.1 Drinking Water Infrastructure

- **Drinking water infrastructure includes the physical components that compr ise a water utility's source of supply, treatment, storage, transmission and di stribution systems**
  - Drinking water infrastructure system is made up of 2.2 million miles of underground pipes that deliver safe, reliable water to millions of people

Metrovancouver. Taken from http://www.metrovancouver.org/services/water/about/regional-system/Pages/default.aspx/, at 2021/09/05

1.1 Drinking Water Infrastructure

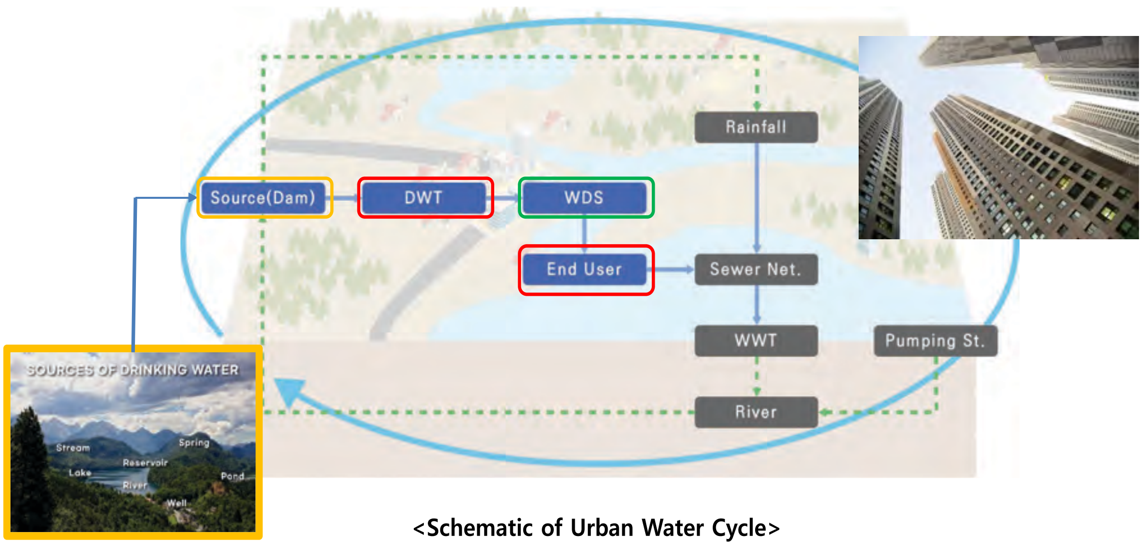
- Extraction from Source, treat extracted water at drinking water treatment (DWT), distribute treated water with water distribution system (WDS) to various end users



<Schematic of Urban Water Cycle>

1.1 Drinking Water Infrastructure

- Sources
  - Water source can be stream, reservoir, spring, pond, lake, river, well, etc.

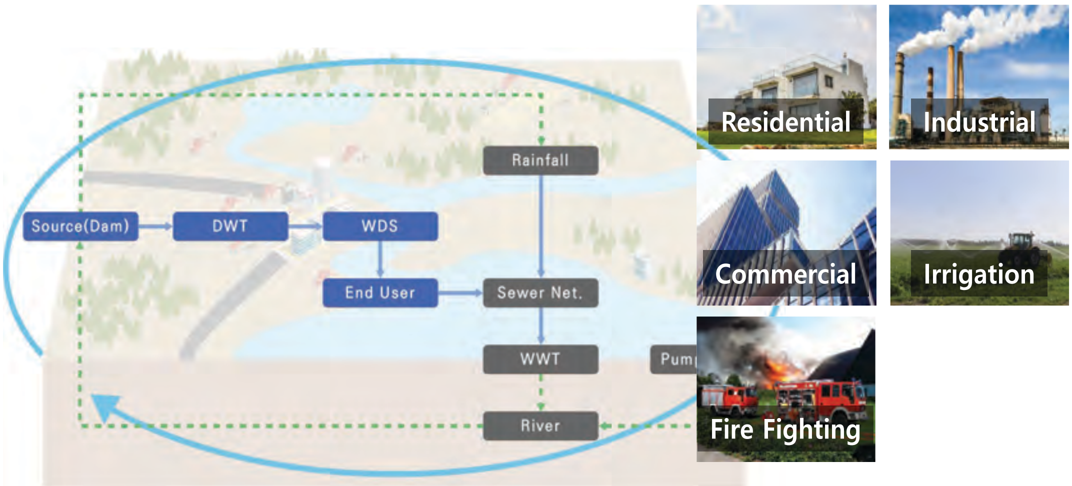


<Schematic of Urban Water Cycle>

1.1 Drinking Water Infrastructure

12p, 54p 동일 이미지 수정

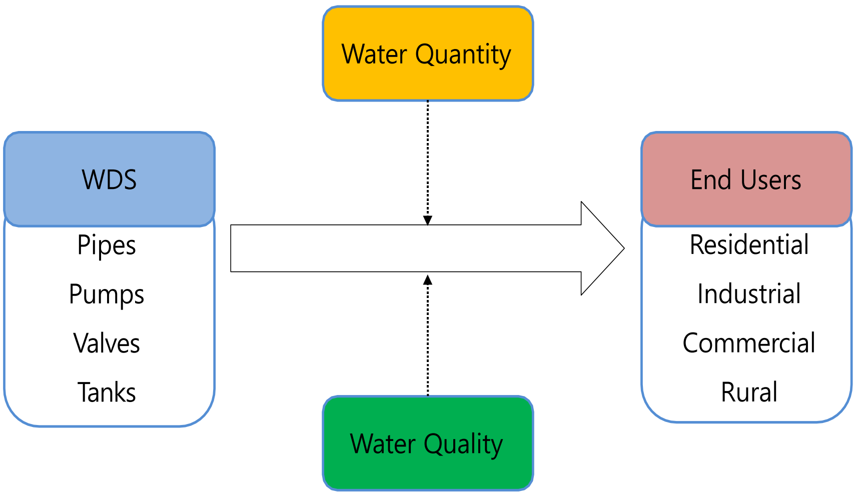
- End users
  - Various end use purposes, residential, industrial, commercial, irrigation (both rural and urban), fire fighting, etc.



<Schematic of Urban Water Cycle>

1.2 Role of Water Distribution System

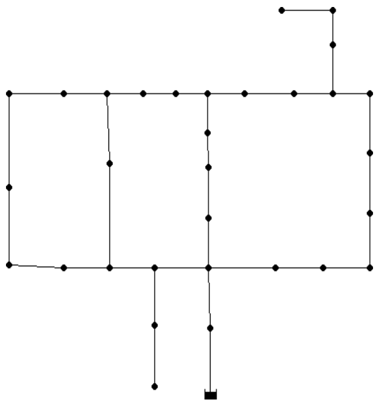
- "including all water utility components for the distribution of finished or potable water by means of gravity storage feed or pumps though distri bution pumping networks to customers or other users, including distrib ution equalizing storage" (AWWA, 1974)



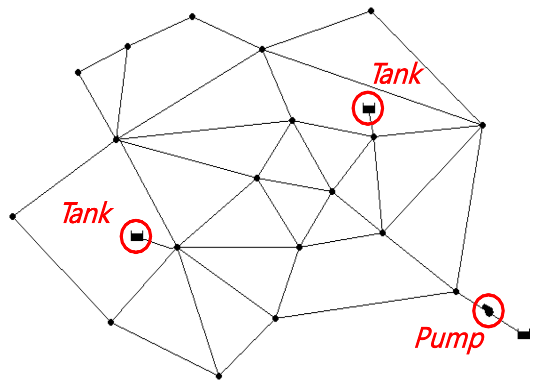
1.2 Role of Water Distribution System

▪ Water Distribution Network vs. Water Distribution System

Water distribution network



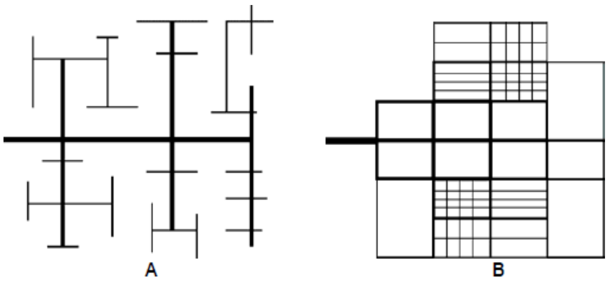
Water distribution system



Water distribution networks (WDNs) are limited to the pipe network, whereas water distribution systems include pumps and tanks as well as the piping net work (Hwang & Lansey, 2017)

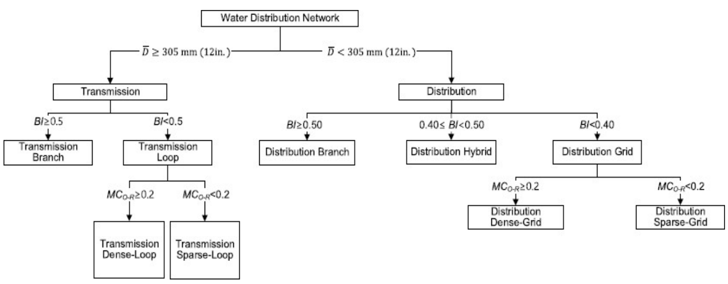
1.2 Role of Water Distribution System

▪ Configuration of Water Distribution System



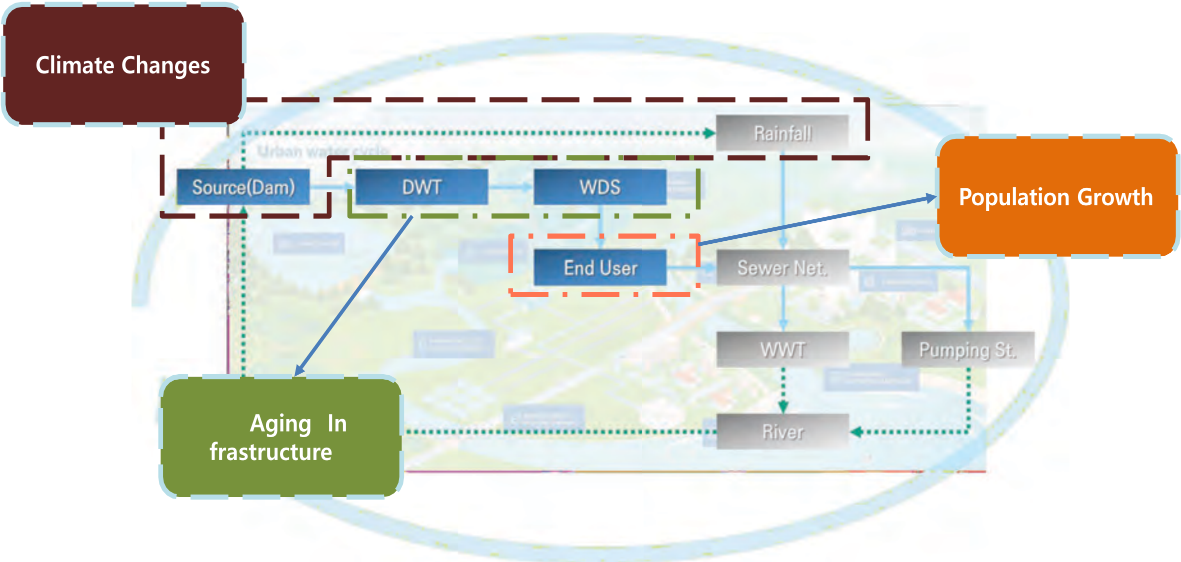
Two Basic Configurations for Water Distribution Systems. (A) Branched configuration. (B) Looped configur ation.
(NRC, 2007)

Water Distribution System Classification Flowchart (Hwang & Lansey, 2017)



1.3 Problems of Drinking Water Infrastructure

- **Aging infrastructure, climate changes, population growth, and competing resource priorities within the communities they serve, etc.**



<Urban Water Cycle>

1.3 Problems of Drinking Water Infrastructure

- **A drinking water infrastructure can be partitioned into three major groups according to the methods necessary for enhancing their security**
  1. a **direct attack** on the main infrastructure: dams, treatment plants, storage reservoirs, pipelines, etc.
  2. a **cyber attack** disabling the functionality of the water utility supervisory control and data ac quisition (SCADA) system, taking over control of key components that might result in water o utages or insufficiently treated water, or changing or overriding protocol codes, etc.
  3. a deliberate chemical or biological **contaminant injection** at one of the system's nodes

Direct Attack

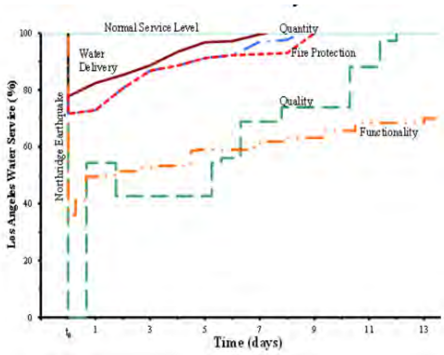
Cyber Attack

Contaminant Injection

1.4 Examples of Drinking Water Infrastructure Failure/Restoration

▪ 1994 Northridge Earthquake Case

- The most significant water losses were in the highly residential San Fernando Valley impacting water services to an estimated 850,000 people, 670,000 of which lost water delivery for some period of time
- Water delivery service dropped to about 78%, with 22% of all Los Angeles customers receiving no water shortly after the earthquake due to water leaking from broken pipes
- Total water system repair costs reached $41 million
- It took 6 years to return Functionality to 99% after completing a number of tank and reservoir repairs and replacements

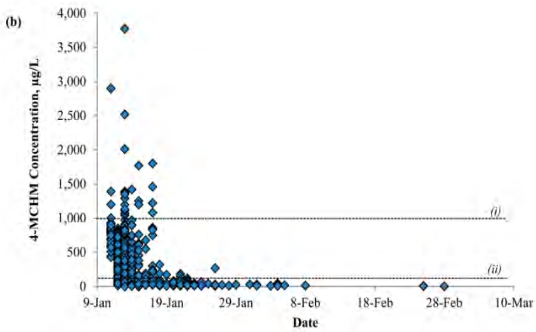


[Water system service restoration (source: Davis, 2015)]

1.4 Examples of Drinking Water Infrastructure Failure/Restoration

▪ 2014 Elf River Chemical Spill Case

- More than 10,000 gallons of a coal cleaning liquid spilled from two above-ground storage tanks into the Elk River
- Potable water with a distinct black-liquorice smell was distributed to 300,000 people on January 9 through 2,200 miles of water distribution pipe, 107 storage tanks, and 120 booster stations across 124 pressure zones to upwards of 90,000 buildings.
- Spent more than $12 million, is facing approximately 54 lawsuits, and considering the installation of source water monitoring equipment
- Impact lasted more than 11 months



[4-MCHM monitoring results (source: Whelton et al, 2015)]

1.5 Review Concept of Resilience

- **Definitions from Oxford Languages**
  1. The capacity to recover quickly; toughness
  2. The ability of a substance or object to spring back into shape; toughness

[Words related to resilience]

1.5 Review Concept of Resilience

- **Resilience definition for different system**

System	Summary of definitions
Ecological system	• Ability to absorb disruption and still maintain the original state or domain of attraction with self-organization
Social/ community system	• Ability of people, groups or communities to withstand disruption, recover from the emergencies, and adapt by changing non-essential attributes
Disaster/ hazard/ engineering system	• Ability to anticipate, prepare for, respond to single or multi hazardous event and rapidly recover to the general and original in a timely and efficient manner
Safety management system	• Ability to respond to unanticipated dangers and recover critical functions and services with minimum damage to public safety and health
Economics	• Ability to cope with market or environmental shocks with minimal or without economic losses and failures of resources allocation
Organization	• Ability of individual or organization to manage and implement positive adaptive behaviors corresponding to disruptive situation with minimal stress

Source : Bruneau et al. (2003), Kendra and Wachtendorf (2003), Rose and Liao (2005), Manyena (2006), Mayunga (2007),Cutter et al. (2008), McDaniels et al. (2008), Norris et al. (2008), Cimellaro et al. (2010), Ouyang et al. (2012), Pflanz and Levis (2012), Tamvakis and Xenidis (2013).....

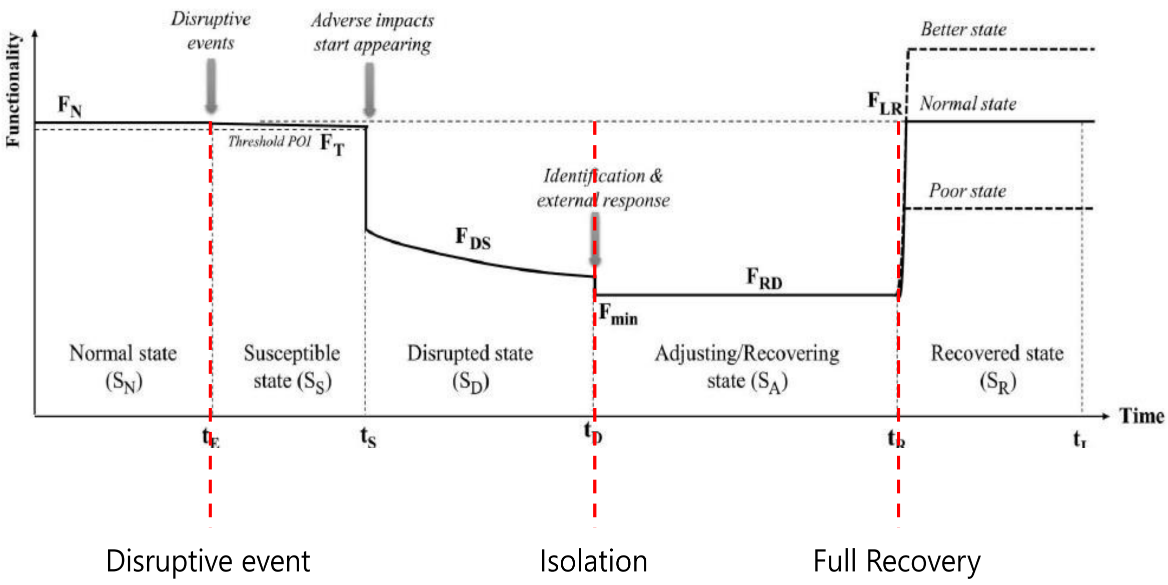
1.5 Review Concept of Resilience

- **Resilience definition in water systems**

- (Hashimoto et al., 1982) Ability to quickly *recover* or *bounce back* from **failure**
- (Lansey, 2012) Ability to *gracefully degrade* and *subsequently recover* from a **potentially catastrophic disturbance**
- (Turnquist and Vugrin, 2013) Ability to *withstand*, *adapt to*, and *rapidly recover* from the effects of a **disruptive event**
- (U.S. EPA, 2015) Ability of the human organizations that manage water to design, maint ain, and operate water infrastructure (e.g., water sources, treatment plants, storage tanks , and distribution systems) in such a way that *limits the effects* of **disasters** on the water infrastructure and the community it serves, and *enables rapid return* to normal delivery of safe water to customers

1.5 Review Concept of Resilience

- **Functionality (system performance) changes to disruptive events and recovery action**



Source: Shin et al (2020)

1.6 Attribute of Resilience

- **Resilience can be defined by the following 4 attributes** (Bruneau and Reinhorn, 2007; Minsker et al., 2015):
  - Robustness
  - Redundancy
  - Resourcefulness
  - Rapidity

Robustness:
The ability of the system to withstand a level of stress without suffering degradation or loss of function

Redundancy:
The ability to substitute parts in the system that is affected to maintain functionality

Resourcefulness:
The ability to identify, prioritize problems, and allocate resources to recover from stress

Rapidity:
The capacity to recover and achieve goals quickly in order to limit loss and prevent future disruptions

1.6 Attribute of Resilience

- **Capabilities of Resilience (Francis and Bekera 2014; Hosseini et al. 2016; Meerow et al. 2016; Shin et al. 2020):**
  - Withstanding
  - Absorptive
  - Adaptive
  - Restorative

Withstanding:
The ability of a system to withstand disruptions and maintain performance within an acceptable state

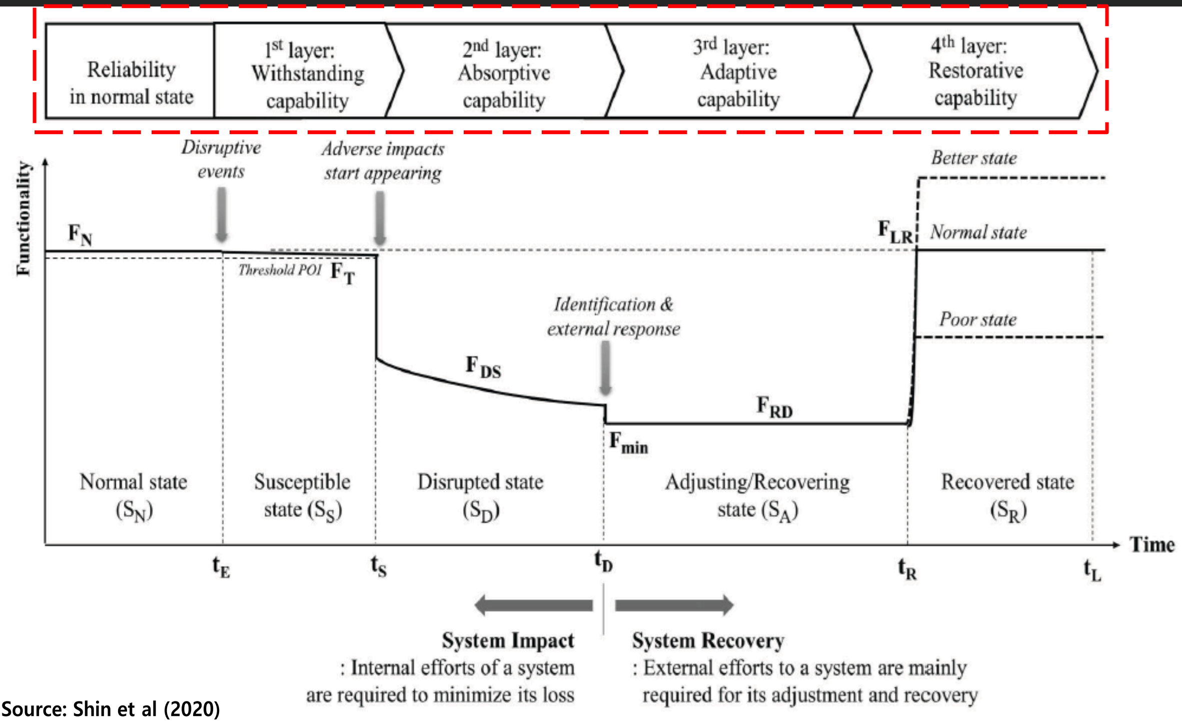
Absorptive:
The ability of a system to minimize adverse consequence when failing to avoid disruptions

Adaptive:
The ability of a system to adjust to its disrupted, undesirable conditions through internal or external response efforts

Restorative:
The ability of a system to recover disrupted performance quickly and completely to the normal state

1.6 Attribute of Resilience

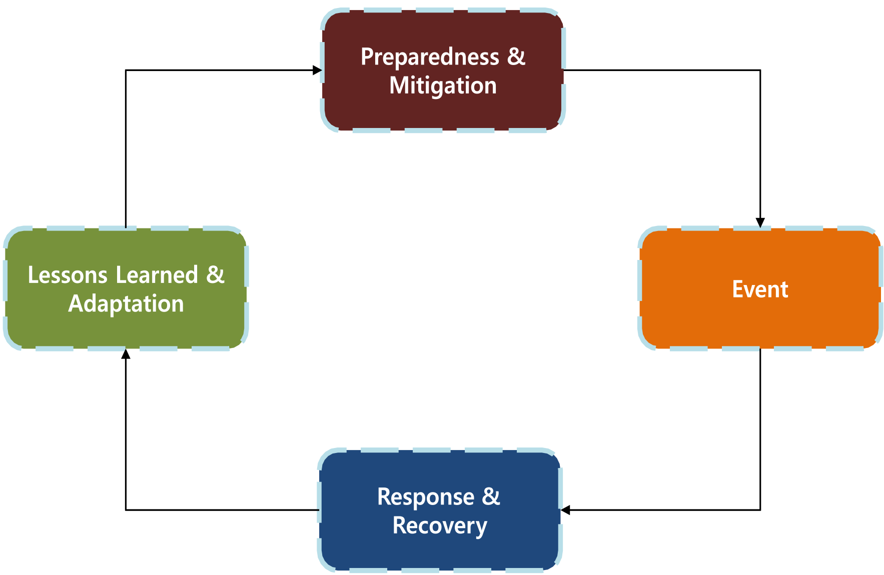
▪ Capabilities of Resilience



Source: Shin et al (2020)

1.7 Resilience Assessment

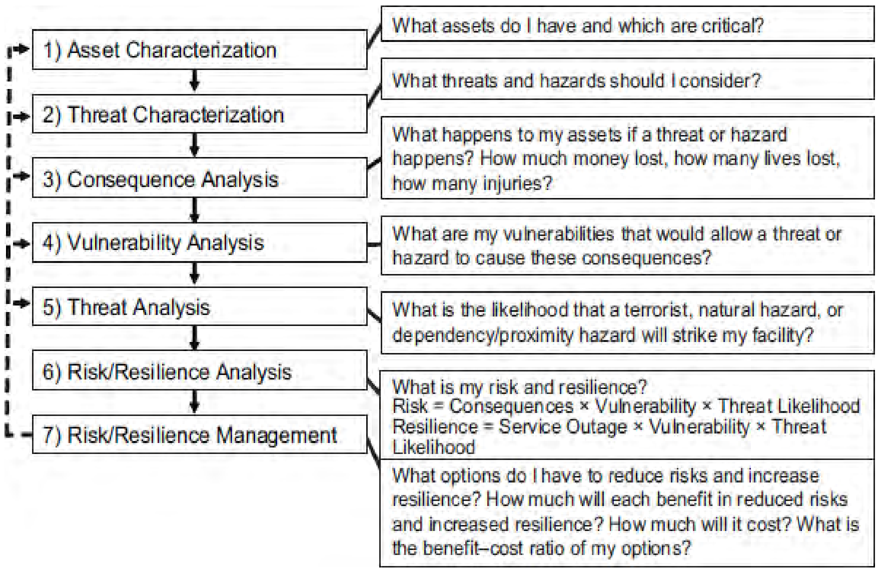
▪ Continuous cycle of building resilience to hazards



U.S. EPA (2015)

1.7 Resilience Assessment

- RAMCAP (Risk Analysis and Management for Critical Asset Protection)



AWWA (2010)

2. Characterizing assets of Drinking Water Infrastructure

1. Why need to know assets?
2. Pipes
3. Valves
4. Pumps
5. Tanks
6. ICT Devices

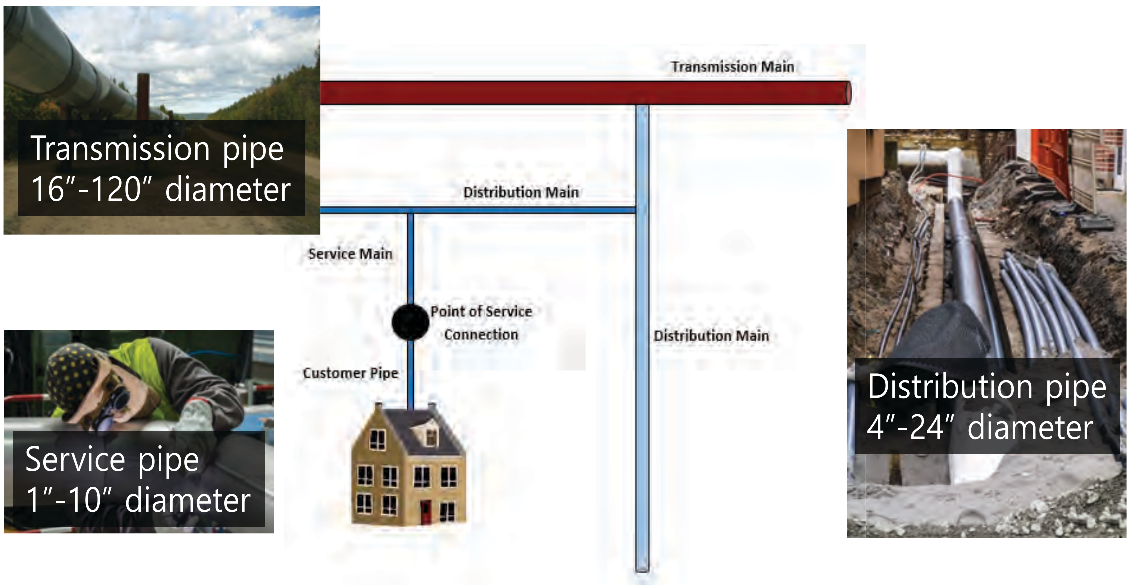
2.1 Why need to know assets?

- **What is asset?**

  - **Something of importance or value** that if *targeted, exploited, destroyed,* or *incapacitated* could result in *injury, death, economic damage* to the owner of the asset or to the community it serves, *destruction of property,* or could profoundly damage a nation's prestige and confidence.
  - Assets may include **physical elements** (tangible property), **cyber elements** (information and communication systems), and **human or living elements** (critical knowledge and functions of people).
  - **Critical Asset** is an asset whose absence or unavailability would significantly *degrade the ability of a utility to carry out its mission* or would have unacceptable *financial or political consequences* for the owner or the community.

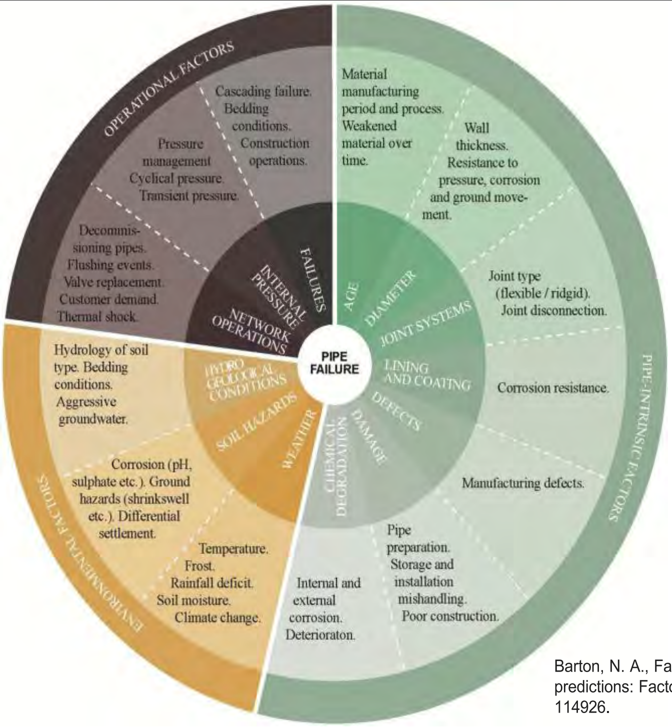
2.2 Pipes

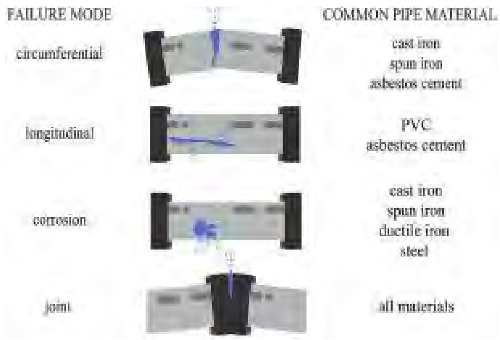
- **Main asset of drinking water infrastructure that convey water from one point in the network to another**



2.2 Pipes

- **Failure(breakage) of pipe induced by multiple reasons …**

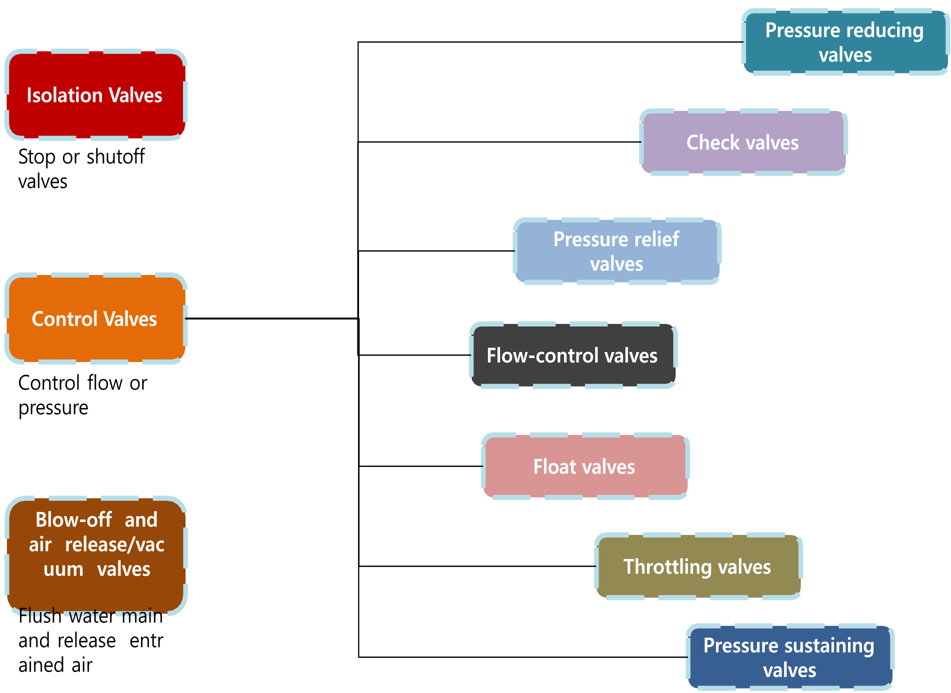




Barton, N. A., Farewell, T. S., Hallett, S. H., & Acland, T. F. (2019). Improving pipe failure predictions: Factors affecting pipe failure in drinking water networks. *Water research*, *164*, 114926.

2.3 Valves

- **Links limiting the pressure or flow at a specific point in the network**

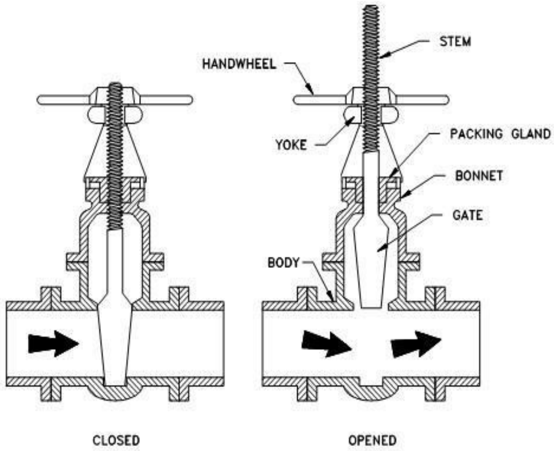


2.3 Valves

- **Links limiting the pressure or flow at a specific point in the network**

When Normal Operation

- Isolating section of a water main/wastewater collection line
- Draining water/wastewater line
- Throttling liquid flow
- Regulating water/wastewater storage levels
- Controlling water hammer
- Controlling bleed off of air
- Preventing backflow



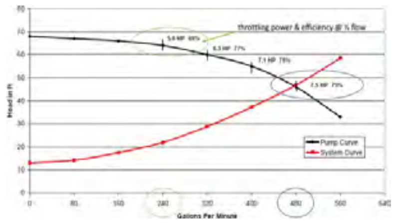
When Valve Fails...

- Mainly nothing can't be done when it was normal operation

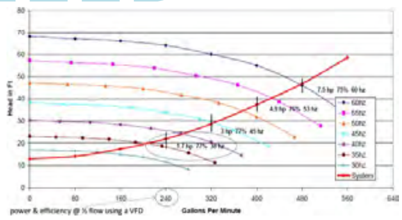
2.4 Pumps

- **Links impart energy to a fluid thereby raising its hydraulic head**
  - Major electrical energy consumption assets

Constant speed pump



Variable speed pump



2.4 Pumps

- **Links impart energy to a fluid thereby raising its hydraulic head**
  - Major electrical energy consumption assets

Why pump fails...

- Physical damage to pump itself
- Electricity outage
- Unauthorized access/changes

And when pump fails...

- Water shortage at the downstream area of the pump unless having an alternative ro ute

2.5 Tanks

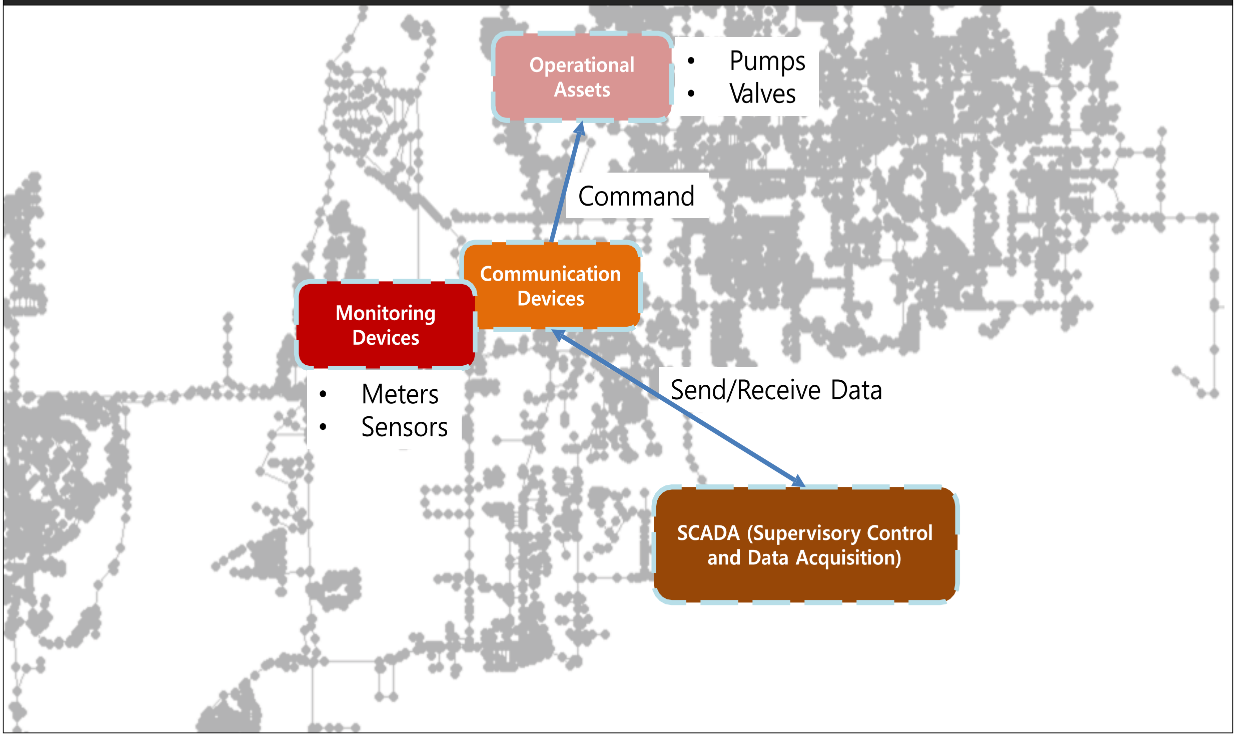
- **Nodes with storage capacity, where the volume of stored water can vary with time during a simulation**
  - Enable demand management
  - Assure water supply in case of system failure and reserves for emergencies such as firefighting
  - Allow for the modulation of pump flow rate

Elevated Tank

Buried Tank

2.6 ICT Devices

- Paradigm shift to smarter water distribution system

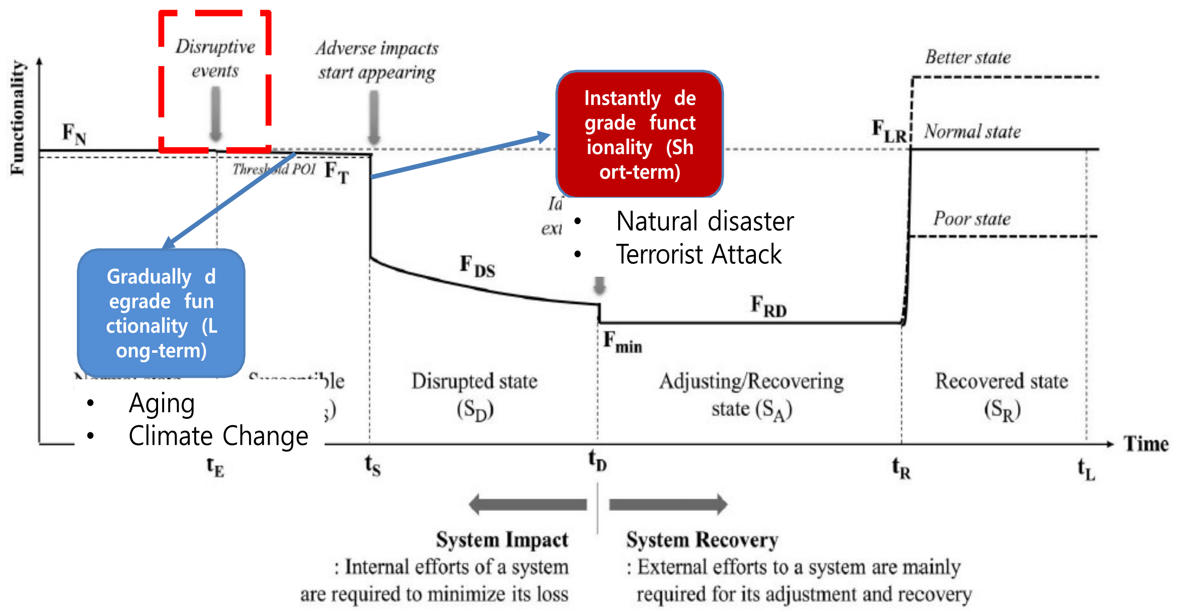


3. Characterizing Threats of Drinking Water Infrastructure

1. Types of Disruption
2. Physical Integrity Loss
3. Hydraulic Integrity Loss
4. Water Quality Integrity Loss
5. Cyber Components Failure

3.1 Type of Disturbances

- **Drinking water systems have been significantly impacted by natural disasters and hazardous releases**



Source: Shin et al (2020)

3.1 Type of Disturbances

- **Potential Hazards**

  - Directly vs. indirectly damage drinking water infrastructure

Climate Change

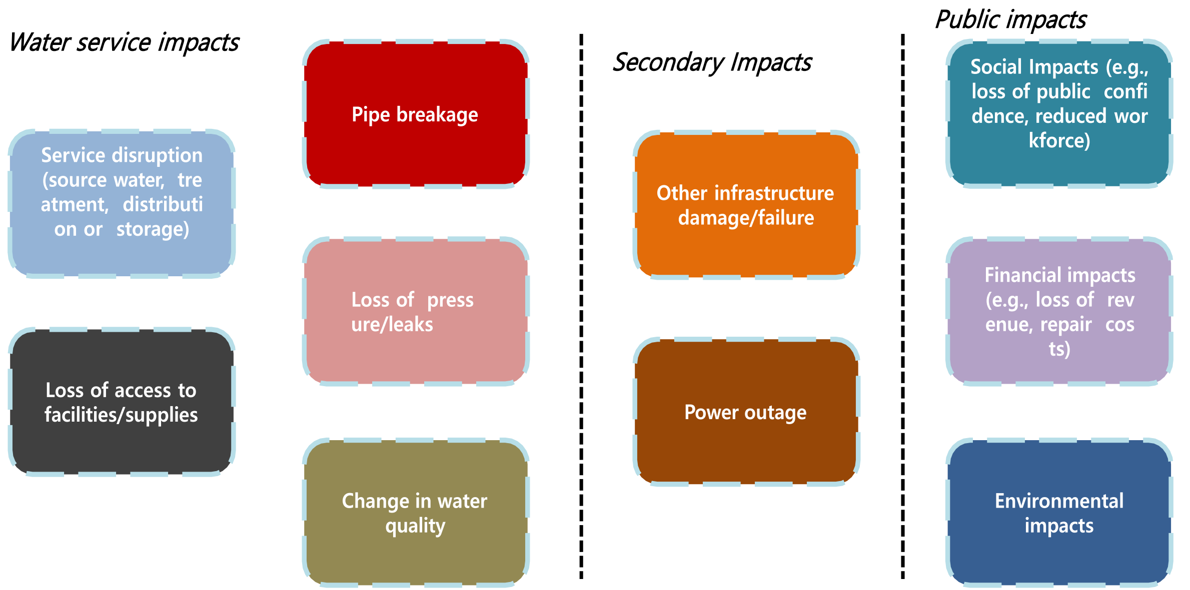
Terrorist Attack
- Physical attack
- Chemical attack
- Cyber attack

Natural Disaster
- Drought
- Earthquakes
- Floods
- Hurricanes
- Tornados
- Tsunamis
- Wildfires
- Winter Storms

Aging Infrastructure

3.1 Type of Disturbances

- **Potential Impacts**
  - Physical, hydraulic, water quality impacts
  - Cascading (or secondary) impacts
  - Public impacts

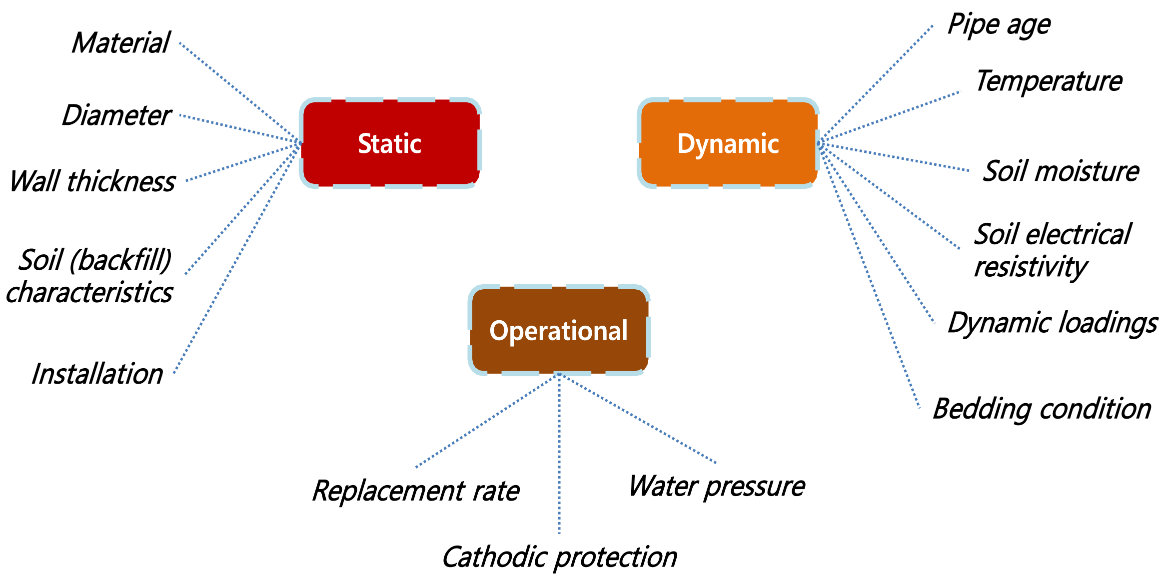


3.2 Physical Integrity Loss

- **The loss of physical integrity is when the system no longer acts as a barrier that prevents external contamination from deteriorating the internal, drinking water supply**

3.2 Physical Integrity Loss

- Factors affecting pipe breakage rates …



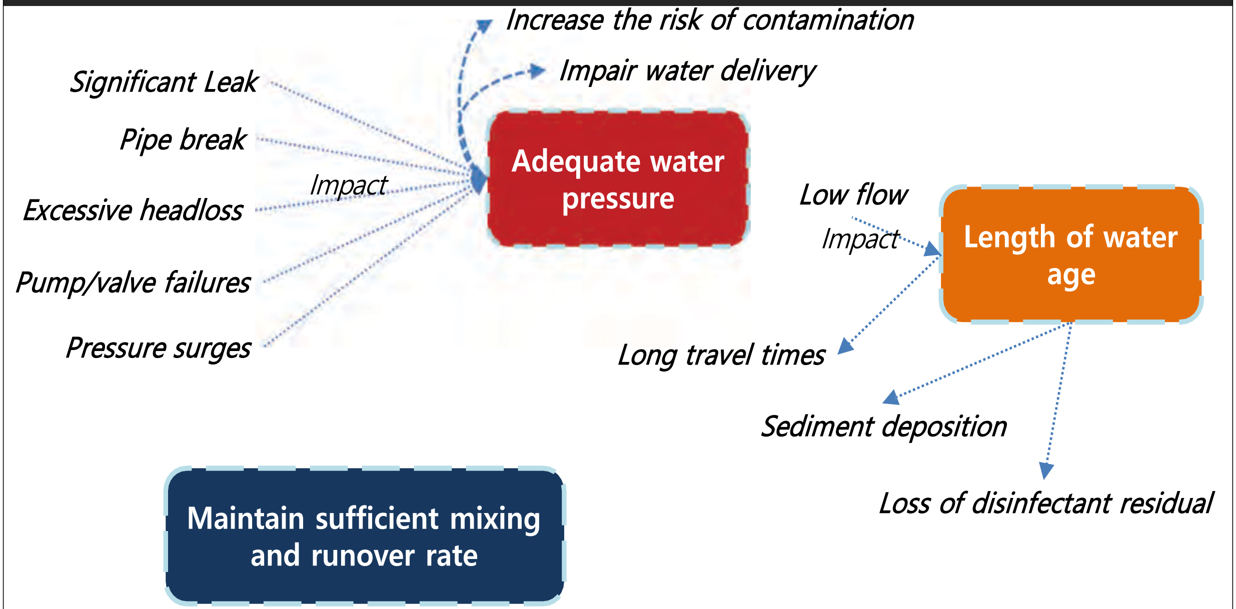
3.2 Physical Integrity Loss

- Recommendations for maintaining and restoring physical integrity

  - Storage facilities should be inspected on a regular basis
  - Better sanitary practices are needed during installation, repair, replacement, and rehabilitation of distribution system infrastructure
  - External and internal corrosion should be better researched and controlled in standardized ways

3.3 Hydraulic Integrity Loss

▪ **Maintaining the hydraulic integrity of distribution systems is vital to ensuring that water of acceptable quality is delivered in acceptable amounts**



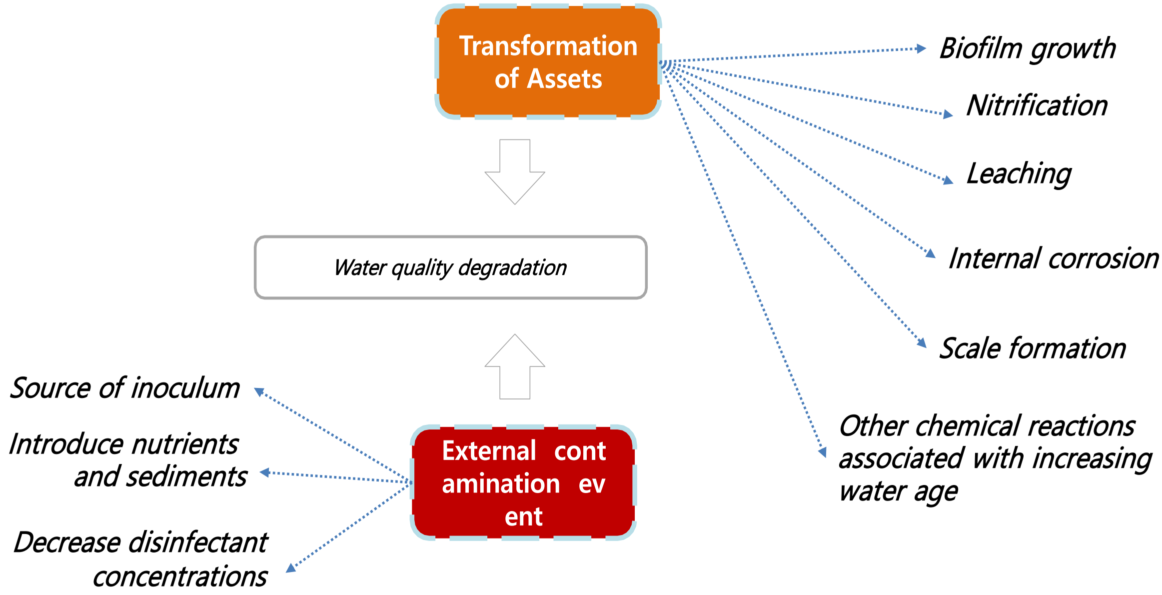
3.3 Hydraulic Integrity Loss

▪ **Recommendations for maintaining and restoring hydraulic integrity**

- Water residence times in pipes, storage facilities, and premise plumbing should be minimized
- Positive water pressure should be maintained
- Distribution system monitoring and modeling are critical to maintaining hydraulic integrity

3.4 Water Quality Integrity Loss

- **Breaches in physical and hydraulic integrity can lead to the influx of contaminants across pipe walls, through breaks, and via cross connections**



3.4 Water Quality Integrity Loss

- **Recommendations for maintaining and restoring water quality integrity**

- Microbial growth and biofilm development in distribution systems should be minimized
- Residual disinfectant choices should be balanced to meet the overall goal of protecting public health
- Standards for materials used in distribution systems should be updated to address their impact on water quality, and research is needed to develop new materials that will have minimal impacts

3.5 Cyber Components Failure

▪ What are the Cyber attack (crime) and Cyber security?

- **Cyber attack**
  - An attack, via cyberspace, targeting an enterprise's use of cyberspace for the purpose of disrupting, disabling, destroying, or maliciously co ntrolling a computing environment/infrastructure; or destroying the in tegrity of the data or stealing controlled information
  - Types:
    - Denial of service, Hacking, Spyware, Trojan Horse, Virus / malware installation, Worm, Sniffer, Key loggers, Phishing
- **Cyber security**
  - The ability to protect or defend the use of cyberspace from cyber attacks

3.5 Cyber Components Failure

▪ Cyber Incidents

- **Queensland, Australia, 2001**
  - Former employee of software development company hacked 46 times into the SCADA system that controlled a sewage treatment plant rele asing over 264,000 gallons of raw sewage into nearby rivers and park s. He altered electronic data for particular sewage pumping stations and caused malfunctions in their operations
- **Harrisburg, Pennsylvania, 2006**
  - Foreign hacker penetrated security of a water filtering plant through t he Internet. The intruder planted malicious software that was capable of affecting the plant's water treatment operation.
- **Los Angeles, 2009**
  - An employee of a Texas Power company temporarily disabled a co mputer system that detected pipeline leaks for oil derricks off the S outhern California coast.

3.5 Cyber Components Failure

- Cyber Incidents

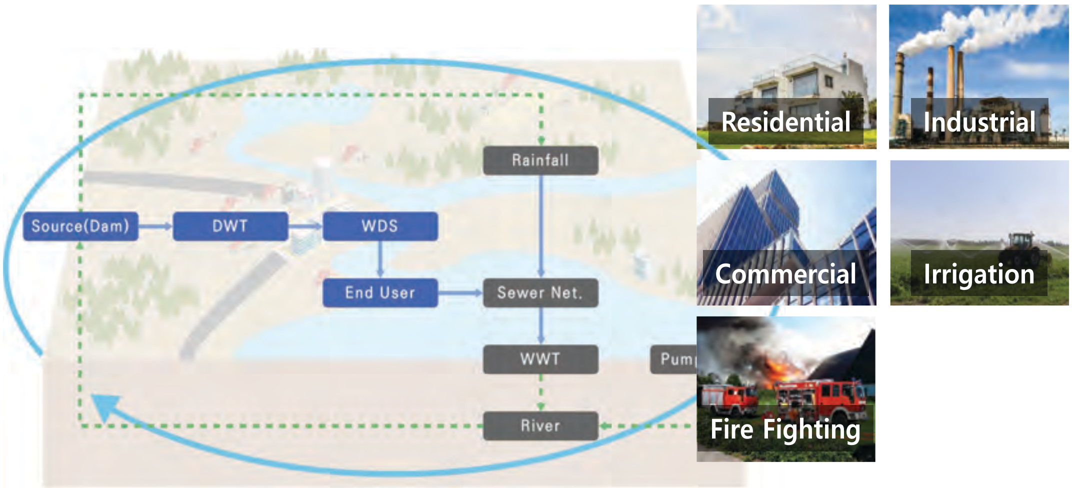
- **Kemuri Water Company, 2016**
  - A hacktivist changed the levels of chemicals used to treat tap water d uring an attack on the outdated IT network of the plant. The compan y look into unauthorized access to system and unexplainable patterns of valve and duct movements that seemed to be manipulating hundred s of Programmable Logic Controller.
- **Long Beach, California, 2016**
  - A recently fired employee of Pacific Energy Resources, Ltd. (PER) dis abled the leak-detection system and safety alarms on offshore oil pl atforms

4. Direct Impacts of Water Distribution System

1. What are Direct Impacts?
2. Abnormal Water Pressure
3. Water Demand Unsatisfaction
4. Water Quality Violation
5. Economic Loss

4.1 What are Direct Impacts

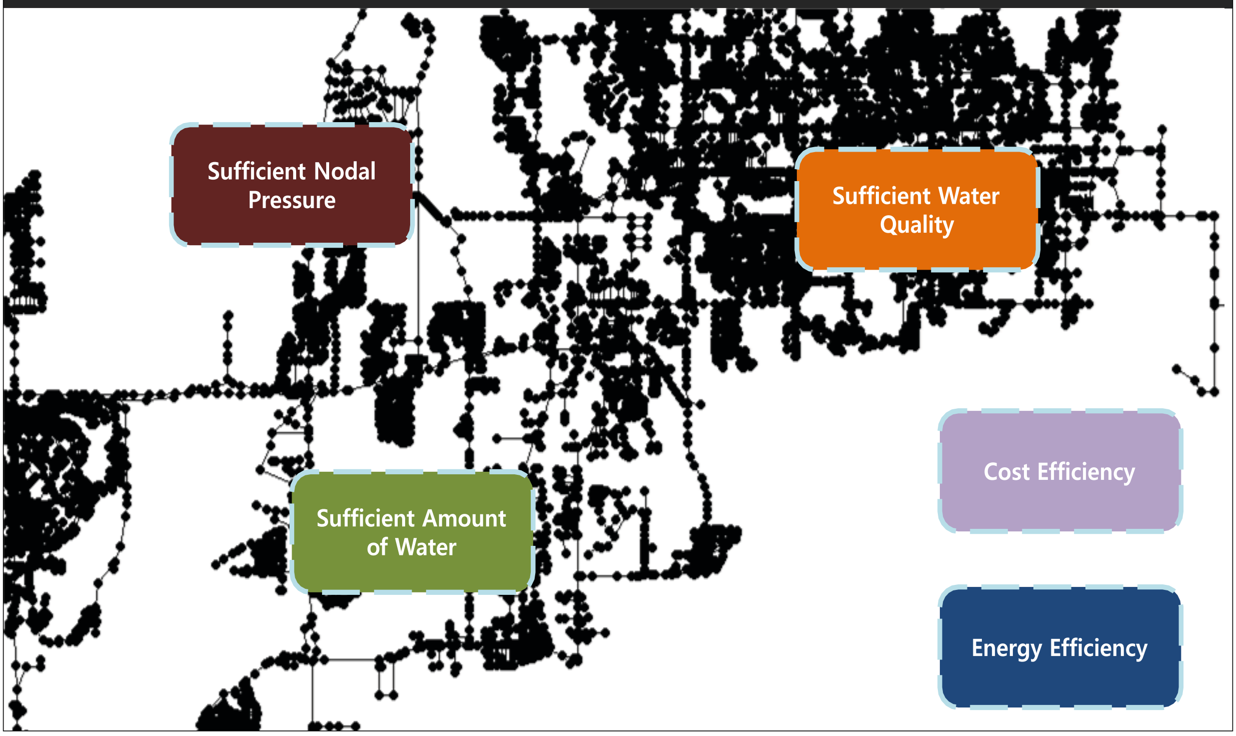
▪ Let's think about the goal of water distribution system.



<Schematic of Urban Water Cycle>

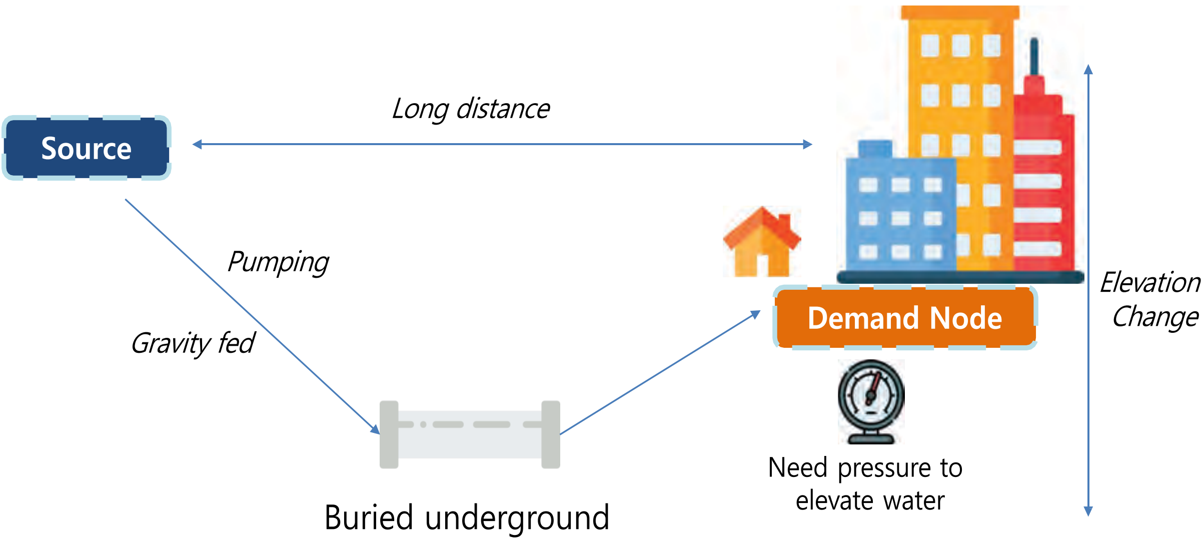
4.1 What are Direct Impacts?

▪ So, what is the performance of water distribution system?



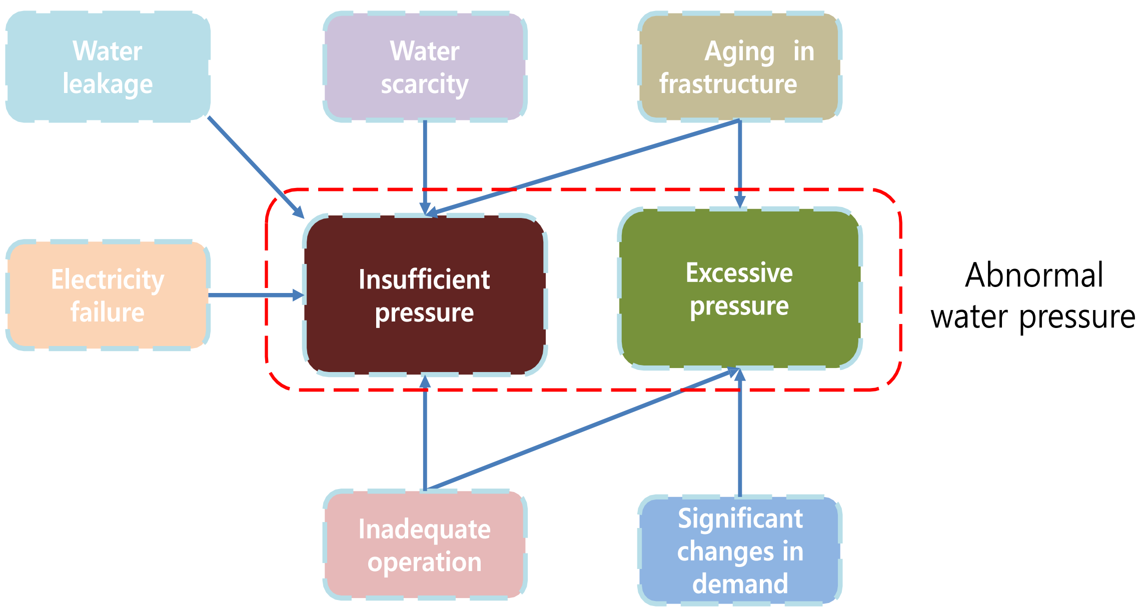
4.2 Abnormal Water Pressure

- **Water distribution system is a pressurized system**



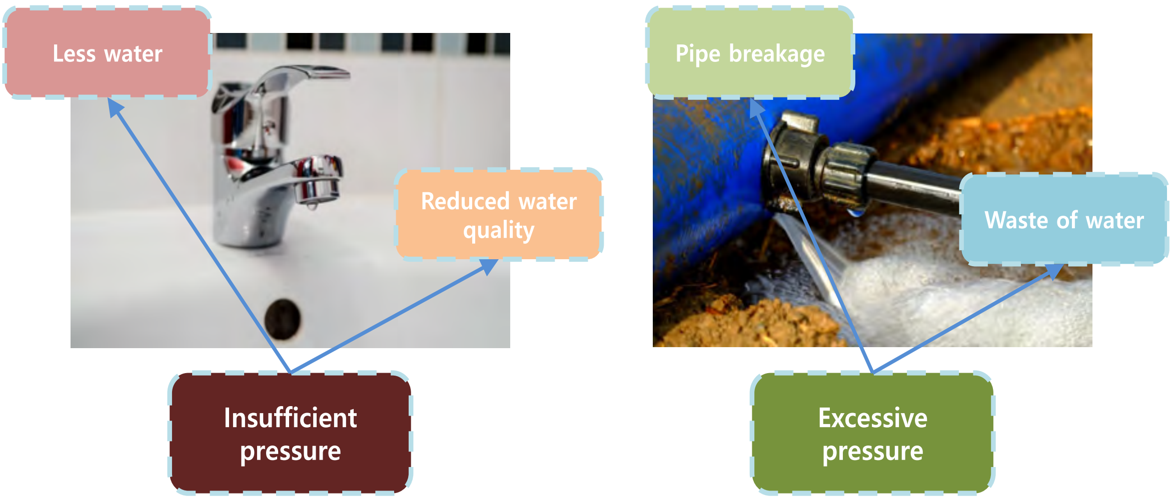
4.2 Abnormal Water Pressure

- **What causes abnormal water pressure?**



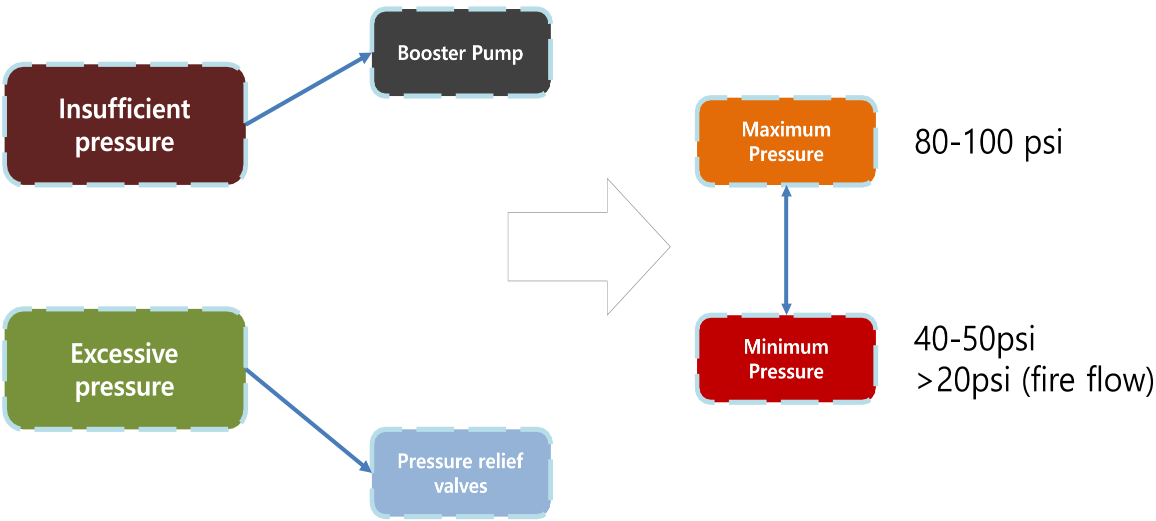
4.2 Abnormal Water Pressure

- What happens if not enough or too much pressure?



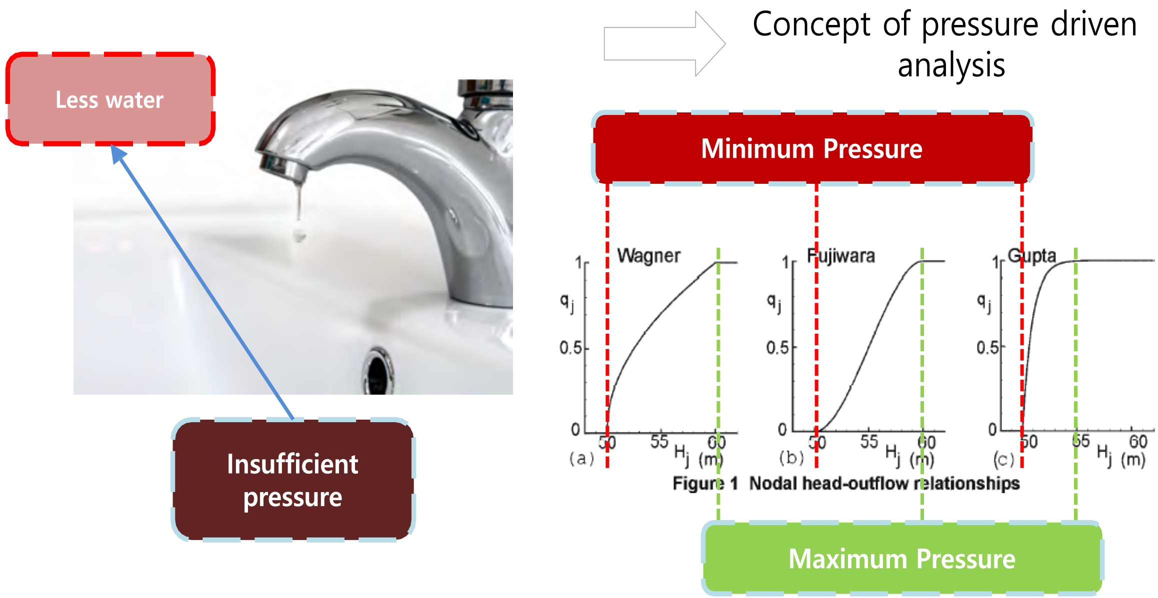
4.2 Abnormal Water Pressure

- How pressure can be controlled?



4.3 Water Demand Unsatisfaction

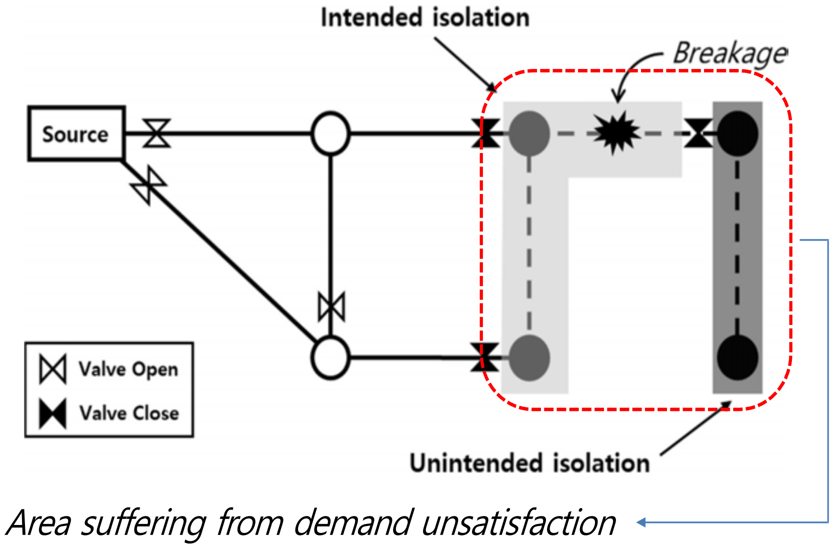
- **What happens when pressure significantly drops?**



Source: Tanyimoh et al. (2003)

4.3 Water Demand Unsatisfaction

- **Water if section of the water distribution system isolated?**



Intended isolation area
– the service suspension area—in which the water supply, al ong with the broken pipe, is c ut off

Unintended isolation area
– the area where water supply is unintendedly cut off from the water source because of isola ting the intended isolation ar ea

Source: Choi & Kang (2020)

4.3 Water Demand Unsatisfaction

- **What happens if water demand is unsatisfied?**

End Users

Economic Loss

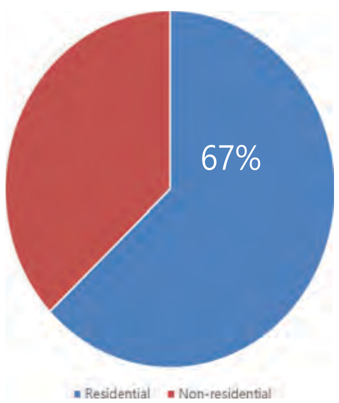
Public Health Issues

Social complaints

Ability to response to emergency

4.4 Water Quality Violation

- **As water distribution system distributes drinking water, contaminant in the system will cause significant health issues**



Human Consumption or Related Use – 17.1 %...... Faucet use – 15.7 %; Dishwasher – 1.4 %

Human Contact Only – 18.5 %........................ Shower – 16.8 %; Bath – 1.7 %

Non-Human Ingestion or Contact Uses – 64.3 %... Toilet – 26.7 %; Clothes Washer – 21.7 %; Leaks – 13.7 %; Other – 2.2 %

*Based on US data

4.4 Water Quality Violation

▪ What cause contaminant intrusion?

- Sudden power failures
- Pump shut-downs
- Back siphonage
- Demand increases
- Pressure drops
- Cross-connection with Wastewater systems
- Leakage
- Breakage

Source: Islam et al. (2017)

4.4 Water Quality Violation

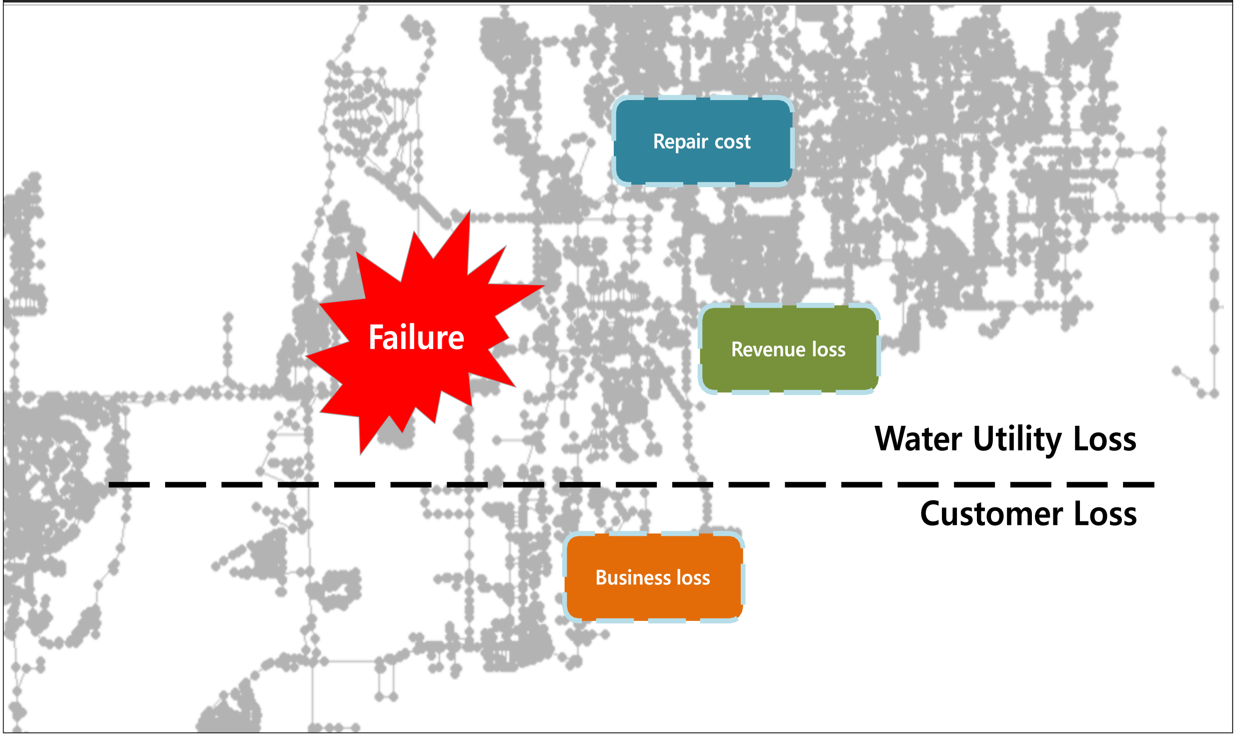
▪ What are the water quality standards?

	Max Chlorine (mg/L)	Turbidity	Color	pH	Manganese (mg/L)	Iron (mg/L)
S. Korea	4	0.5 NTU	5	5.8~8.5	0.05	0.3
WHO	5(C)					
US EPA	4	5 NTU	(15)*	(6.5 ~ 8.5)*	(0.05)*	(0.3)*
Japan	1	2	5	5.8 - 8.6	0.05	0.3
Canada		0.3/1.0/0.1 NTU	15 TCU	6.5~8.5	0.05	0.3
Australia	*Health : 5 *Aesthetic : 0.6	5 NTU	15 PCU	6.5~8.5	0.5	0.3
EU		4 NTU	20 mg/L Pt/Co	6.5~9.5	0.05	0.2
Ireland		4NTU	20mg/L pt/Co	6.5~10.0	0.05	0.2
Germany		1.0NTU		6.5~9.5	0.05	0.2
France		1.0FNU	15mg/L pt/Co	6.5~9	0.05	0.2

* not mandatory (recommended)
- TCU: True color unit
- PCU: Platinum Cobalt Units

4.4 Economic Loss

- Most of water utilities make revenue by selling water!



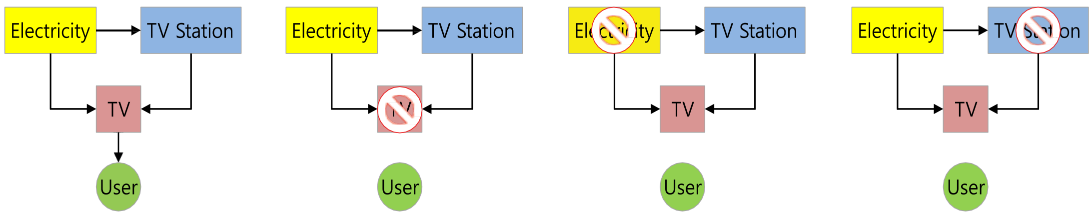
5. Cascading impact of Water Distribution System

1. What is Interdependency?
2. Business Loss induced by Water Distribution System
3. Public Health Concerns induced by Water Distribution System
4. Blackout Impact to Water Distribution System

5.1 What is Interdependency?

- **"Nothing truly exists in isolation"? (Lessons from Ch.1)**

- Systems rely on the availability of each element to operate
- Example, watching TV requires electricity and a broadcaster to operate. With out electricity, the TV cannot be turned on. Without broadcaster, there is not hing to watch on the TV



Watch TV normally

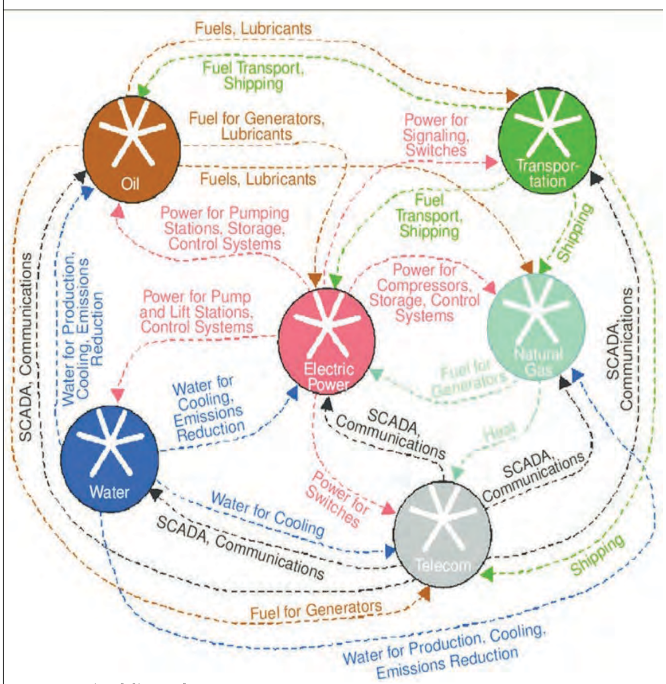
Can't watch TV without the TV

No electricity; TV and TV station doesn't work

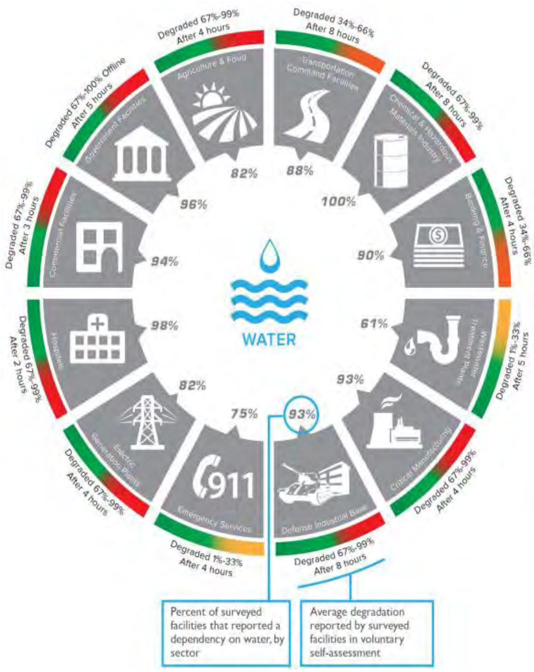
No TV station; TV can be turned on but there is noth ing to watch

5.1 What is Interdependency?

- **All critical infrastructures are connected**



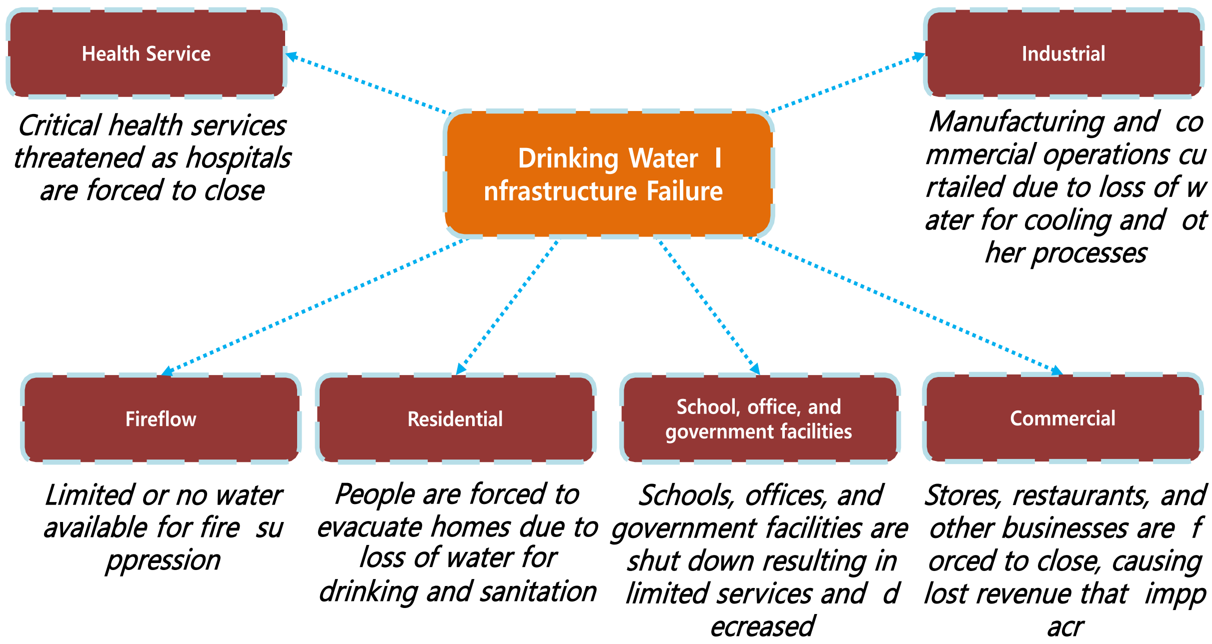
Source: Rinaldi et al. (2001)



Source: Baylis et al. (2016)

5.1 What is Interdependency?

- **Critical infrastructure rely on drinking water infrastructure**

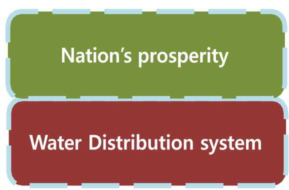


Source: Baylis et al. (2016)

5.2 Business Loss induced by Water Distribution System

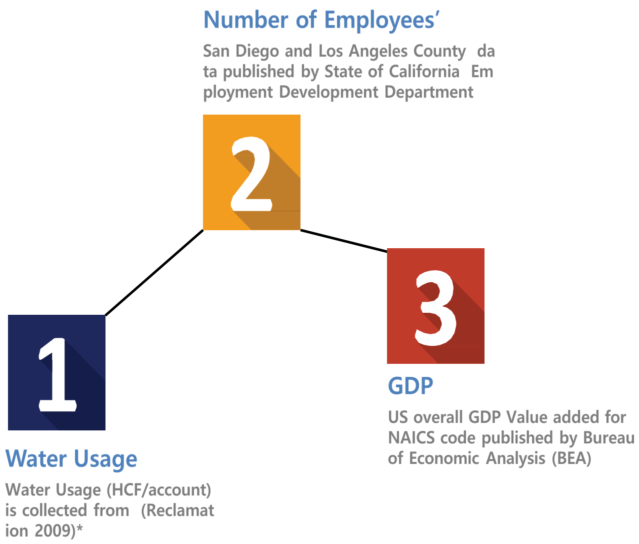
- **Negative impacts on the nation's economy are a result of businesses and households managing unreliable water delivery and wastewater**
- **treatment services**

- About $734 billion in business sales will be lost cumulatively in the next 10 years, from 2011 to 2020.
- By 2040, the total will amount to $7.5 trillion over 30 years.
- The loss of business sales will include $416 billion in GDP from 2011 to 2020, representing the actual productivity in the U.S.
- By 2040, the cumulative lost GDP will exceed $4 trillion



5.2 Business Loss induced by Water Distribution System

- **Concept of ECLIPS (Economic Consequence Linked to Interruption in Providing Service)**
  - ECLIPS links economic (or business) loss induced by water shortage



3-Digit NAICS	Description	ECLIPS (M $/Gal)
515	Broadcasting (except Internet)	0.028257
518	Internet Service Providers, Web Search Portals, and Data Processing Services	0.006780
517	Telecommunications	0.005268
491	Postal Service	0.002229
446	Health and Personal Care Stores	0.001925
621	Ambulatory Health Care Services	0.001254
334	Computer and Electronic Product Manufacturing	0.000956
447	Gasoline Stations	0.000922
622	Hospitals	0.000819
325	Chemical Manufacturing	0.000663
335	Electrical Equipment, Appliance, and Component Manufacturing	0.000521
611	Educational Services	0.000080
000	Landscape Irrigation or Other Non-Revenue Generating Use	0.000000

5.3 Public Health Concerns induced by Water Distribution System

- **All critical infrastructures are connected**

- Annually in the U.S., up to 45 million people are impacted by water quality health-related standard violations, with the most frequent violation pertaining to total coliforms, an indicator of fecal contamination
- Of the 42 waterborne disease-related outbreaks associated with drinking water in the United States between 2013 and 2014, over 80% were associated with public drinking WDS, indicating that public drinking WDS can be a vector of contamination events.
- Ensuring suitable water quality is essential for the health of the community that the WDS serves.

5.4 Blackout Impact to Water Distribution System

- **The Water Sector relies on energy, specifically electricity, to operate its pumps, treatment facilities, delivery systems, and processing**

- Long-term power outages can overwhelm a water utility's backup energy supply or deplete fuel reserves
- This scenario is worsened if the outage is systemic, in that multiple energy utilities in a region are shut down or multiple water utilities in a region ha ve to compete for scarce backup resources
- In addition, energy prioritization (the order in which disrupted sectors ob tain energy services) may be an issue for water utilities as they work to re store services

7. Closing Remarks

1. Important Consideration of Resilience
2. Summary

7.1 Important Consideration of Resilience

- **How can we define drinking water infrastructure is resilient?**

- Enhancing resilience will related to enhancing all common attributes of resilience (redundancy, robustness, rapidity, resourcefulness)
    - Each attribute will have different strategy to be enhanced
        - Redundancy: dual-lining, decentralized sources
        - Robustness: renewal of system, booster pumps
        - Rapidity: rapid identification
        - Resourcefulness: human resources
- For resilient system, measuring tools to quantify resilience of the system is required to compare all alternatives in perspective of resilience
- Also, systems modeling approaches to explicitly calculate the effects of hazards on a system and its interacting components is needed

7.2 Summary

- Drinking water infrastructure are subject to a range of hazards, from natural disasters to man-made disasters such as terrorist attacks or hazardous mat erial releases
- All assets of the drinking water infrastructure are exposed to such disturbances
- Resilience is a property of a system and differs from these concepts in that it also includes the ability to effectively and rapidly recover from unforese en events
- The impacts of such events on drinking water systems can include direct impacts such as pipe breaks, service disruptions, power outages, and etc. and also cascading impacts depending on interdependency.


Thank you very much

Resilience of Drinking Water Infrastructure: Quantification Measures

Water Security and System Resilience

6. Resilience of Drinking Water Infrastructure : Quantification Measures

UNESCO | i-WSSM

United Nations Educational, Scientific and Cultural Organization | International Centre for Water Security and Sustainable Management

Aims & Objectives

- The aims of the course are to:

  (1) Introduce the quantification measures of resilience
  (2) Explain threats to the drinking water infrastructure
  (3) Explain connection between hydraulic and water quality modeling to resilience assessment

- The objectives are that trainees will understand:

  (1) Quantification of water distribution system resilience
  (2) Water distribution system impacts by failure of assets

References

Optimal location of isolation valves in water distribution systems: A reliability/optimization approach (Ozgar and Mays, 2004)

Drinking water distribution systems: assessing and reducing risks. (NAC, 2007)

Pattern Recognition for Reliability Assessment of Water Distribution Networks. (Trifunovic, 2012)

A Systematic Review of Quantitative Resilience Measures for Water Infrastructure Systems(Shin et al., 2018)

System Measures of Water Distribution System Resilience (USEPA, 2015)

A review of definitions and measures of system resilience (Hosseini et al., 2016)

Contents

1. Approaches to Measuring Resilience

1. Why Measure Resilience?
2. What needs to be considered?
3. Overview of Resilience Measures
4. Classifying Quantification Measure

1.1 Why Measure Resilience?

▪ **Why we consider resilience?**

▪ As drinking water infrastructures are exposed to various threats, we need to **protect infrastructure** and **continue quality service** regardless of threats

Climate Change

Natural Disaster
- Drought
- Earthquakes
- Floods
- Hurricanes
- Tornados
- Tsunamis
- Wildfires
- Winter Storms

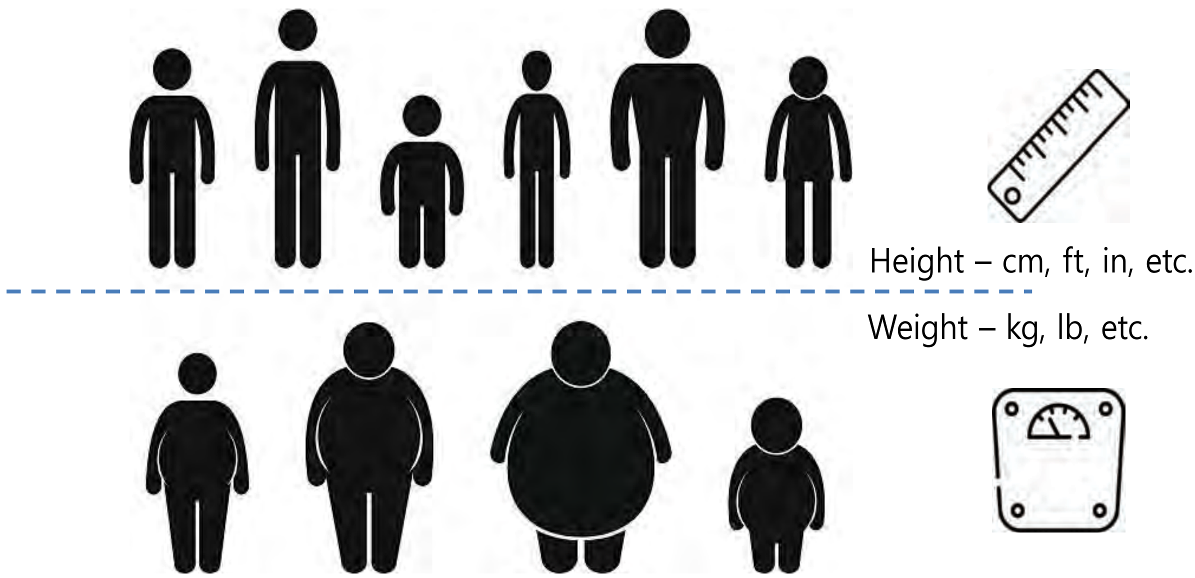
Terrorist Attack
- Physical attack
- Chemical attack
- Cyber attack

Aging Infrastructure

→ How can we make our system resilient to thr eats?

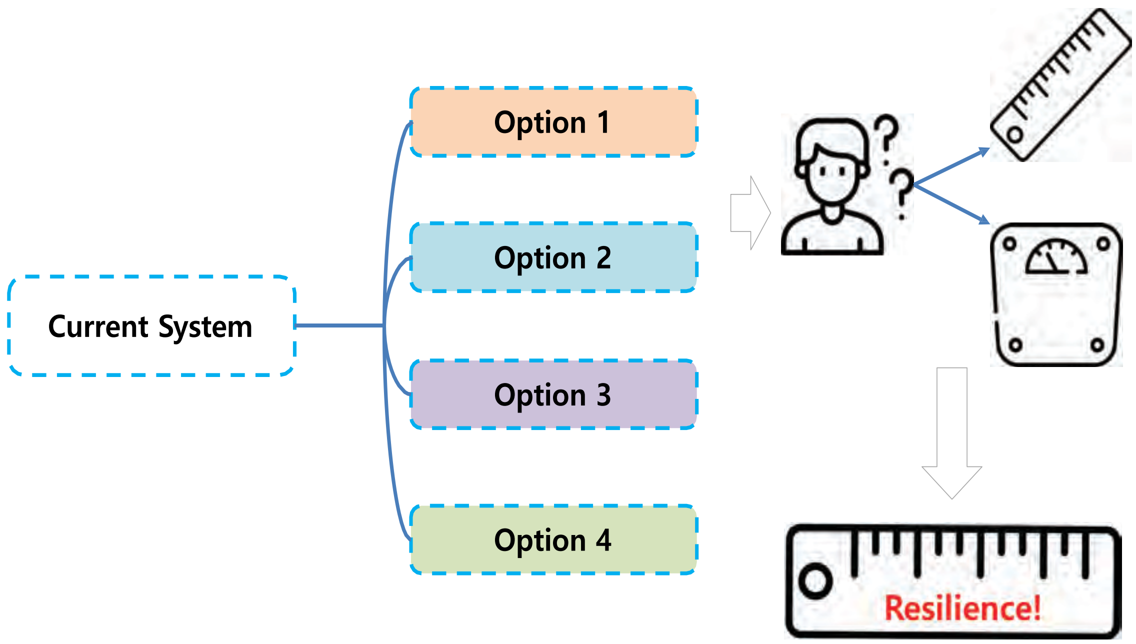
1.1 Why Measure Resilience?

- When comparing two or more objects, we put on scale on it



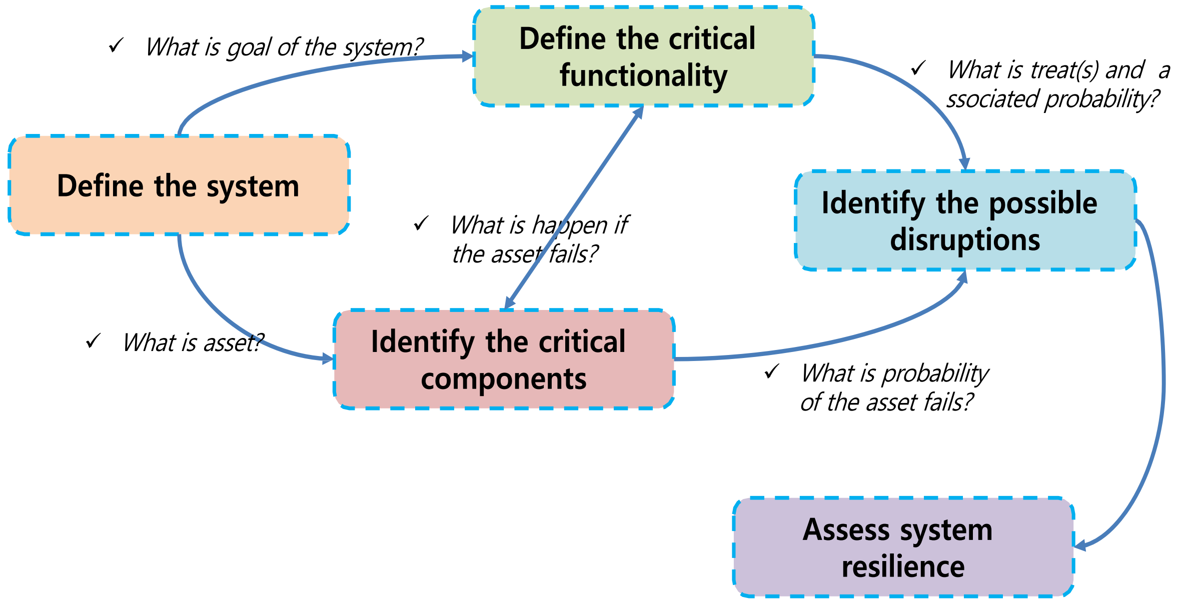
1.1 Why Measure Resilience?

- Then how can we decide one option is more resilient than others?
- Need guidance to compare different alternatives!



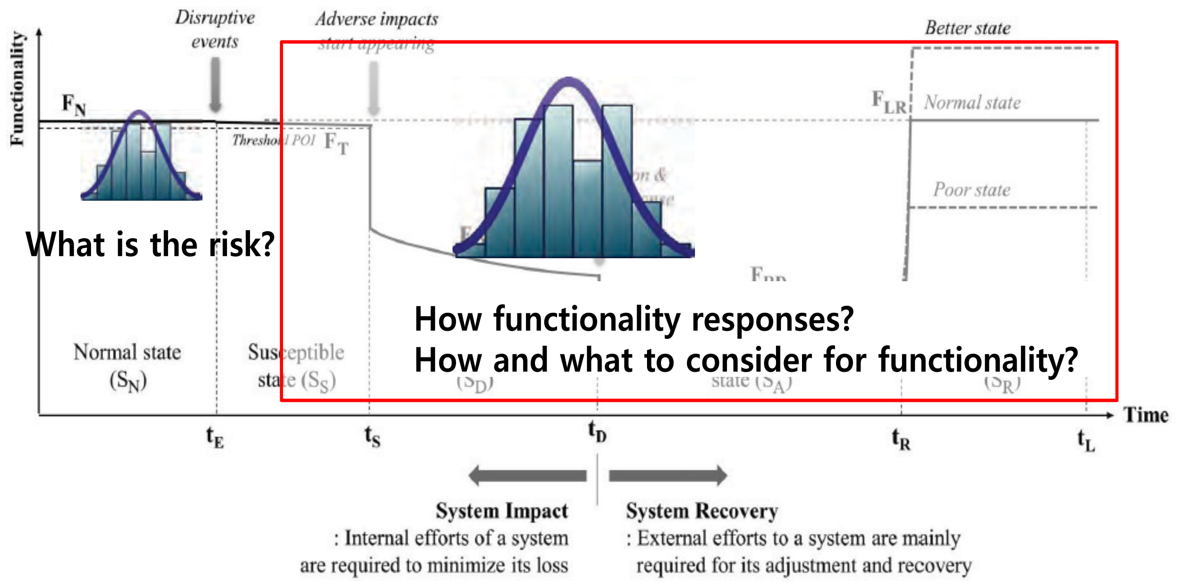
1.2 What needs to be considered?

- **Resilience needs a goal!**



1.2 What needs to be considered?

- **As resilience is designed to assess a system against probable risk, a degree of uncertainty needs to be considered**



Source: Shin et al (2020)

1.3 Overview of Resilience Measures

▪ **Resilience can also be assessed qualitatively (Lessons from Ch.1)**

- In project management, risk analysis is carried out before and during the project implementation (Young, 2003)
- A brainstorming is carried out to:
  - Identify source and type of risk
  - Classify the type of risk and its effect
  - Analyze the consequences associated with the risk
  - Consider how to respond to the risk
- After the assessment is made, each risk is ranked by probability of occurrence and scale of the impact

	Impact on the Project			
		Low	**Medium**	**High**
Probability	**7–9**	Medium	High	Unacceptable
	4–6	Low	High	Unacceptable
	1–3	Low	Medium	High

[Example of risk probability and impact parameters]

1.3 Overview of Resilience Measures

▪ **Qualitative approach can be subjective from person to person**

I think it has high probability

No, I think it has medium probability

Need to get sufficient number of samples!

	Impact on the Project			
		Low	**Medium**	**High**
Probability	**7–9**	Medium	High	Unacceptable
	4–6	Low	High	Unacceptable
	1–3	Low	Medium	High

[Example of risk probability and impact parameters]

1.3 Overview of Resilience Measures

▪ Resilience can be measured by quantitative analysis (Lessons from Ch.1)

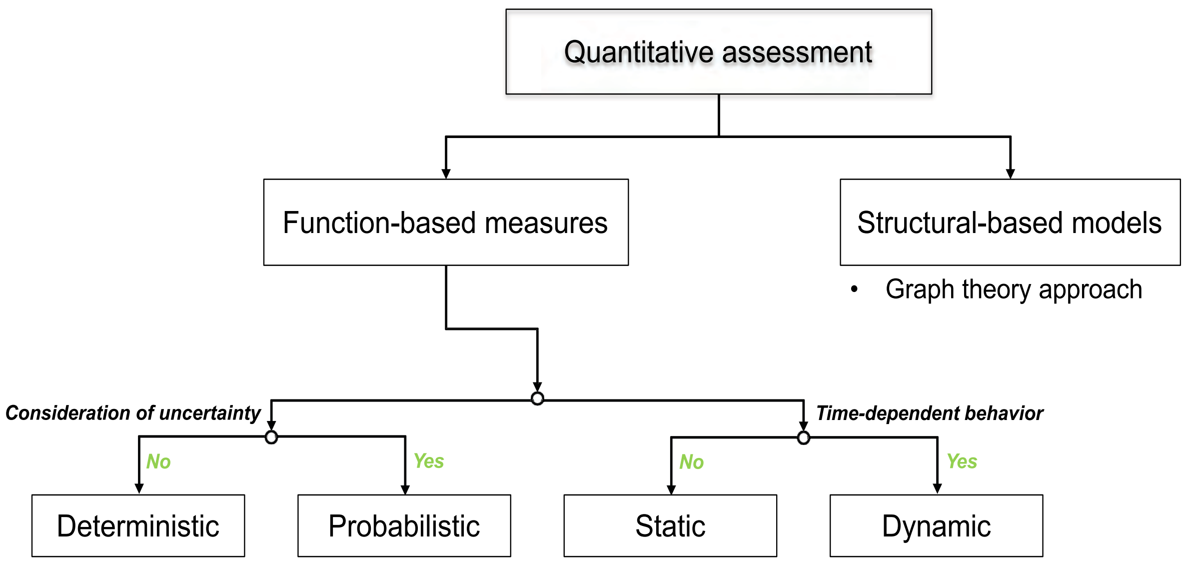
- In the simplest term, resilience can be measured by comparing normal performance to performance during disruption
- Ex, in a production line, if a disruption happens, the output reduces; then the resilience can be defined as:

$$Resilience = \frac{Output\ during\ disruption}{Output\ during\ normal\ condition}$$

- Another simple and measurable factor is the time it takes for the system to recover. The more time the system needs to recover, the less resilient it is
- Cost is also a good measure. The cost needed to recover the system signifies resilience

1.4 Classifying Quantification Measure

▪ Resilience of water distribution system can be quantified in various ways...



Source : Hosseini et al.(2016), Shin et al. (2018)

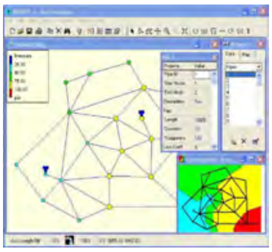
2. Role of hydraulic/water quality models

1. Hydraulic Analysis
2. Pressure Driven Analysis
3. Water Quality Analysis

2.1 Hydraulic Analysis

- **Hydraulics of a water distribution system can be approached from two different perspectives**
  - Primacy given to nodal demands: Demand driven analysis (DDA)
  - Primacy given to nodal pressures: Pressure driven analysis (PDA)

EPANET, EPA

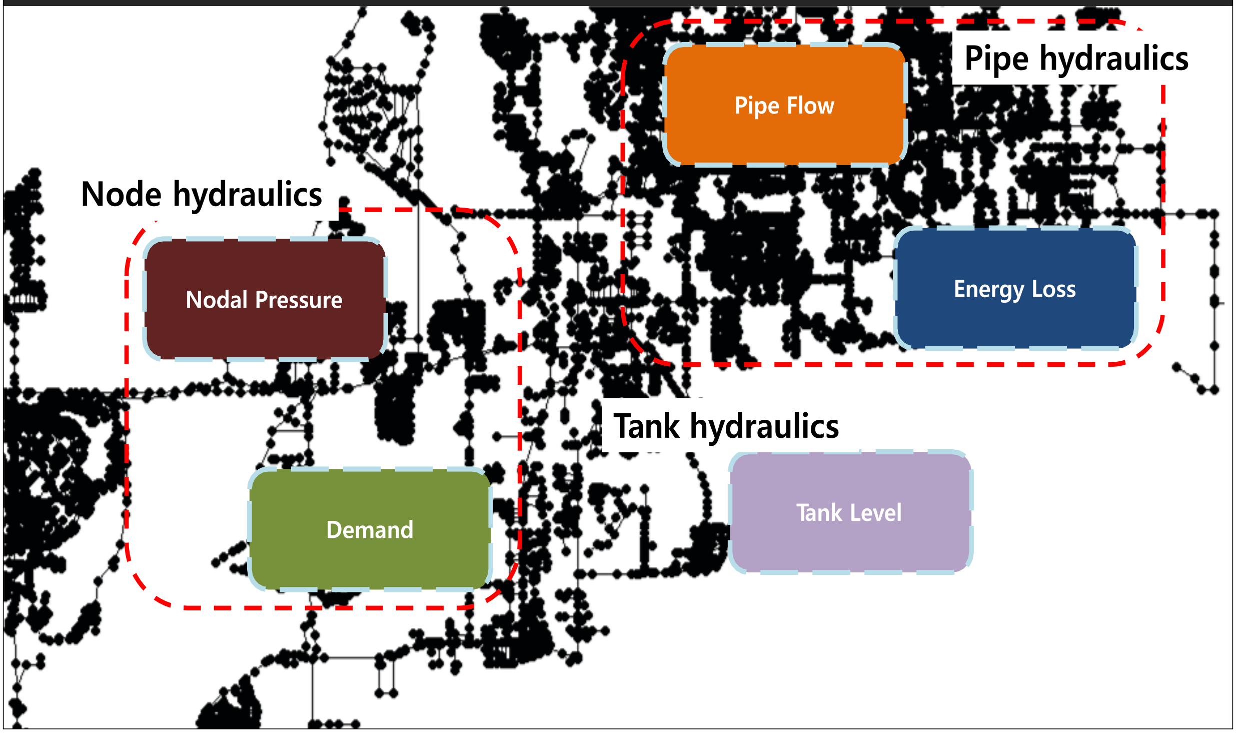


WaterGems, Bently

KYPIPE, KYPIPE

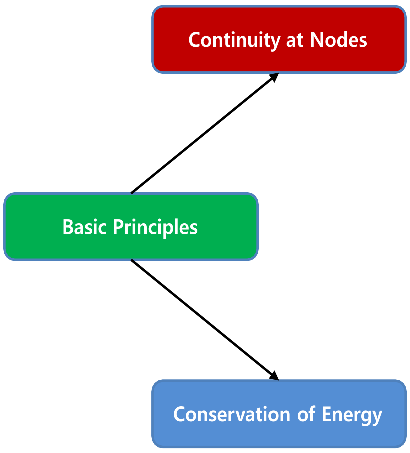
2.1 Hydraulic Analysis

- **So, what is the goal of hydraulic analysis?**



2.1 Hydraulic Analysis

- **EPANET is widely applied for hydraulic analysis**
  - Primacy given to nodal demands (demand driven analysis; DDA)
  - demands at each point in time are fixed values that must be delivered no matter what nodal pressures and link flows are produced by a hydraulic solution



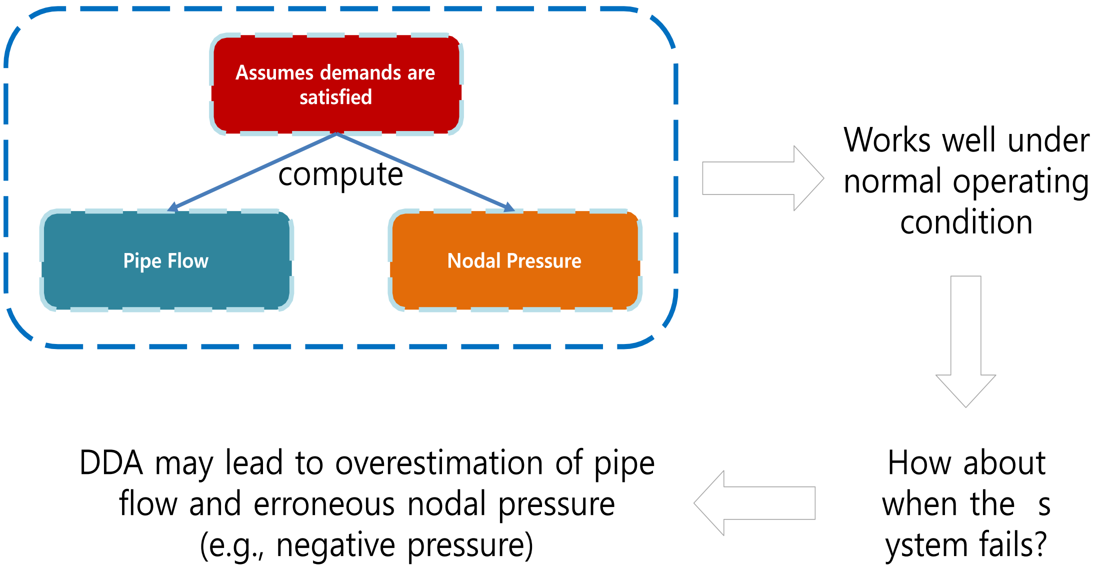
$$\Sigma Q_{in} t - \Sigma Q_{out} \Delta t = \Delta V$$

where ΣQ_{in} = total flow into node
ΣQ_{out} = total demand at the node
ΔV = change in storage volume
Δt = change in time

$$\Sigma h_{Loop} = 0$$

2.1 Hydraulic Analysis

- **What is problem of DDA?**



2.2 Pressure Driven Analysis

- **PDA allows estimation of the actual demand delivered at a node depending on the node's pressure**

$$q_j = \left(\frac{H_j - H_j^{\min}}{H_j^{des} - H_j^{\min}}\right)^{\frac{1}{n_j}}$$

EPANET2.2

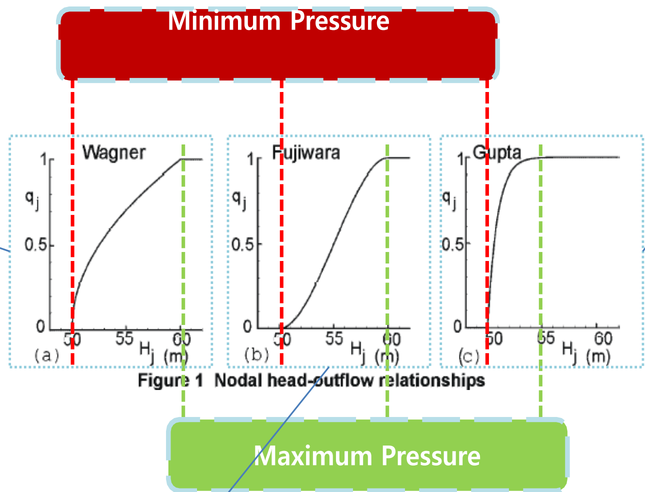


Figure 1 Nodal head-outflow relationships

$$q_j = 1 - 10^{b_j\left(\frac{H_j - H_j^{\min}}{H_j^{des} - H_j^{\min}}\right)}$$

$$q_j = \frac{\int_{H_j^{\min}}^{H_j} (H_j - H_j^{\min})(H_j^{des} - H_j^{\min})\,dH}{\int_{H_j^{\min}}^{H_j^{des}} (H_j - H_j^{\min})(H_j^{des} - H_j^{\min})\,dH}$$

2.2 Pressure Driven Analysis

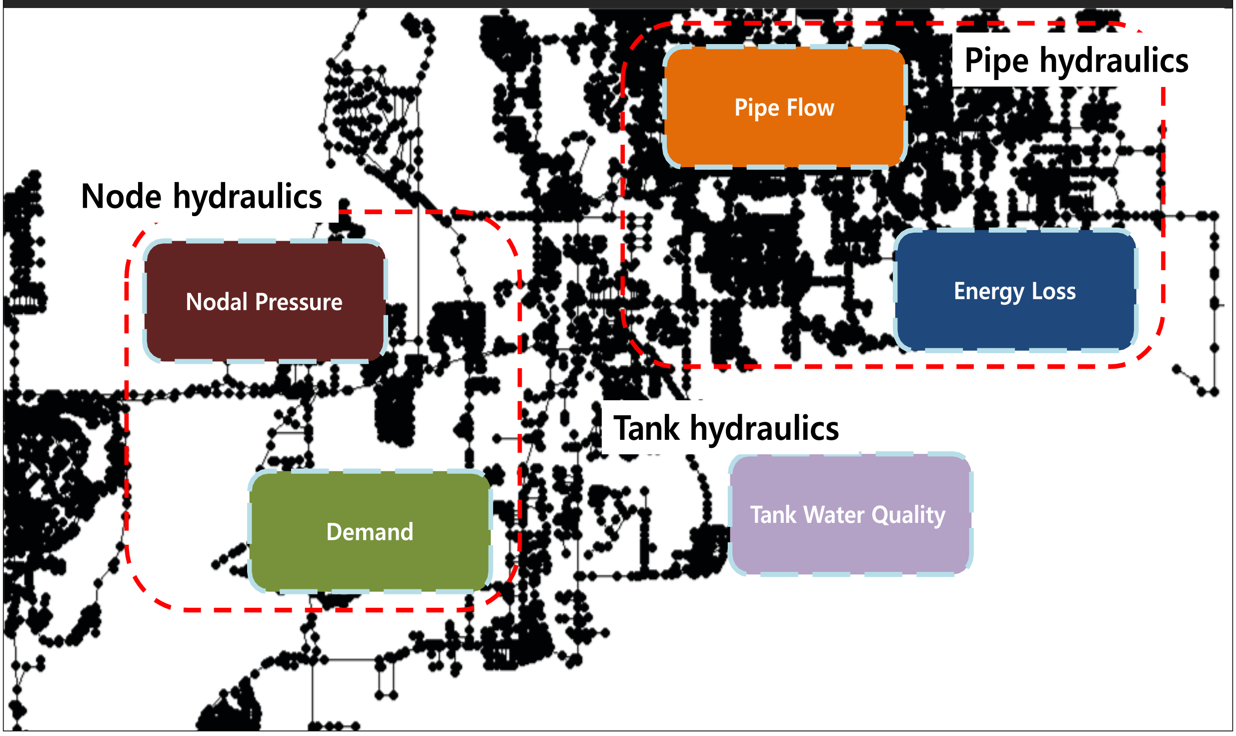
▪ PDA vs. DDA

	DDA (Demand Driven Analysis)	PDA (Pressure Driven Analysis)
Assumptions	Demands of nodes are always fully satisfied	Demands of nodes are dependent on available nodal head
Applications	Normal operation condition	Abnormal operation condition (leakage, failure, pump problem, fire fighting demand, etc.)
Reliability for abnormal operating conditions	Low	High
Defects	Negative nodal pressure heads may occur under an abnormal operating condition	Need of a relation equation between nodal heads and nodal flows Solving nodal demand and head simultaneously is very difficult
Solving Method	Iterative procedures to satisfy continuity and loop equations	Iterative procedure using the DDA simulation

Source: Baek et al. (2010)

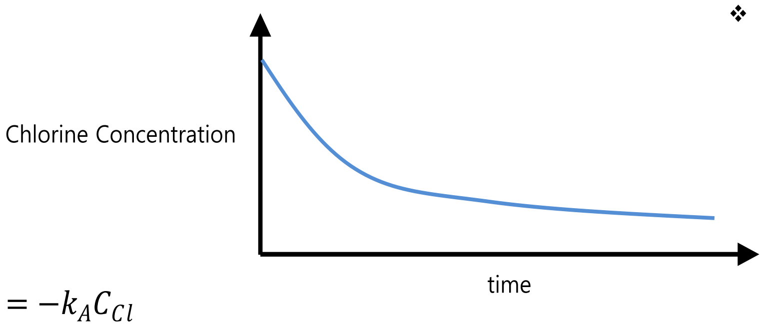
2.3 Water Quality Analysis

▪ Hydraulic analysis is prerequisite for water quality analysis



2.3 Water Quality Analysis

- **Hydraulic analysis is prerequisite for water quality analysis**



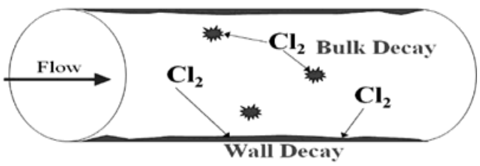
$$\frac{d_{Cl}}{dt} = -k_A C_{Cl}$$

Here, C_{Cl} is the concentration of chlorine (mg/L) and k_A is t he chlorine decay constant (hr-1)

❖ **Requirements**

- Initial Condition
- Flow
- Time

Result of hydraulic analysis



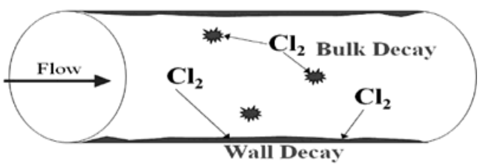
Schematic drawing of chlorine decay reaction in a distribution system
Adapted from Speight 2003

2.3 Water Quality Analysis

- **Consumption of residual chlorine in the distribution system is influenced by a number of factors**

Reactions with organic and i norganic che micals

Reactions with b iofilms attached t o the pipe wall



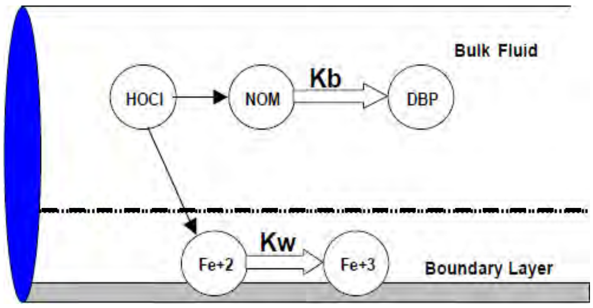
Schematic drawing of chlorine decay reaction in a distribution system
Adapted from Speight 2003

Reaction to corrosion process

Mass transport of chlorine and other reactants between the bulk flow and pipe wall

2.3 Water Quality Analysis

- **Reactions can occur both within the bulk flow and with material along the pipe wall (Rossman, 2002)**
  - Two main reactions considered in EPANET



Bulk Reactions

Free chlorine (HOCl) react with natural organic matter (NOM) in the bulk phase

Wall Reactions

Free chlorine transport through a boundary layer at the pipe wall to oxidize iron (Fe) re leased from pipe wall corrosion

Source: Rossman (2000)

2.3 Water Quality Analysis

- **Bulk Reactions**
  - n-th order reaction kinetics

$$R = K_b (C_L - C) C^{(n-1)}, \text{ for } n > 0,\ K_b > 0$$
$$R = K_b (C - C_L) C^{(n-1)}, \text{ for } n > 0,\ K_b < 0$$

where K_b is a bulk reaction rate coefficient, C is reactant concentration (mass/volume), C_L is the limiting concentration, and n is a reaction order

Model	Parameters	Examples
First-Order Decay	$C_L = 0,\ K_b < 0,\ n = 1$	Chlorine
First-Order Saturation Growth	$C_L > 0,\ K_b > 0,\ n = 1$	Trihalomethanes
Zero-Order Kinetics	$C_L = 0,\ K_b <> 0,\ n = 0$	Water Age
No Reaction	$C_L = 0,\ K_b = 0$	Fluoride Tracer

Source: Rossman (2000)

2.3 Water Quality Analysis

▪ Wall Reactions

- The rate of water quality reactions occurring at or near the pipe wall can be considered to be dependent on the concentration in the bulk flow by using an expression of the form

$$R = (A/V)K_w C^n$$

where K_w = a wall reaction rate coefficient, (A/V) = the surface area per unit volume within a pipe (equal to 4 divided by the pipe diameter)

Headloss Formula	Wall Reaction Formula
Hazen-Williams	$K_w = F/C$
Darcy-Weisbach	$K_w = -F/\log(e/d)$
Chezy-Manning	$K_w = F \times n$

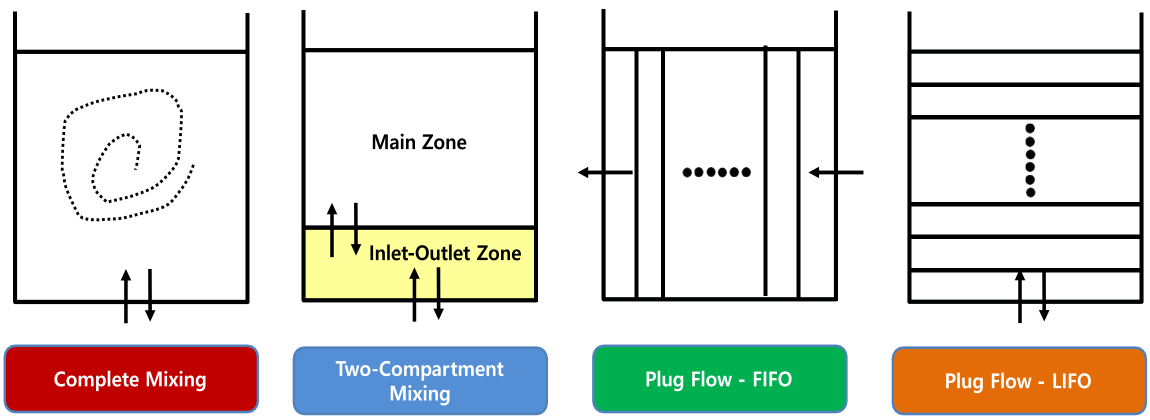
where C is Hazen-Williams C-factor, e is Darcy-Weisbach roughness, d is pi pe diameter, n is Manning roughness coefficient, and F is wall reaction - p ipe roughness coefficient

Source: Rossman (2000)

2.3 Water Quality Analysis

▪ Mixing in storage tanks…

- are also important aspect of water quality analysis
- Can be characterized in four different types of models



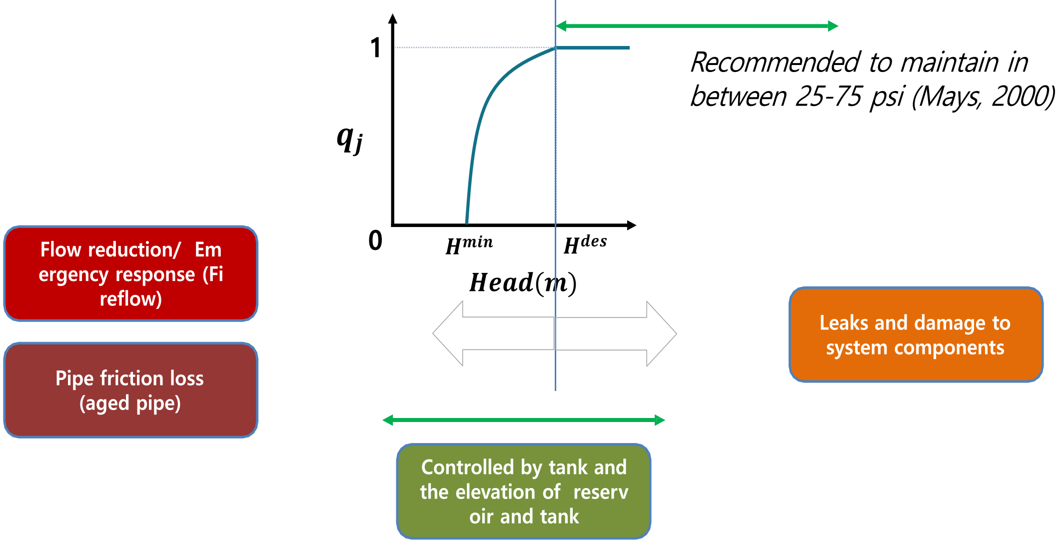
Source: Rossman (2000)

3. Standard Performance Measures

1. Water Pressure
2. Availability Index
3. Water Quality
4. Other Performance Metric

3.1 Water Pressure

- **Water distribution networks must maintain adequate water pressure throughout the network to ensure continuity in service and for fire suppression**
  - Low water pressure can result in flow reductions and high water pressure can cause leaks and damage to system components



3.1 Water Pressure

- **A systems analysis can be performed to ensure that a specific network meets pressure range requirements under normal and abnormal operating conditions**

  - The number of nodes that satisfy the pressure requirement over the entire specified time period can be considered as performance measure

$$N_p = \sum_{i=1}^{NCount} k_i \text{, } where\ k = \begin{cases} 1 & if\ H^{des} \leq H_i \\ 0 & otherwise \end{cases}$$

  - where N_p is number of nodes in the network that satisfy the pressure requirement, $NCount$ is number of nodes, k_n is a binary variable set to 1 if the pressure requirement is satisfied at node i, H^{des} is desired head at node i, and H_i is head at node i

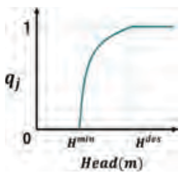
  - Cost would be an important metric to use to account for upgrades required to enhance resilience to a given hazard, or to repair the system following an event.

3.2 Availability Index

- **Availability is used as the quantifiable metric for the resilience of a WDS (Zhuang et al. 2013)**
  - Availability is defined as the percentage of demand that has been supplied during the failure events
  - Availability also can describe intensity of the failure events

  - Mathematically, nodal availability is expressed as the ratio of total available demand to total required demand

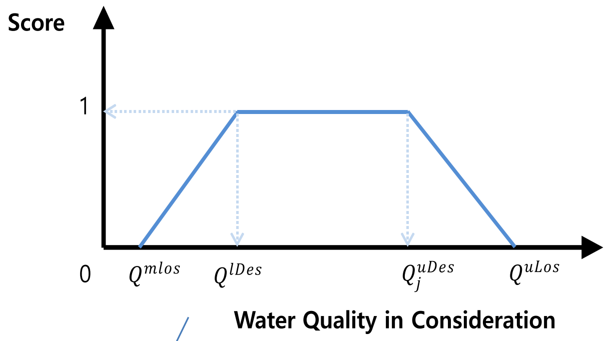
$$R_i = \frac{\sum_{t=1}^{Period} Q_{i,t,avl}}{\sum_{t=1}^{Period} Q_{i,t,req}}$$



  - where R_i is nodal availability of i^{th} node, $Q_{i,t,avl}$ represents flow delivered to the i^{th} node at time t, $Q_{i,t,req}$ is required demand of i^{th} node at time t, Period is time duration under system failure, and $NCount$ denotes total number of demand nodes.

3.3 Water Quality

- **Usually, water quality has been considered in a range between maximum and minimum**



Requirements are different to water utilities

$$U_j(q) = \begin{cases} 0, & Q_j \le Q_j^{mLos} \ or \ Q_j \ge Q_j^{uLos} \\ \dfrac{(Q_j - Q^{mLos})}{(Q_j^{mDes} - Q^{mLos})}, & Q_j^{mLos} < Q_j < Q_j^{mDes} \\ \dfrac{(Q_j^{ulos} - Q \ )}{(Q^{ulos} - Q_{de} \ )}, & Q_j^{uLos} < Q_j < Q_j^{uDes} \\ 1 & Q_j^{lDes} \le Q_j \le Q_j^{uDes} \end{cases}$$

where,

$U_j(q)$ = water quality score at node j at time t
Q_j = water quality at normal condition at node j at time t
Q_{mLos} = acceptable minimum level of service
Q_{lDes} = lower level of desired level of service
Q_{uDes} = upper limit of desired
Q_{uLos} = maximum level concentration that generates water quality utility.

Source: Shafiqul Islam(2014)

3.3 Water Quality

- **What are the water quality standards?**

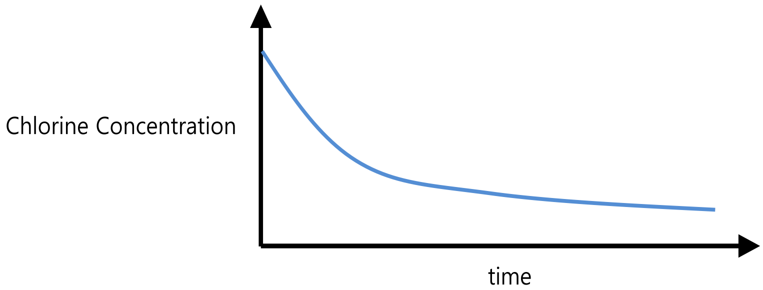
	Max Chlorine (mg/L)	Turbidity	Color	pH	Manganese (mg/L)	Iron (mg/L)
S. Korea	4	0.5 NTU	5	5.8~8.5	0.05	0.3
WHO	5(C)					
US EPA	4	5 NTU	(15)*	(6.5 ~ 8.5)*	(0.05)*	(0.3)*
Japan	1	2	5	5.8 - 8.6	0.05	0.3
Canada		0.3/1.0/0.1 NTU	15 TCU	6.5~8.5	0.05	0.3
Australia	*Health : 5 *Aesthetic : 0.6	5 NTU	15 PCU	6.5~8.5	0.5	0.3
EU		4 NTU	20 mg/L Pt/Co	6.5~9.5	0.05	0.2
Ireland		4NTU	20mg/L pt/Co	6.5~10.0	0.05	0.2
Germany		1.0NTU		6.5~9.5	0.05	0.2
France		1.0FNU	15mg/L pt/Co	6.5~9	0.05	0.2

* not mandatory (recommended)

- TCU: True color unit
- PCU: Platinum Cobalt Units

3.3 Water Quality

- **Water age (residence time) is another good indicator for water quality**



$$\frac{d\;_{Cl}}{dt} = -k_A C_{Cl}$$

Here, C_{Cl} is the concentration of chlorine (mg/L) and k_A is the chlorine decay constant (hr^{-1})

- Water age is the <u>time that a specific volume of water is in the water distribution system after leaving the treatment plant or reservoir</u>
- Water utilities try to **minimize water age** (also called residence time) as chlorine residuals are known to decay and disinfection byproducts increase over time

3.4 Other Performance Metric

- Cost (EPA, 2015)

- As water utilities operate on tight budgets, cost (usually minimizing problem) is an important consideration
- To evaluate cost, both the capital (usually installation cost) and operational costs (energy costs to operate pumps and maintenance costs) associated with any change to the system have to be considered

$$Cost = \sum_{c=1}^{C}(CE_c + OE_c)$$

- where $Cost$ is the total cost, CC_c is the capital cost of new component c and OC_c is the operational cost for new component c
- Cost would be an important metric to use to account for upgrades required to enhance resilience to a given hazard, or to repair the system following an event.

3.4 Other Performance Metric

- **Greenhouse Gas Emissions (EPA, 2015)**

  - GHG emissions are important to consider given that water utilities might need to adhere to regulations that limit emissions in the future (carbon neutral, carbon tax, etc.)
  - GHG emissions are calculated by adding the capitol emissions associated with production, transport, and installation of components with the oper ational emissions resulting from fossil fuel sources to operate pumps and generators

$$GHG = \sum_{c=1}^{C}(CE_c + OE_c)$$

  - where CE_c is the capitol emissions from component c and OE_c is the oper ational emissions from component c (emission factor of 1.04 kg-CO2- e/k Wh)
  - The metric is particularly relevant to measuring resilience to climate change.

4. Resilience Quantification Measures

1. Deterministic-Static Approaches
2. Deterministic-Dynamic Approaches
3. Probabilistic Measures
4. Water Quality Resilience

4.1 Deterministic-Static Approaches

▪ Resilience Index (Todini, 2000)

- The physical and hydraulic failures (e.g., pipe breakage and growing dema nd) in the water distribution network may entail more internal energy dissi pation (losses) with variation of the water flow and pressure
- Considered energy surplus as an evidence of overcoming failure, and prop osed resilience measure as a fraction of the available energy surplus at the nodes over the maximum energy surplus in the network

$$I_r = \frac{\sum_{i=1}^{n} q_i^*(h_i - h_i^*)}{\sum_{j=1}^{r} Q_j H_j + \sum_{k=1}^{p}(P_k/\gamma) - \sum_{i=1}^{n} q_i^* h_i^*}$$

- where I_r is resilience index, n is number of nodes, r is number of reservoir, q_i^* is demand at node i, h_i is head at node i, h^* is required head at node i, Q_j is discharge at reservoir k, P_k is energy supplied from pump k, γ: specific weight of water (9.81kN/m^3), and H_k is head at reservoir k

4.1 Deterministic-Static Approaches

▪ Network Resilience Index (Prasad and Park, 2004)

- Extended Todini's measure by incorporating the effects of energy surplus and loop reliability.
- Loop reliability has been considered as a uniformity (C_i) in diameters, which is the ratio of average diameter for the maximum diameter of the connect ed pipes to the demand nodes

$$I_n = \frac{\sum_{i=1}^{n} C_i q_i^*(h_i - h_i^*)}{\sum_{j=1}^{r} Q_j H_j + \sum_{k=1}^{p}(P_k/\gamma) - \sum_{i=1}^{n} q_i^* h_i^*}, where\ C_i = \frac{\sum_{j=1}^{N_{p,i}} d_i}{N_{p,i} \times max\{d_j\}}$$

- where $N_{p,i}$ is the number of connected pipes to a node i, d_i is diameter of j^{th} pipe connected to node i

4.1 Deterministic-Static Approaches

▪ Modified Resilience Index (Jayaram and Srinivasan, 2008)

- Improved Todini's measure to be more appropriate to the water distribution system with multiple reservoir case
  - When one of the reservoirs, which has higher total head compared with others, delivers a large portion of total demand, this would increase energy surplus fe eding to the network. In addition, this may increase energy surplus at demand nodes.

- Modifed resilience index is varied in direct proportion to the total energy surplus at the demand nodes

$$I_m = \frac{\sum_{i=1}^{n} q^*(h_i - h_i^*)}{\sum_{i=1}^{n} q_i^* h_i^*}$$

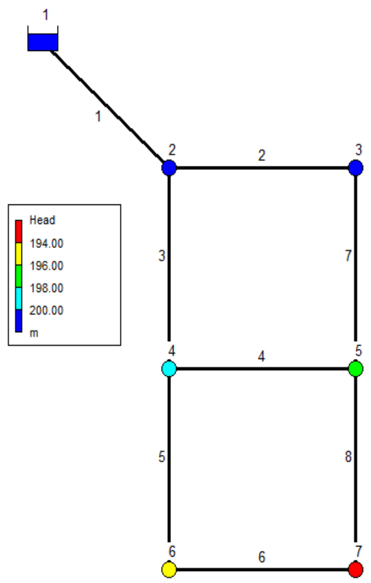
4.1 Deterministic-Static Approaches

▪ Example

$$\sum_{j=1}^{r} Q_j H_j = 235200$$

Node ID	Elevation (m)	Demand (CMH)	Head (m)
Junc 2	150	100	203.25
Junc 3	160	100	200.19
Junc 4	155	120	198.38
Junc 5	150	270	196.19
Junc 6	165	330	195.99
Junc 7	160	200	191.35

Node ID	C_i	$q_i^*(h_i - h_i^*)$	$q_i^* h_i^*$
Junc 2	0.889	2325	18000
Junc 3	0.938	1019	19000
Junc 4	0.810	1605.6	22200
Junc 5	0.714	4371.3	48600
Junc 6	0.536	326.7	64350
Junc 7	0.550	270	38000



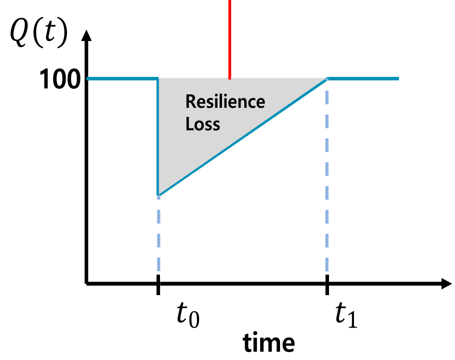
- **RI**: 0.396
- **NRI**: 0.310
- **MRI**: 0.047

4.2 Deterministic-Dynamic Approaches

- **Resilience triangle mode**
  - **Bruneau et al. (2003)**
    - Focused on the triangle area of the functionality curve to estimate resilience loss of a system

$$RL = \int_{t_0}^{t_1} [100 - Q(t)]dt$$

- t_0: time at which the disruption occurs
- t_1 : time at which the system returns to its normal pre-disruption state
- Q : System performance

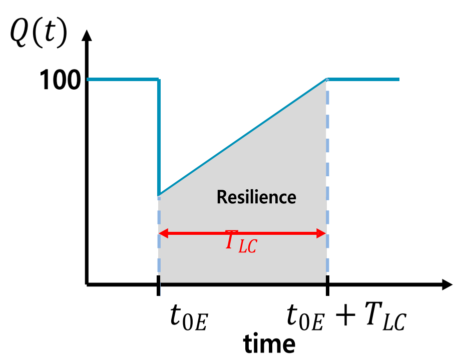


4.2 Deterministic-Dynamic Approaches

- **Resilience triangle mode**
  - **Cimellaro et al. (2010)**
    - Also focused on the triangle area of the functionality curve to estimate resilience loss of a system but slightly different

$$R = \int_{t_{0E}}^{t_{0E}+T_{LC}} Q(t)/T_{LC}\,dt$$

- T_{LC}: control time of the system



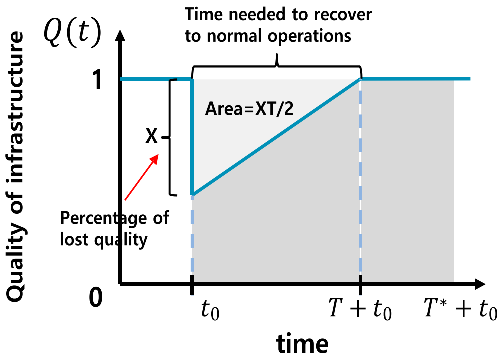
4.2 Deterministic-Dynamic Approaches

- **Resilience to subsequent multi-events**

- **Zobel (2011); Zobel and Khansa (2014); Hosseini et al. (2016)**
  - Percentage of loss in system functionality

$$R(X,T) = \frac{T^* - XT/2}{T^*} = 1 - \frac{XT}{2T^*}, X \in [0,1], T \in [0, T^*]$$

- T^*: Sufficiently long time interval from event occurrence time
- X : Percentage of initial performance loss
- T : Time required to recover in pre-disaster condition
- t_0: time at which the disruption occurs



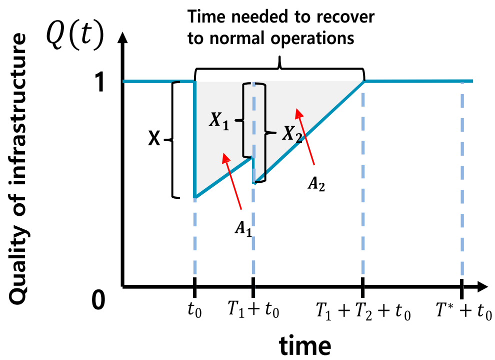
4.2 Deterministic-Dynamic Approaches

- **Resilience to subsequent multi-events**

- **Zobel (2011); Zobel and Khansa (2014); Hosseini et al. (2016)**
  - Percentage of loss in system functionality

$$R = 1 - \sum_i \frac{(X_i + X')T_i}{2T^*} \ (Multiple\ event)$$

- X_i: total amount of loss in a system immediately after event i occurs
- X' : total amount of loss in a system immediately before event (i+1) occurs
- T : interval time between event i and (i+1)
- T^* : Sufficiently long time interval from event occurrence time



4.2 Deterministic-Dynamic Approaches

▪ Availability based resilience measure

- **Zhuang et al. (2013)**
  - As a measure of system resilience, availability is defined as the percent age of water supplied to customers over a system failure period
  - Mathematically, system availability is expressed as the ratio of total system available demand to total system required demand

$$R_{Sys} = \frac{\sum_{t=1}^{Period} \sum_{i=1}^{NCount} Q_{i,t,avl}}{\sum_{t=1}^{Period} \sum_{i=1}^{NCount} Q_{i,t,req}}$$

  - where R_{sys} is system availability, $Q_{i,t,avl}$ represents flow delivered to the i^{th} node at time t, $Q_{i,t,req}$ is required demand of i^{th} node at time t, Period is time duration under system failure, and $NCount$ denotes total number of demand nodes.

4.3 Probabilistic Measures

▪ Hashimoto (1982); Fowler et al. (2003)

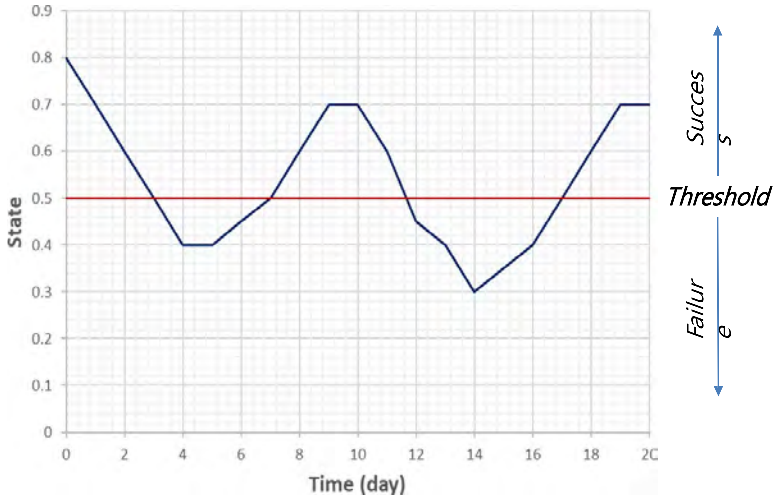
"How quickly a system is likely to recover or bounce back from failure once failure has occurred"

- Inverse of the expected time periods that a system remains unsatisfactory state
- the average probability of recovery (R) to the satisfactory state (S) at time step t+1 once a failure (F) has occurred at time step t

$$R = \frac{P(S_t \in S \text{ and } S_{t+1} \in F)}{P(S_t \in F)} = \frac{P(S_t \in F \text{ and } S_{t+1} \in R)}{P(S_t \in F)} = P(S_{t+1} \in R | S_t \in F)$$

4.3 Probabilistic Measures

▪ Hashimoto (1982); Fowler et al. (2003)



# of failure state (F) = 8
# of recovery (R) = 2

$$R = \frac{2}{8} = 0.25$$

Time(day)	1	2	3	4	5	6	7	8	9	10
State	0.7	0.6	0.5	0.4	0.4	0.45	0.5	0.6	0.7	0.7
Time(day)	11	12	13	14	15	16	17	18	19	20
State	0.6	0.45	0.4	0.3	0.35	0.4	0.5	0.6	0.7	0.7

4.3 Probabilistic Measures

▪ Modification of Hashimoto (1982)

- Moy et al. (1986)
  - Inverse of the maximum consecutive time periods (d) under unsatisfactory state of the system

$$R = [\max\{d_j\}]^{-1}$$

- Kjeldsen and Rosbjerg (2004); Jain and Bhunya (2008)
  - the inverse of the mean time duration that the system remains in an unsatisfactory state (Hashimoto's def.)

$$R = \left\{\frac{1}{m}\sum_{j=1}^{m} d(j)\right\}^{-1}$$

    - d(j) : time duration over the jth failure event
      m : total number of failure events

  - the inverse of pth percentile in CDF fitted to the time duration of the failure events

$$R = \{F_d^{-1}(p)\}^{-1}$$

4.3 Probabilistic Measures

- **Aydin et al. (2014)**
  - Example of Application of Hashimoto's resilience measure to water distribution system
  - Two different consideration of the states were considered: Water pressure and water age

$$RES_{k,ij} = \frac{\#\, of\ time\ satisfactory\ follows\ unsatisfactory}{total\ \#\, of\ unsatisfactory\ occurs}$$

$$P_{i,j,t} = \int_{1}^{0} \begin{matrix} P_{i,j,t} < P_{min} \vee P_{i,j,t} > P_{max} \\ P_{i,j,t} \geq P_{min} \vee P_{i,j,t} \leq P_{max} \end{matrix}$$

$$WA_{i,j,t} = \int_{1}^{0} \begin{matrix} WA_{i,j,t} < WA_{max} \\ WA_{i,j,t} \leq WA_{max} \end{matrix}$$

4.3 Probabilistic Measures

- **Ayyub (2013)**
  - Measured system resilience that includes failure and recovery profiles and accounts for system degradation over time
  - Failure profile (F) is measure of robustness and redundancy and recovery profile (R) is measure of recoverability

$$R_e = \frac{T_i + F\Delta T_f + R\Delta T_r}{T_i + \Delta T_f + \Delta T_r}$$

$$F = \frac{\int_{t_i}^{t_f} f dt}{\int_{t_i}^{t_f} Qdt}, R = \frac{\int_{t_i}^{t_f} rdt}{\int_{t_i}^{t_f} Qdt}$$

- where T_i is the time to incident, T_f is the time to failure, T_r is he time to r ecovery, $\Delta T_f = T_f - T_i$ is the duration of failure, and $\Delta T_r = T_r - T_f$ is the dur ation of recovery

4.5 Water Quality Resilience

- **Contamination assessment index (Karamouz et al. 2017)**
  - Assessment of contamination status for each node, based on providing water with desirable quality, CAI_i for Node i, is obtained
  - considering the demand in the network, a weight is assigned to each node (W_i).
  - The contamination assessment index (CAI_{DWDN}) is estimated, in which vulnerabilities for nodes are composed to obtain the index for the network
  - CAI_{DWDN} value between 0 and 1, where lower values are desired

$$CAI_i = 1 - \frac{\sum_{n=1}^{T} u_{ni} \times v_{ni}}{T \times D_i}$$

$$CAI_{DWDN} = \frac{\sum_{i=1}^{N} W_i \times CAI_i}{\sum_{i=1}^{N} W_i}$$

$$W_i = \frac{D_i}{D_{max}}$$

- CAI_i = contamination assessment index for Node I
- T = time period in which the co ntamination exists in the node
- N = total number of nodes with water demand in the network
- u_{ni} = weight representing the quality of water in Node i in Time step n
- v_{ni} = available water at Node i in Time step n.

4.5 Water Quality Resilience

- **Contamination assessment index (Karamouz et al. 2017)**
  - Assessment of contamination status for each node, based on providing water with desirable quality, CAI_i for Node i, is obtained
  - considering the demand in the network, a weight is assigned to each node (W_i).
  - The contamination assessment index (CAI_{DWDN}) is estimated, in which vulnerabilities for nodes are composed to obtain the index for the network
  - CAI_{DWDN} value between 0 and 1, where lower values are desired

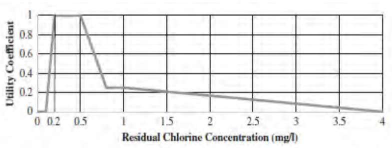


Fig. 4. Variation in utility coefficient corresponding to residual chlorine concentration in the DWDN (adapted from Coelho 1996)

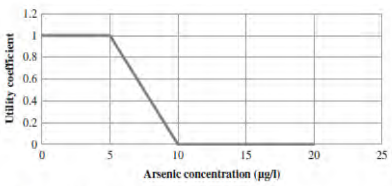


Fig. 5. Variation in utility coefficient corresponding to arsenic concentration in the DWDN

Figures from Karamouz et al. (2017)

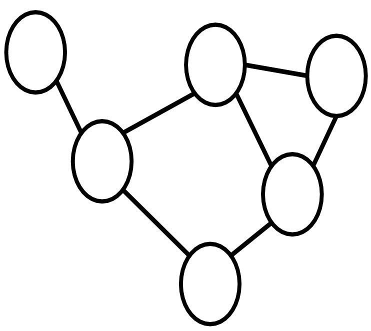
- CAI_i = contamination assessment index for Node I
- T = time period in which the co ntamination exists in the node
- N = total number of nodes with water demand in the network
- u_{ni} = weight representing the quality of water in Node i in Time step n
- v_{ni} = available water at Node i in Time step n.

5. Graph Theory Application to Water Distribution System

5.1 What is Graph Theory?

- **The study of graphs (made up of vertices and connected by edges) used to model pairwise relations between objects**

$$G = (V, E)$$

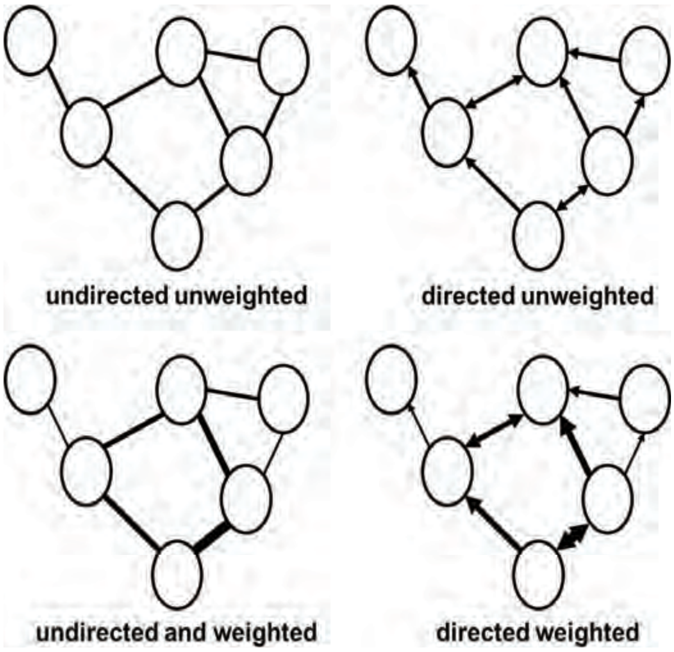


- V, a set of vertices (also called nodes or points);
- $E \in \{\{x, y\} | x, y \in V \; and \; x \neq y\}$, a set of ed ges (also called links or lines), which are u nordered pairs of vertices (that is, an edg e is associated with two distinct vertices)

*Description from Wikipedia (https://en.wikipedia.org/wiki/Graph_theory)

5.2 Type of Graph Theory

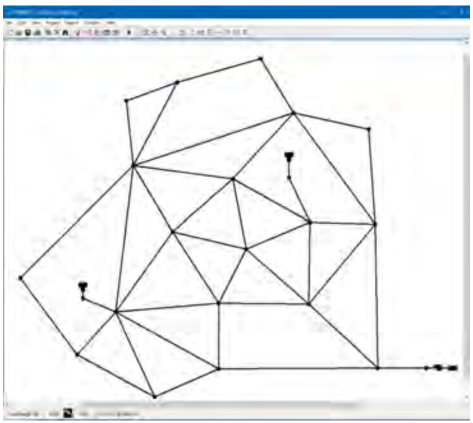
▪ **Weighted vs. Unweighted, Directed vs. Undirected**



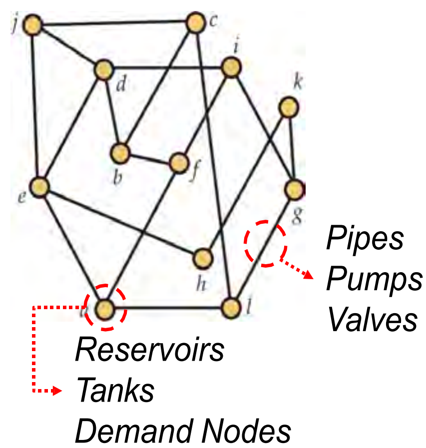
<Source: Lee & Jung (2018)>

5.3 Why Graph Theory to Water Distribution Systems?

▪ **Water distribution system can be considered as a planar graph…**

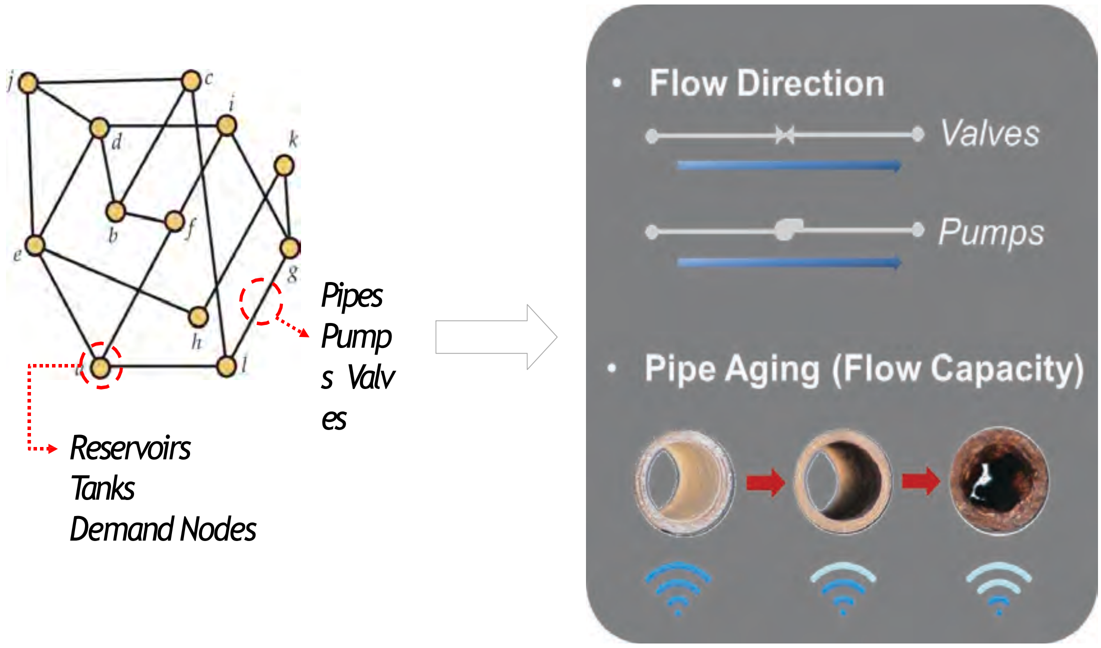


<Water Distribution System>



5.3 Why Graph Theory to Water Distribution Systems?

▪ What can be considered as a weight?



5.4 Graph Theoretic Indicators

▪ Statistical and spectral measurements in graph theory

- Weighted bi-directional networks ➔ the physical and operational attributes (nodes demand, water flow in pipe)

Measurements	Definition	Quantification
Average degree ($degree_{avg}$)	• Average value of the node degree in graph	Connectivity
Link-per-node ratio (e)	• Ratio between number of edges and nodes in graph	Structure
Link density (q)	• Ratio between the total and the maximum possible number of edges (how much the nodes are connected among them)	Connectivity
Diameter (d_T)	• The largest geodesic distance between possible pair of nodes	Structure
Average path-length (l_T)	• Average geodesic distance of the shortest paths between all possible pairs of nodes	Structure

5.4 Graph Theoretic Indicators

▪ Statistical and spectral measurements in graph theory

- Weighted bi-directional networks ➔ the physical and operational attributes (nodes demand, water flow in pipe)

Measurements	Definition	Quantification
Betweenness centrality (B_C)	• The number of all the shortest paths passing through a node (how often a node is put in the shortest path between other nodes)	Connectivity
Closeness centrality (C_c)	• Inverse average distance of the shortest paths between a node and other nodes (how accessible a node is to other nodes in graph)	Connectivity
Central point dominance (C_B)	• Average difference between maximum betweenness centrality and betweenness centrality of all other nodes	Connectivity
Clustering coefficient (C)	• Ratio between number of triangles ($N_{trigangles}$) and all number of possible connected triplets ($N_{triples}$)	Redundancy

5.4 Graph Theoretic Indicators

▪ Statistical and spectral measurements in graph theory

- Weighted bi-directional networks ➔ the physical and operational attributes (nodes demand, water flow in pipe)

Measurements	Definition	Quantification
Meshed-ness coefficient (R_m)	• Ratio between number of loops (cycles) and all number of possible loops in planar graph	Redundancy
Density of articulation points or bridge edge (D_{ap}, D_{br})	• Percentage of the nodes and edges whose removal from a graph disconnects the network (percentage of cut-point and bridge edges)	Connectivity
Spectral gap ($\Delta\lambda$)	• Difference between the first and the second eigenvalues of adjacency matrix of the graph (measure on "good expansion" properties)	Connectivity
Algebraic connectivity (λ_2)	• The second smallest eigenvalue of normalized Laplacian matrix of the graph	Connectivity

5.5 Use of Graph Theory for Resilience Measure

- A few recognized researches...

- **Yazdani et al. (2011)**
  - Examined resilience of water distribution networks in growing city with expansion options

- Proposed resilience metric for water distribution system as 9 indicators quantifying connectivity, structural robustness, and path redundancy

  i.e., 1) link density, 2) average node-degree, 3) diameter, 4) average path-length, 5) clustering coefficient, 6) meshed-ness coefficient, 7) central-point dominance, 8) Density of articulation points, 9) density of bridges, 10) spectral gap, 11) algebraic connectivity

5.5 Use of Graph Theory for Resilience Measure

- A few recognized researches...

- **Archetti et al. (2015) and Soldi et al. (2015)**
  - Used indicators suggested by Yazdani et al. (2011): 1) link density, 2) line-per-node ratio, 3) diameter, 4) average path-length, 5) clustering coefficie nt, 6) central point dominance, 7) Spectral Gap, and 8) algebraic connect ivity
  - Suggested spectral gap and algebraic connectivity as the most relevant measure of graph theory to assess the overall resilience of a WDS for the physical disconnection and failure due to disruptions.

5.5 Use of Graph Theory for Resilience Measure

▪ Herrera et al. (2015)

- Used closeness centrality for analyzing WDN resilience and identifying low resilience node
- Incorporated energy losses related to flow in pipe into the concept of geodesic distance of link (pipe) in WDN

➔ "water-flow closeness (W-Fc)"

$$C_C(i) = \frac{n-1}{\sum_{t \neq i} d(t,i)}$$

→ *Dissipated energy along the pipe with water flowing between nodes*

$$C_{WC}(i) = \frac{n-1}{\sum_{t \neq i} \lambda(t,i)}$$

$$\lambda(t,i) = \min\{\sigma_{j=1}^{m} sign(q_j) r_j q_j^2\}$$

where, n: number of nodes, λ: energy loss, l: paths between nodes, r: head loss pipe resistance coefficient, q: flow rate, d: distance between nodes

5.5 Use of Graph Theory for Resilience Measure

▪ Herrera et al. (2015)

- Considered K 'shortest' routes as connectivity of nodes to water sources (resilience of individual nodes)

$$I_{GT}(i) = \sum_{s=1}^{S} \frac{1}{K} \sum_{k=1}^{K} \frac{1}{r(k,s)}$$

$$r(k) = \sum_{m=1}^{M} f(m) \frac{L_m}{D_m}$$

where, s: number of water sources, r(k, s): surrogate measure of the energy loss associated the kth to source s, f(): friction factor by pipe age and mat erial

5.5 Use of Graph Theory for Resilience Measure

- **Herrera et al. (2016)**

- Extended resilience evaluation to the large scale water networks
- Proposed multiscale resilience measure for water networks divided into sectors
    - Mean resilience: Transform the resilience of n^* demand nodes of sector i to the sector resilience)

$$I^*_{GT}(Sector\ i) = \sum_{j=1}^{n_i^*} \frac{I_{GT}(j)}{n_i^*}$$

where, n^*: nodes of sector i

- Variability of resilience: Standard deviation normalized by the mean resilience value

$$S^2_{GT}(Sector\ i) = \sum_{j=1}^{n_i^*} \frac{1}{n^* - 1}\left(\frac{I_{GT}(j) - I^*_{GT}}{I^*_{GT}}\right)^2$$

7. Closing Remarks

1. Filling gaps to Existing Resilience Measures
2. Summary

7.1 Filling gaps to Existing Resilience Measures

▪ Improvements in the existing resilience measures

Major features of resilient system	Improvements for decision making
❑ Withstanding system disruptions	• Considering multiple functionalities • Estimating system functionality considering interaction with other critical infrastructures
❑ Absorbing system disruptions	• Defining thresholds of network redundancy and connectivity (graph measure) • Developing fragility functions for various components and disturbances • Coupling water system resilience and community resilience
❑ Rapidly recovering to normal functionality	• Improving recovery time estimation considering various affecting factors (system damage, budget, labor, scheduling, accessibility, etc) • Estimating failure detection time
❑ Adapting to changing and uncertain disruptions	• Addressing multiple / compounded disruptive events • Considering spatial and temporal variation of disturbances and resilience • Developing a standardized form of structure-based measures (graph measure)

7.1 Filling gaps to Existing Resilience Measures

▪ Improvements in the existing resilience measures

- Encourage water-related research and engineering communities in development of improved and quantitative resilience measures
- Provide insights on improving existing resilience measures for water infrastructure systems
- Challenges as the future works
  - Reviewing more various types of water infrastructure system (e.g., wastewater treatment plants)
  - Investigating resilience measure in various fields (e.g., economic, social, and organizational resil.)
  - Integrating with sustainability concept (or green growth, etc.)
- Provide information for new resilience measure, which addresses requirements (criteria) reflecting major features of resilient systems

7.1 Filling gaps to Existing Resilience Measures

▪ Improvements in the existing resilience measures

- Although there is not a single measure suitable for measuring the resilience of water systems to hazards, multiple performance measures might be useful

- Existing software, like EPANET, needs to be modified to allow for failure of components in some parts of a system, while remaining operational in other parts

- These tools need to incorporate uncertainty inherent in the disaster scenarios and in the utility response, using Monte Carlo or stochastic simulation approaches

- By enhancing systems-modeling tools and enabling network models to robustly handle failures and s tresses, a comprehensive evaluation of the benefits of each resilience metric can be conducted, and i mproved resilience tools can be provided to the water sector

7.2 Summary

- Quantification of the resilience can be done in two different ways: (1) function-based or (2) structural-based

- Function based can be divided into four categories by first consideration of uncertainty (either dete rministic or probabilistic) and second consideration of time-dependent behavior (either static or dyn amics)

- Function-based approach highly rely on hydraulic and water quality analysis while structural-based approach doesn't
    - As resilience assessment involves failure state, pressure driven analysis is more suitable approach to analysis hydraulics of the system

- Structural-based approach needs topological configuration of the system


Thank you very much

Resilience of Drinking Water Infrastructure: Applications

Water Security and System Resilience

7. Resilience of Drinking Water Infrastructure : Applications

UNESCO
United Nations Educational, Scientific and Cultural Organization
i-WSSM
International Centre for Water Security and Sustainable Management

Aims & Objectives

- The aims of the course are to:

  (1) Explain strategies enhancing resilience of drinking water infrastructure
  (2) Explain considerations for modeling resilience for drinking water infrastructure
  (3) Introduce tools for resilience assessment

- The objectives are that trainees will understand:

  (1) Strategies to enhance resilience of water distribution system
  (2) Requirements for modeling resilience of water distribution system

References

Drinking water distribution systems: assessing and reducing risks. (NAC, 2007)

Public Water Supply Distribution Systems: Assessing and Reducing Risks: First Report (NAC, 2005)

Pattern Recognition for Reliability Assessment of Water Distribution Networks. (Trifunovic, 2012)

Review of modeling methodologies for managing water distribution security (Berglund et al 2020).

System Measures of Water Distribution System Resilience (USEPA, 2015)

A review of data-driven approaches for burst detection in water distribution systems. (Wu and Liu, 2017)

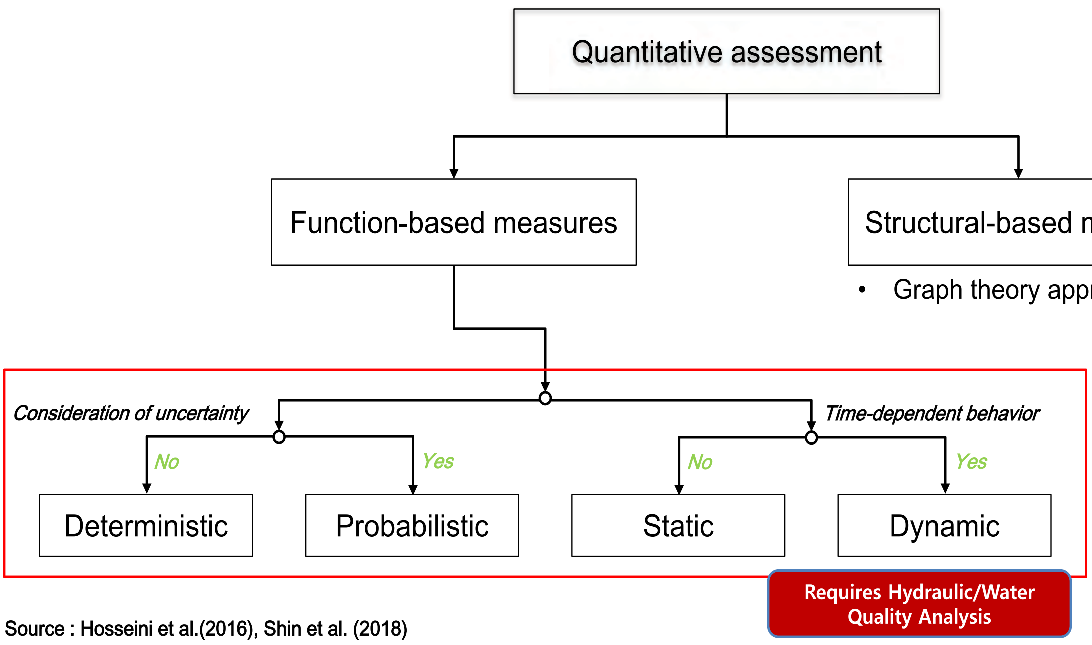
Contents

1. Overview of the Resilience Assessment

1. What have We Learnt?
2. Water Distribution System Functionality Response
3. Criticality Analysis
4. Uncertainty Analysis
5. Tuning the Model for Resilience Analysis
6. Programming Needs

1.1 What have We Learnt?

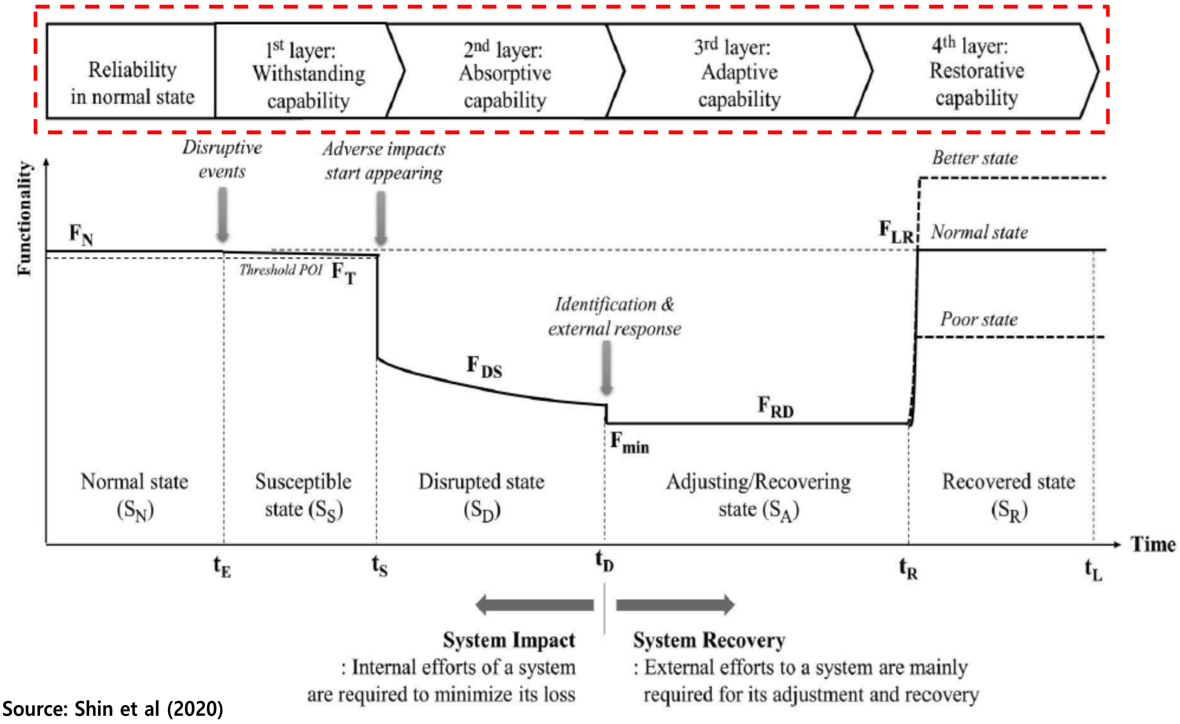
- **Classification of quantification measures**



Source : Hosseini et al.(2016), Shin et al. (2018)

1.1 What have We Learnt?

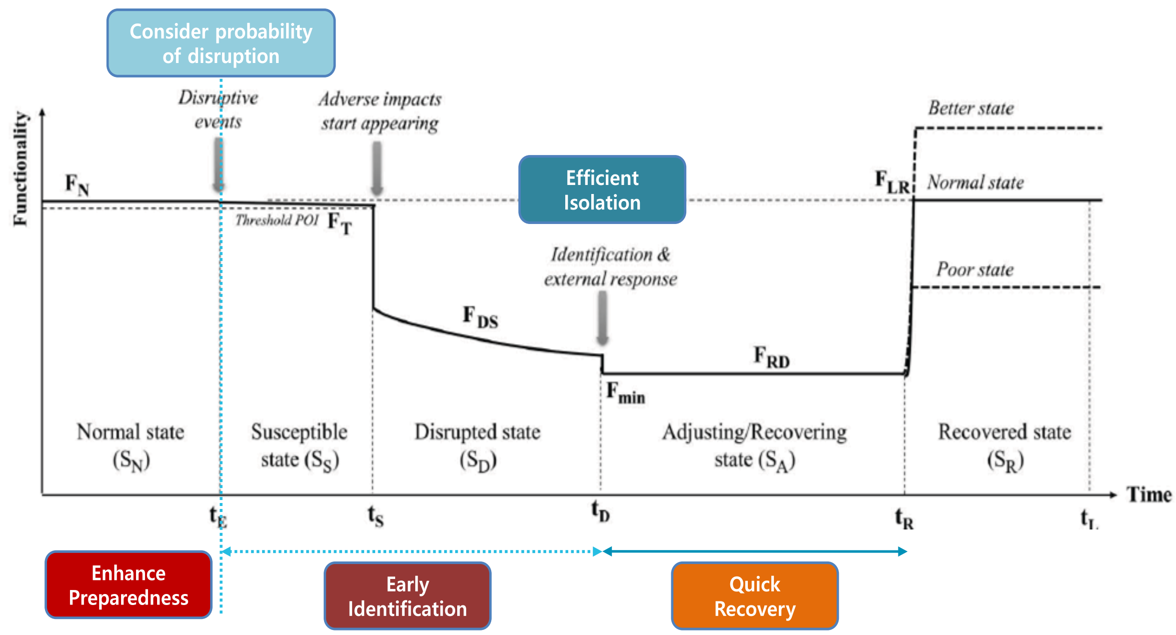
- **Functionality curve**



Source: Shin et al (2020)

1.2 Water Distribution System Functionality Response

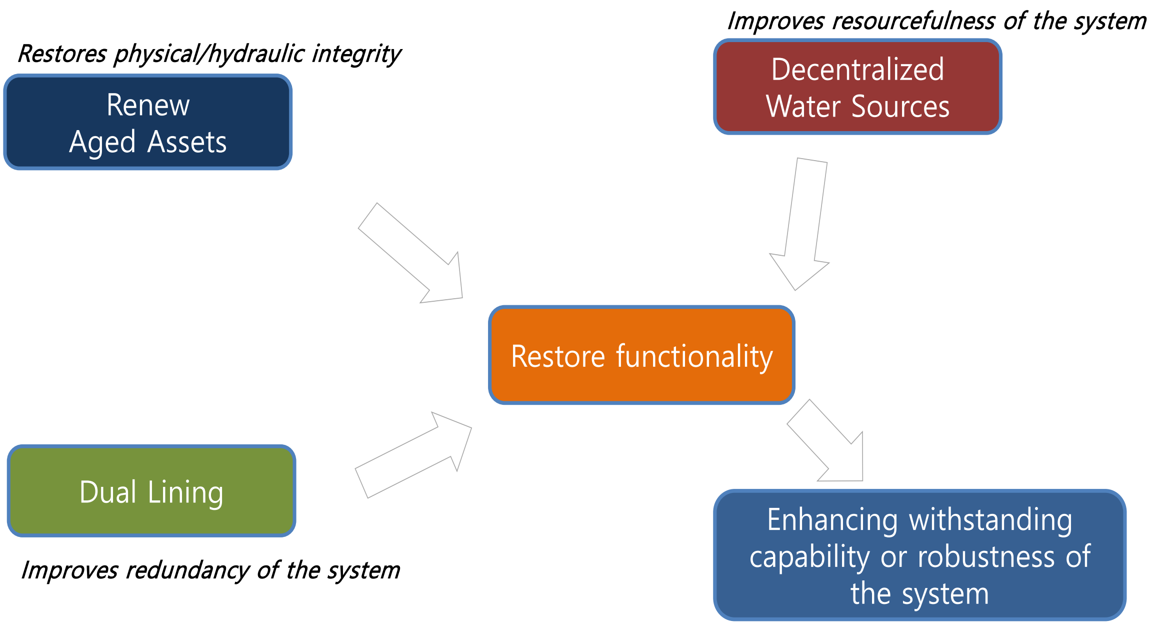
- **The goal of a resilient system is to minimize the magnitude and duration of disruption**



Source: Shin et al (2020)

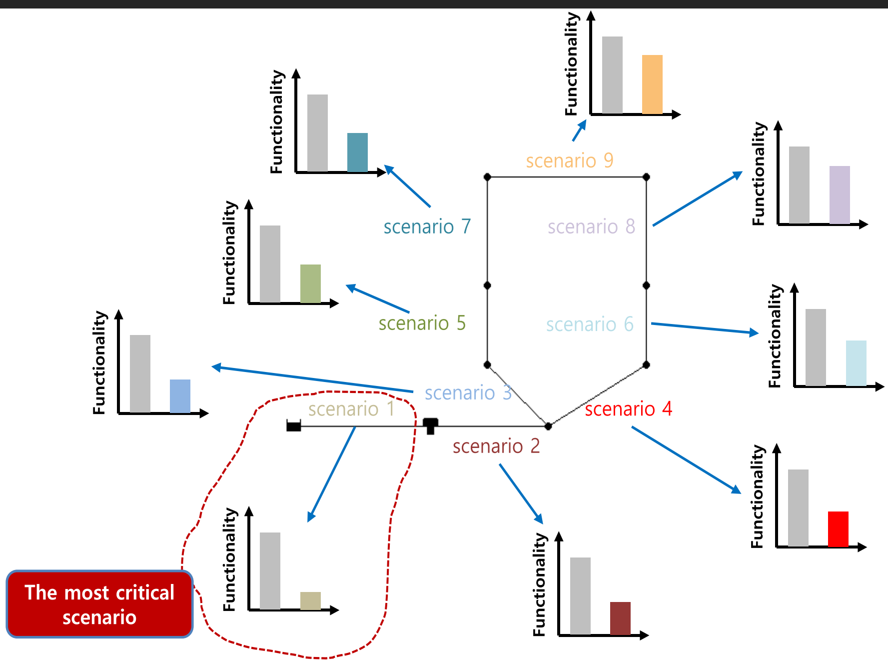
1.2 Water Distribution System Functionality Response

- **Enhancing preparedness includes renewal of aged assets, dual lining, decentralized water sources, etc.**



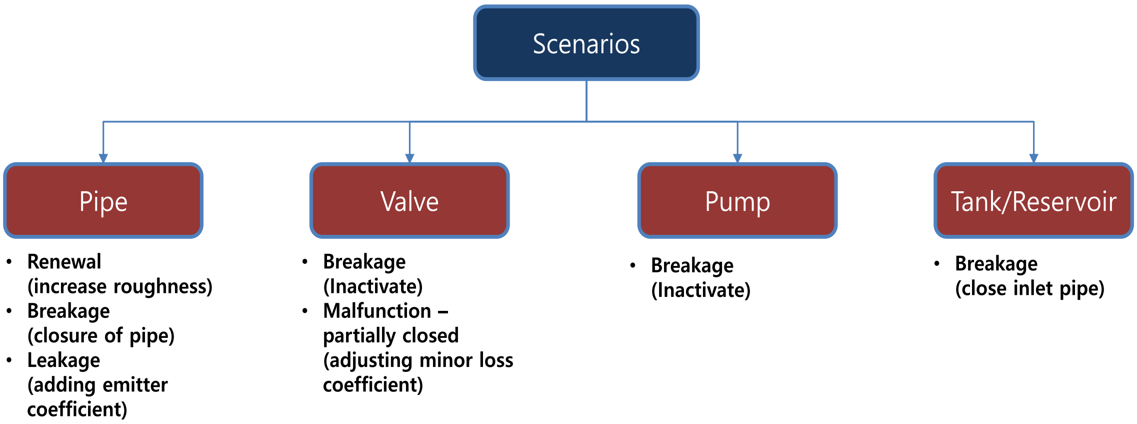
1.3 Criticality Analysis

- **Criticality is defined as the quality, state, or degree of unsuccessful operation directly cased by a failed component**



1.3 Criticality Analysis

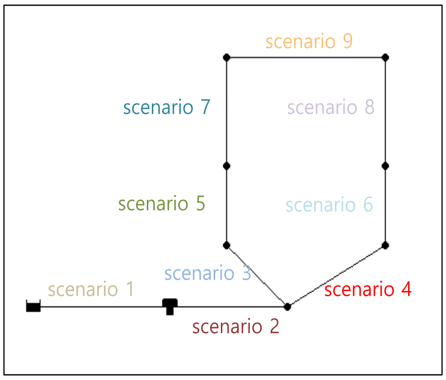
▪ **Scenarios can be considered for all assets for different cause of failures**



1.4 Uncertainty Analysis

▪ **All scenarios have different probabilities (Lessons from Ch1)**

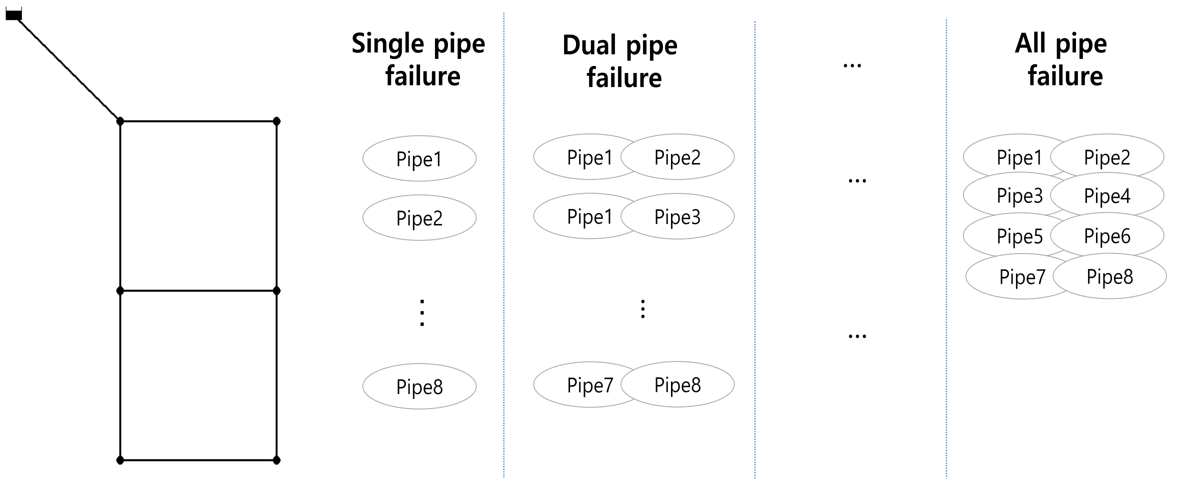
- In a WDS, uncertainties can be applied by generating many random disruption scenarios
- On a small scale, all the disruptions might be able to be defined
- On a complex system, it would be too much to exhaust all possible risks
- Major uncertainties of resilience assessment is in the probabilities and types of disruption scenarios



[Scenario variance]

1.4 Uncertainty Analysis

- **How can we minimize uncertainty?**
  - Best way is to run all possible scenarios…

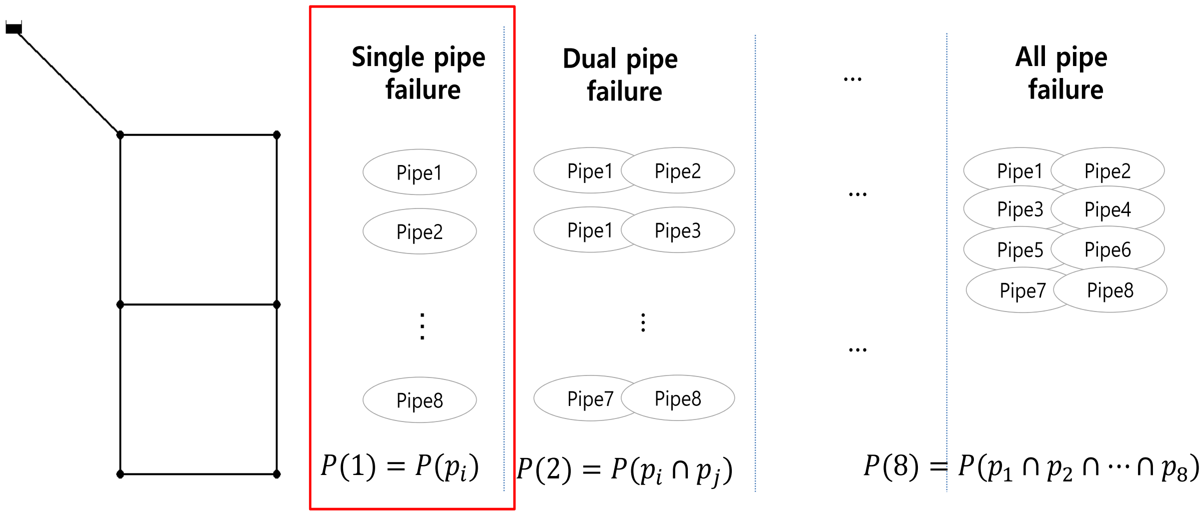


If number of pipe is np then total number of simulation is 2^{np} for this simple network, 256 case

What if possible scenarios are too much?

1.4 Uncertainty Analysis

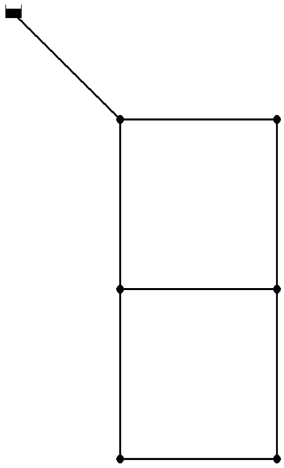
- **Often only single failure can be considered (usually from criticality perspective)**



Single pipe possess larger possibility of occurrence

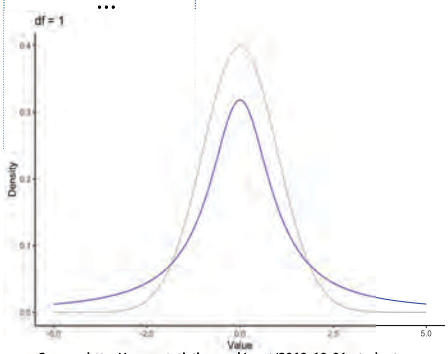
1.4 Uncertainty Analysis

- **Let's sample some of the scenarios instead of running all possible scenarios**



Single pipe failure	Dual pipe failure	…	All pipe failure
Pipe1	Pipe1 Pipe2	…	Pipe1 Pipe2
Pipe2	Pipe1 Pipe3		Pipe3 Pipe4
⋮	⋮		Pipe5 Pipe6
Pipe8	Pipe7 Pipe8	…	Pipe7 Pipe8

⇨ More samples will increase accuracy



Source: http://www.statistics.cool/post/2019-10-01-student-s-t-and-the-normal-distribution_files/figure-html/tplot-.gif

1.4 Uncertainty Analysis

- **What kind of uncertainty analysis we can consider?**

First-order Second-moment (FOSM)

Estimates the variance by **approximating a function with a Taylor series expansion** around the mean value of the parameters and dropping the higher-order terms (Tung and Yen 2005).

Latin Hypercube Sampling (LHS)

A stratified sampling method that randomly selects samples of each input parameter over its range in a stratified manner (Kang et al. 2009)

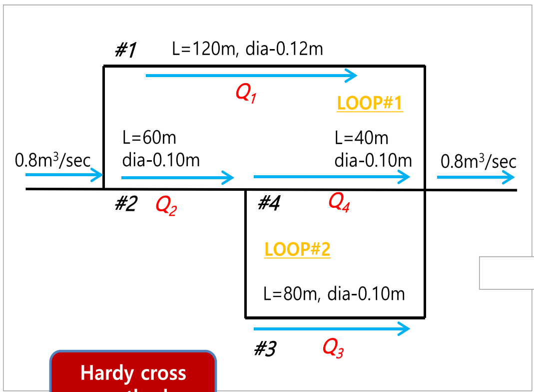
Monte Carlo Simulation (MCS)

An enumeration technique that generates and evaluates a large number of parameter sets (known as realizations) based upon the probability distribution of the input parameters (Kang et al. 2009)

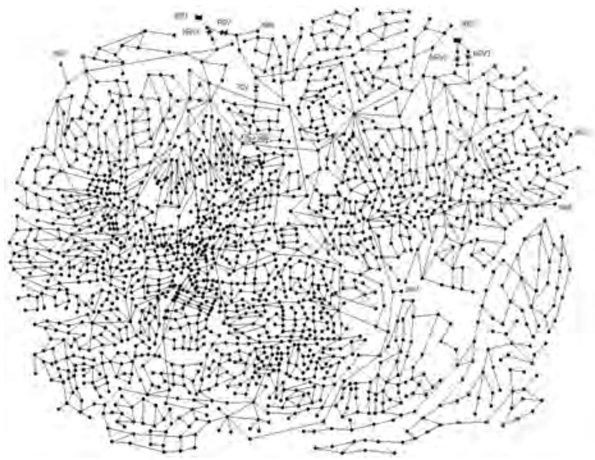
⇨ Requires additional modeling work

1.5 Tuning the Model for Resilience Analysis

- Modeling is necessary to assess resilience as the most water distribution system have complex network topology



Hardy cross method



Hydraulic Analysis tool

1.5 Tuning the Model for Resilience Analysis

- Accuracy of the hydraulic/water quality analysis depends on the accuracy of the model

Calibration of network model

Water Quality

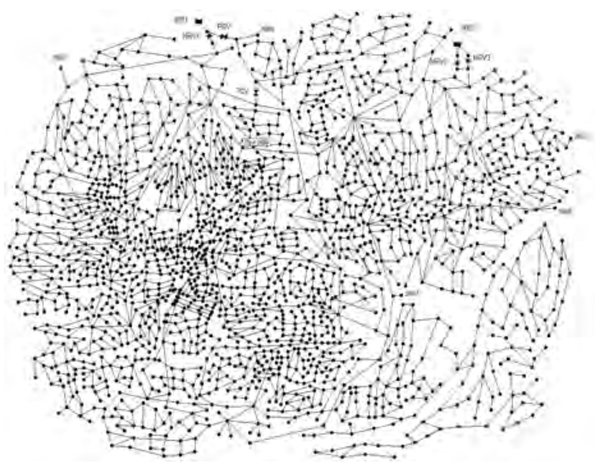
- Reaction rate
- Wall decay coefficient
- Bulk decay coefficient

Node

- Demand
- Elevation

Link

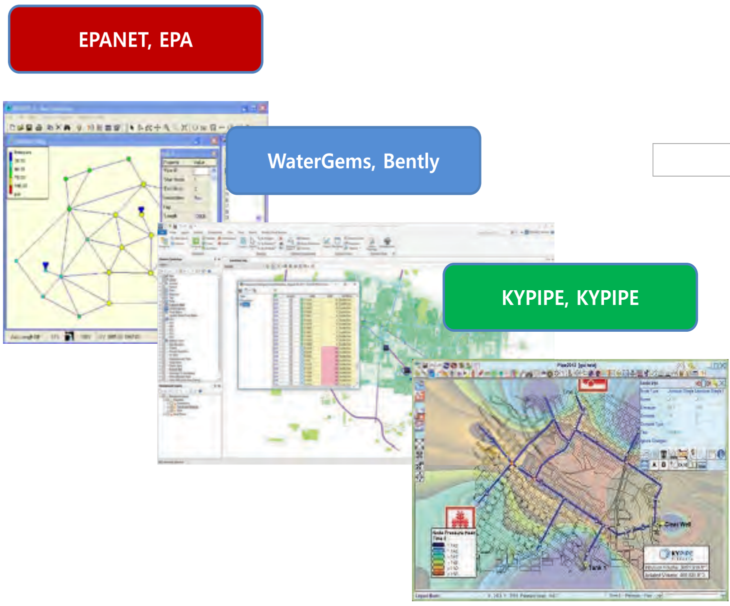
- Pipe Roughness Coefficient
- Diameter
- Length
- Minor loss coefficient



Hydraulic Analysis tool

1.6 Programming Needs

- **Most of the hydraulic models are capable to investigate hydraulics and water qualities of the network but not resilience**



- Resilience should be assessed **externally** but with the hydraulic/water quality analysis results
- Also, multiple simulation can be executed by programming

1.6 Programming Needs

- **Computer programming language helps to interact with the hydraulic model (EPANET)**

python

R

④ Calculate Resilience

THE C PROGRAMMING LANGUAGE

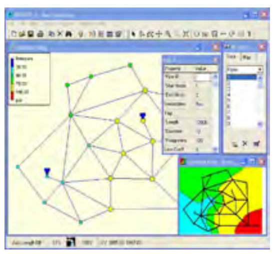
MATLAB

Some of the common Programming Languages

① Call epanet2.dll

③ Send Hydraulic analysis Results

EPANET, EPA



② Run hydraulic/ water quality simulation

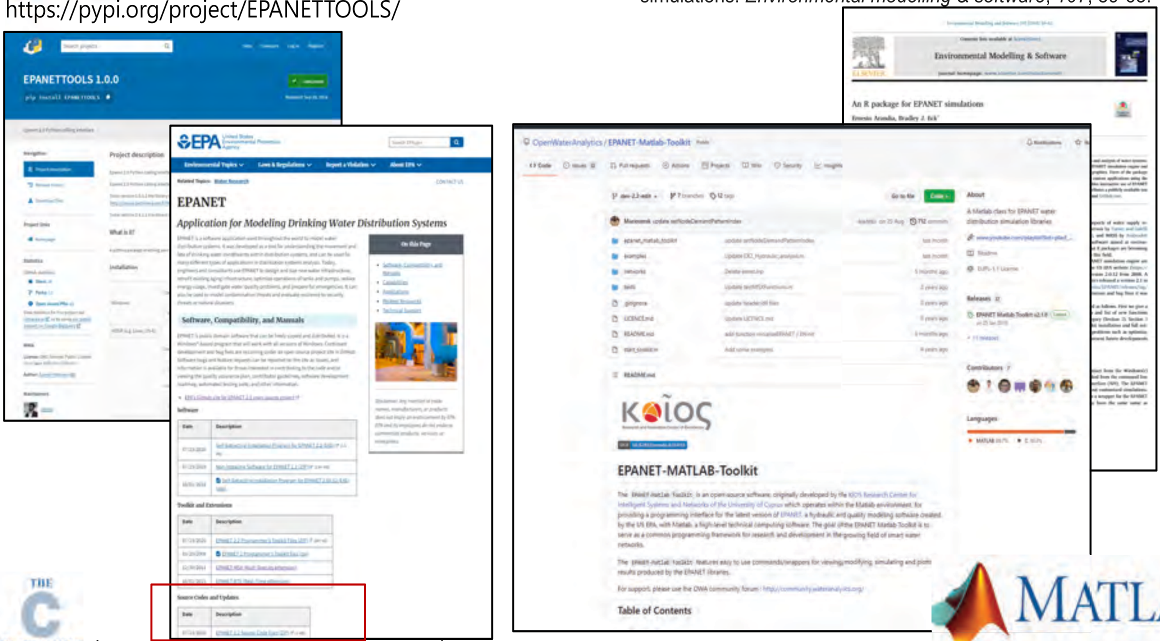
1.6 Programming Needs

- **Some useful sources to access EPANET with programming languages**

python

https://pypi.org/project/EPANETTOOLS/

Arandia, E., & Eck, B. J. (2018). An R package for EPANET simulations. *Environmental modelling & software*, *107*, 59-63.



THE C PROGRAMMING LANGUAGE https://www.epa.gov/water-research/epanet

MATLAB https://github.com/OpenWaterAnalytics/EPANET-Matlab-Toolkit

2. Water Distribution System Failure Modeling

1. Modeling Failures in Water Distribution System
2. Pipe Failures
3. Lifetime Distribution Models
4. Fragility Curve
5. Tree Analysis

2.1 Modeling Failures in Water Distribution System

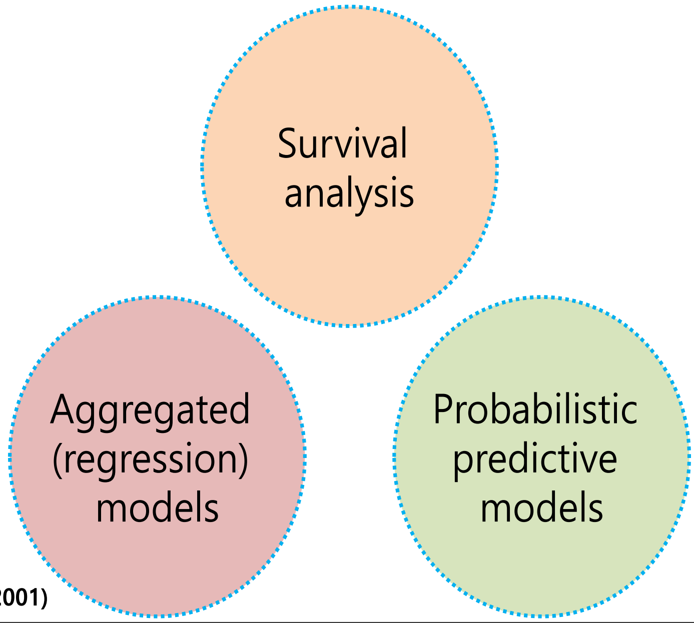
- **Two distinct types of events can induce a water distribution system to a failure state**
  - Hydraulic performance failure
  - Mechanical failure

- Hydraulic performance failure
  - Related to the situation where the demand imposed on a system exceeds the capacity of the system

- Mechanical failure
  - Related to a component failure which can lead (but not necessary) to the hydraulic performance failure
  - Involves actual failures of the network reducing its conveying capacity during the failure but also after the failed component is isolated and undergoing repair

2.2 Pipe Failures

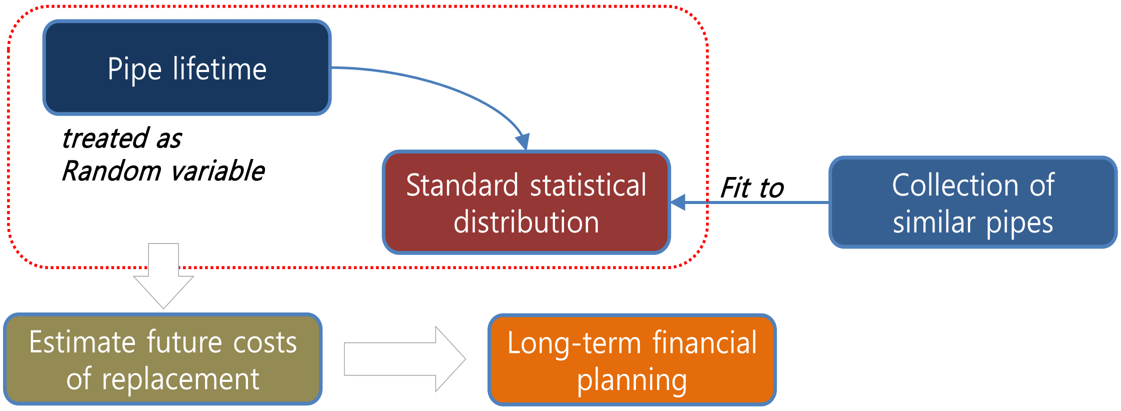
- **Pipes are commonly analyzed on mechanical failures**
  - The objective of modelling pipe failure rate is to reproduce adequately the average tendency of the annual number of pipe breaks and to predict breakage rates in the future.



Source: Watson et al. (2001)

2.2 Pipe Failures

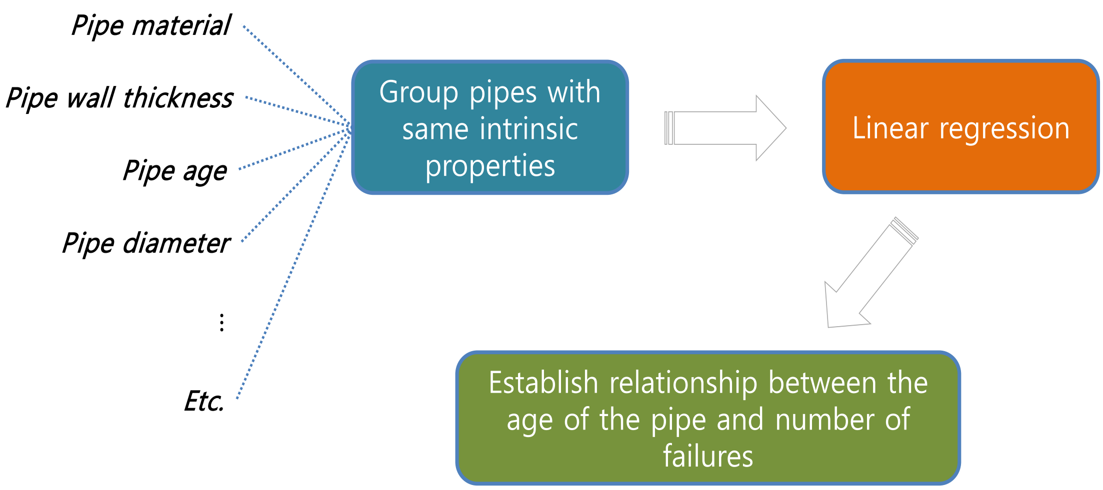
▪ Survival analysis



- Survival analyses focus on the lifetime of a pipe
- The pipe lifetime is treated as a random variable and a standard statistical distribution is then fitted to a collection of similar pipes
- The pipe group can then be aged to assess what the likely future costs of replacement would be for a long-term financial planning

2.2 Pipe Failures

▪ Aggregated (regression) models



2.2 Pipe Failures

- **Aggregated (regression) models**

- **Su et al. (1987)**
  - Used pipe failure data from the 1985 St. Louis Main Break Report to derive a regression equation correlating the failure rate λ and pipe diameter D

$$\lambda = \frac{0.6858}{D^{3.26}} + \frac{2.7158}{D^{1.3131}} + \frac{2.7685}{D^{3.5792}} + 0.042$$

  - where, D: pipe diameter (inches), λ: failure rate in (breaks/mile/year)

2.2 Pipe Failures

- **Aggregated (regression) models**

- **Shamir and Howard (1979)**
  - Proposed an exponential model at which the pipe failure is increased with time:

$$\lambda(t) = \lambda(t_0)e^{A(t-t_0)}$$

  - where, λ(t) is the average annual number of failures per unit length of the pipe surveyed at year t, t_0 is the base year for analysis, and A is the growth rate coefficient between year t_0 and t.

  - A number of researchers have used the multiple regressions to improve the above equation to relate the environmental and intrinsic properties of the pipe.

2.2 Pipe Failures

▪ Probabilistic predictive models

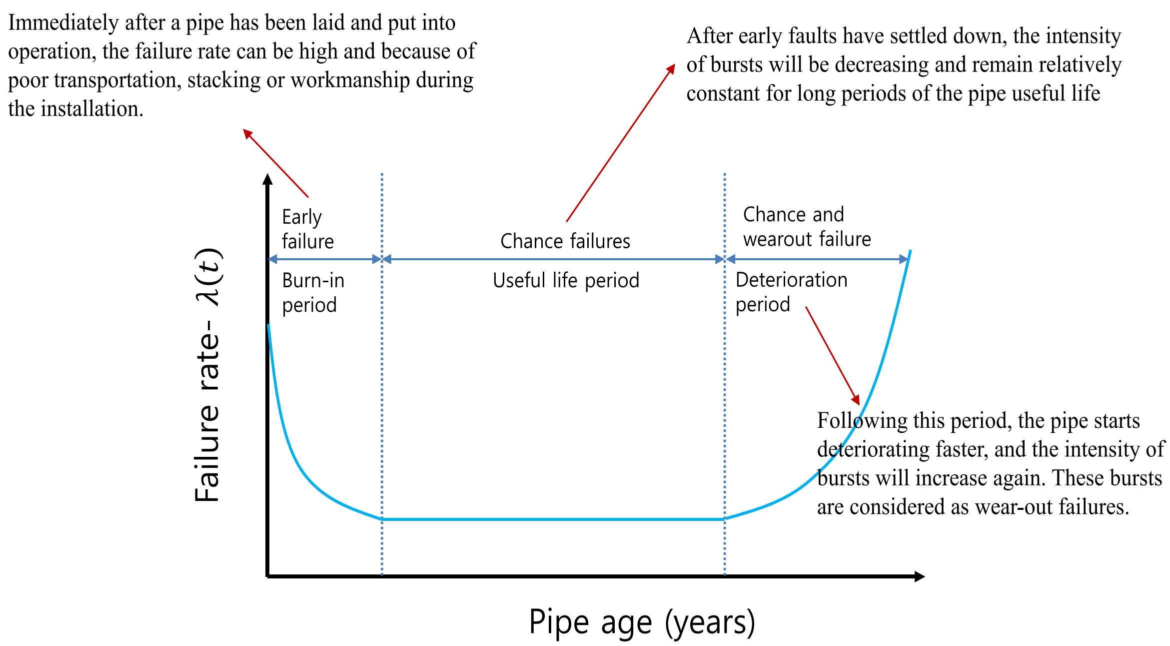
- Predict the probability that a pipe will burst at a particular moment
- The probability can help to identify the economic life of the pipe which can be used to schedule pipe replacement
- **Andreo et al. (1987)**
  - Used the Cox Proportional Hazard Model to consider the hazard function to probabilistic predictive model:

$$h(t:z) = h_0(t)e^{zb}$$

  - where, h(t:z) is the failure rate at time t related to factor z , $h_0(t)$ baseline hazard function, z is a vector of explanatory variables (diameter, soil, etc.), and b is a vector of regression coefficients

2.3 Lifetime Distribution Models

▪ Bathtub shaped intensity function



(adapted from Neubeck, 2004)

2.3 Lifetime Distribution Models

- **Failure lifetime distribution**
  - Homogeneous Poisson Process (HPP): Neglects the time component of the failure
  - Non-homogeneous Poisson Process (NHPP): Considers the time component

HPP

$$p_j = 1 - e^{-\beta_i}, \quad where \quad \beta_i = \lambda_i L_i$$

β_i is expected number of failures per year for pipe i, λ_i is expected number of failure per unit length of pipe i, and L_i is length of pipe i

NHPP

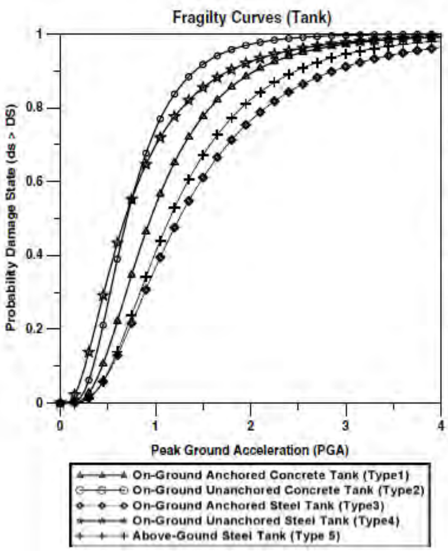
(1) Power relation model: $\lambda_i(t) = e^{c+bt}$

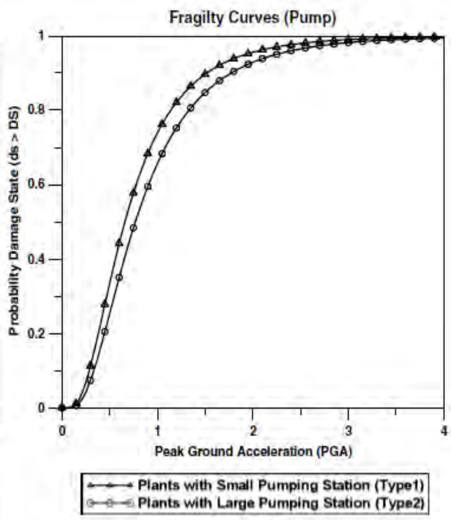
(2) Exponential model: $\lambda_i(t) = \frac{dM(t)}{dt} = abt^{b-1}$

$\lambda_i(t)$ is the pipe failure rate at time t, $dM(t)$ is expected number of failures between time 0 and t, and a, b, and c are empirically determined parameters from the historical burst records

2.4 Fragility Curve

- **A mathematical expression that relates the probability of reaching or exceeding a particular damage state, given a particular level of earthquake hazard (ALA, 2001)**





Source: Yoo et al. (2016)

2.4 Fragility Curve

▪ Calculating repair rate for seismic event

Calculate seismic attenuation

↓

Calculate repair rate

- **Kawashima et al. (1984)**

$$PGA = 403.8 \times 10^{0.265M} \times (R + 30)^{-1.218}$$

- **Baag et al. (1998)**

$$\ln PGA = 0.40 + 1.2M - 0.76\ln\Delta - 0.0094\Delta$$

- **Lee and Cho (2002)**

$$\log PGA = -1.83 + 0.386M - \log R - 0.0015R$$

where PGA is peak ground acceleration (cm/s^2), M is earthquake magnitude, R is epicenter distance (km), and Δ is distance (km) from focus assuming a focal depth of 10 km

- **Isoyama et al. (2000)**

$$RR = C1 \times C2 \times C3 \times C4 \times 0.00187 \times PGA$$

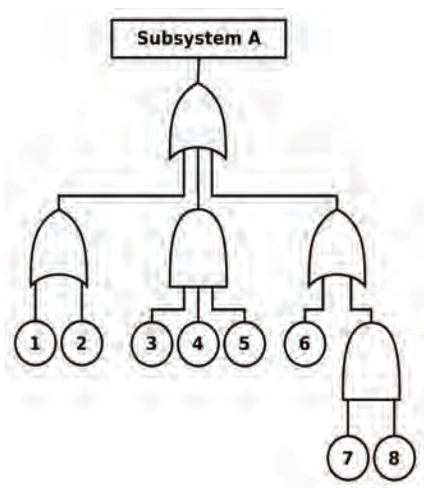
where $C1$, $C2$, $C3$, and $C4$ represent the correction factors for the pipe diameter, pipe material, topography, and liquefaction, respectively. Details of each factor can be found in Isoyama et al. (2000) or Yoo et al. (2016)

Source: Yoo et al. (2016)

2.5 Tree Analysis

▪ Fault tree analysis

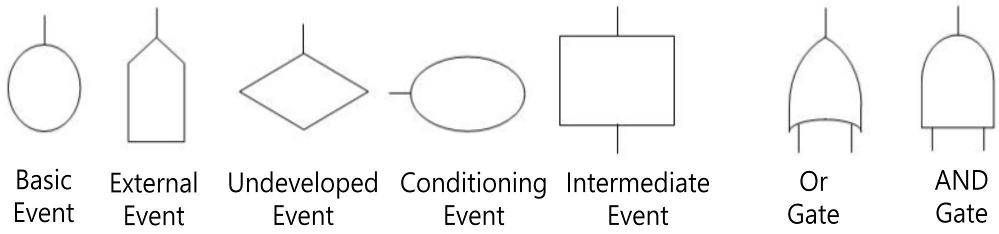
- Fault tree analysis (FTA) is a top-down, deductive failure analysis in which an undesired state of a system is analyzed using Boolean logic to combine a series of lower-level events
- This analysis method is mainly used in safety engineering and reliability engineering
- Helps to understand how systems can fail and to identify the best ways to reduce risk and to determine (or get a feeling for) event rates of a safety accident or a particular system level (functional) failure.



2.5 Tree Analysis

▪ Explaining symbols of fault tree

Event symbols **Gate symbols**

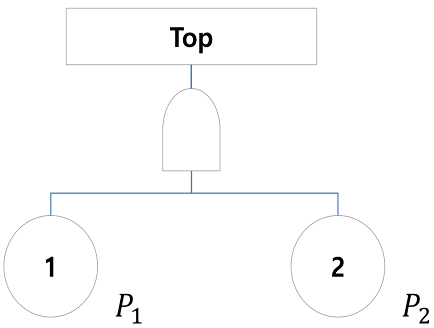


- **Basic event** - failure or error in a system component or element (example: switch stuck in open position)
- **External event** - normally expected to occur (not of itself a fault)
- **Undeveloped event** - an event about which insufficient information is available, or which is of no consequence
- **Conditioning event** - conditions that restrict or affect logic gates (example: mode of operation in effect)
- **An intermediate event gate -** can be used immediately above a primary event to provide more room to type the event description.
- **OR gate** - the output occurs if any input occurs.
- **AND gate** - the output occurs only if all inputs occur (inputs are independent)

2.5 Tree Analysis

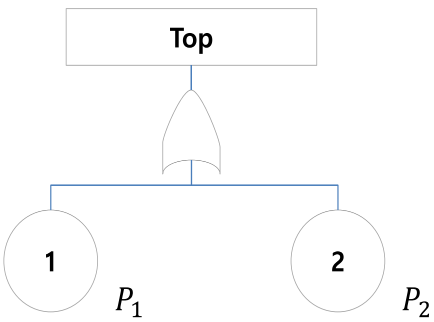
▪ Calculating probabilities of each gate symbol

AND Gate



$$P_T = P_1 \times P_2$$

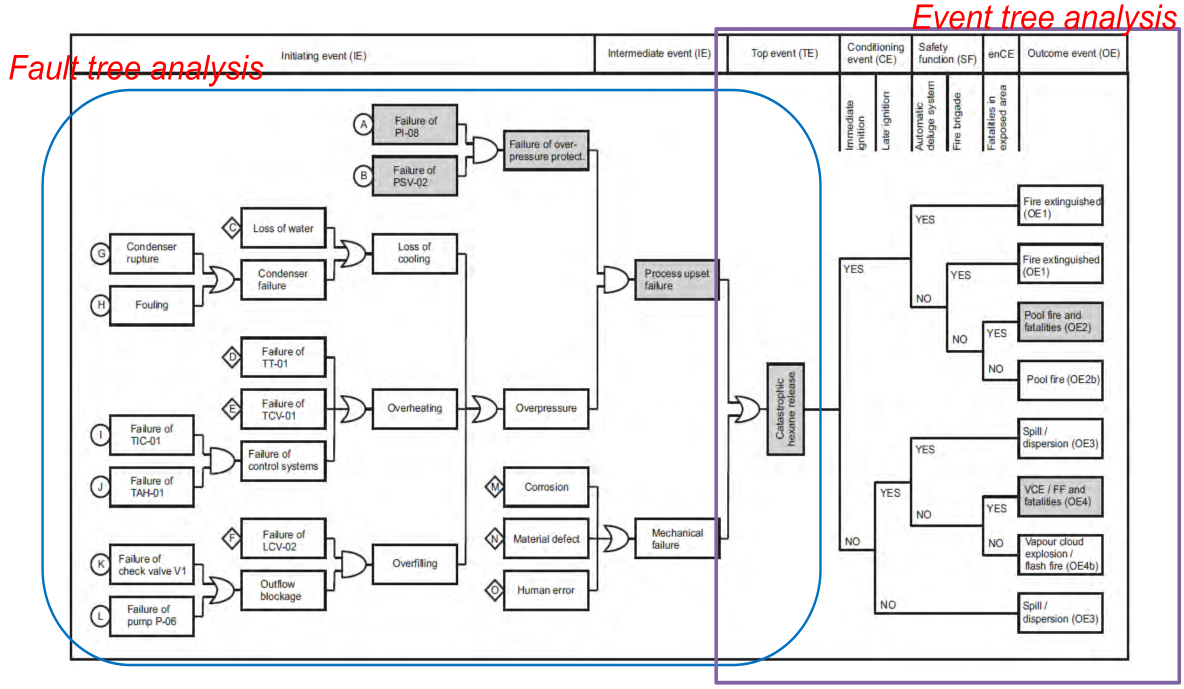
OR Gate



$$P_T = P_1 + P_2 - (P_1 \times P_2)$$

2.5 Tree Analysis

▪ Connection to Event tree analysis



Source: Markowsk and Kotynia (2011) “Bow-tie” model in layer of protection analysis

3. Detection of Abnormal Conditions

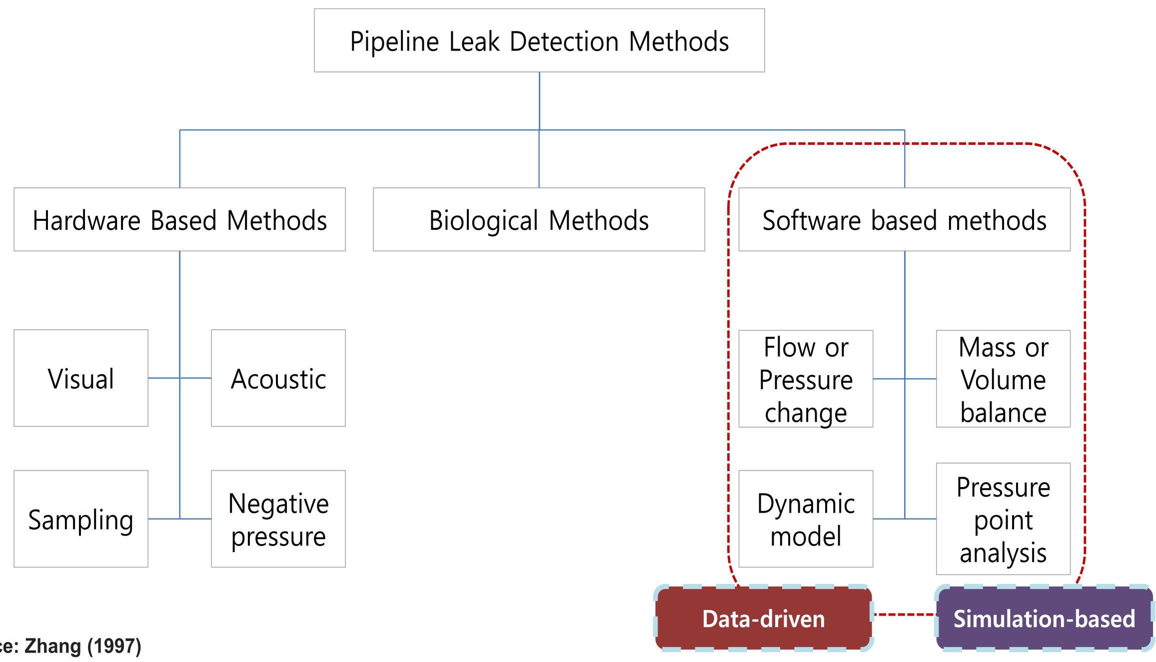
1. Overview of Abnormality Detection
2. Identification of Failure
3. Water Quality Failure
4. Enhancing Security

3.1 Overview of Abnormality Detection

	Physical Threats	Contamination Threat	Cybernetic threats	Interconnected infrastructure threats
Risk Assessment	▪ Assess network serviceability for threat scenarios ▪ Identify vulnerable infrastructure assets	▪ Rank vulnerable nodes ▪ Conduct QMRA (Quantitative Microbial Risk Assessment) ▪ Develop design basis threats	▪ Characterize potential attack scenarios ▪ Conduct modified contingency analysis	▪ Assess network serviceability for threat scenarios
Mitigation	▪ Implement countermeasures ▪ Harden infrastructure by replacing pipes	▪ Implement countermeasures ▪ Install water quality sensors ▪ Design network sectors for isolation ▪ Install chlorine boosters ▪ Maintain disinfectant residuals ▪ Control valves and pumps for pressure	▪ Design redundancy, diversity, and hardening in cyber networks	▪ Install backup power sources ▪ Add electrical bypass lines ▪ Harden electrical substations

3.2 Identification of Failure

▪ **Fault detection and diagnosis methods**



Source: Zhang (1997)

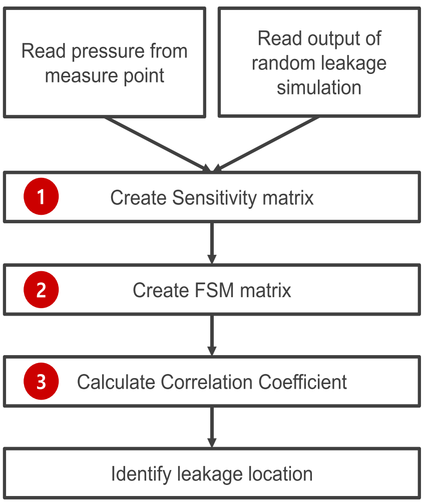
3.2 Identification of Failure

▪ Data-driven approaches

Category	Methodology	Limitation	Method Improvement
Classification methods	• Static/time-delay ANN • Self-organizing map ANN	• Lacking labels of hydraulic data to train and test models • Easily affected by unbalanced class sizes	• Unsupervised models
Prediction-classification methods	• MDN (mixture density network) • Fuzzy inference system • Linear Kalman Filter • Nonlinear Kalman Filter • Support vector regression • Evolutionary polynomial regression • Bayesian inference system • Statistical process control	• Propagation of data uncertainty • Misleading results because of deterministic model outputs	• Ensuring stationary conditions in historical data using statistical tests before model construction • Removing abnormal data in an unsupervised manner during model construction • Developing probabilistic methods to express the degree of conviction in model outputs
Statistical methods	• Statistical process control • Principal component analysis	• Inappropriate distribution assumptions	• Selecting robust statistics • Using asymmetric control limits to fit imperfect data

3.2 Identification of Failure

▪ Model-based failure detection example
▪ Pressure sensitivity (Pérez et al. 2010)



# of leakage (nl)

$$S(k)=\begin{pmatrix}\frac{\hat{p}_{1f_1}(k)-\hat{p}_{10}(k)}{f} & \cdots & \frac{\hat{p}_{1f_{nl}}(k)-\hat{p}_{10}(k)}{f}\\ \vdots & \ddots & \vdots\\ \frac{\hat{p}_{nsf_1}(k)-\hat{p}_{ns0}(k)}{f} & \cdots & \frac{\hat{p}_{nsf_{nl}}(k)-\hat{p}_{ns0}(k)}{f}\end{pmatrix} \quad ①$$

# of sensor (ns)

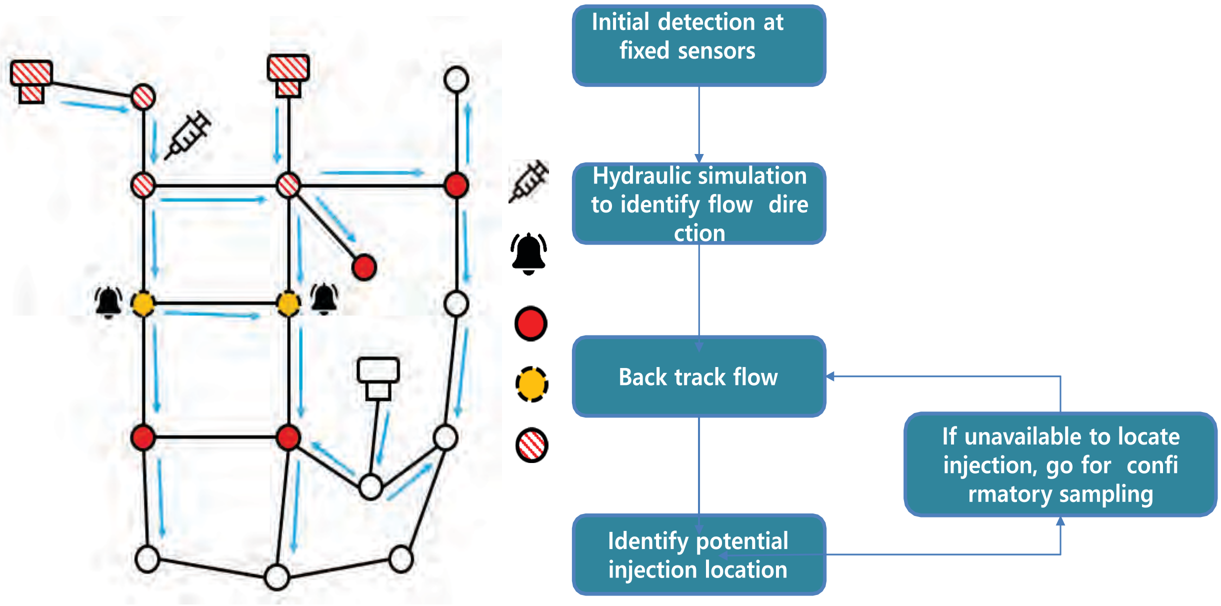
$$\phi_k=\begin{pmatrix}p_1(k)-\hat{p}_{10}(k)\\ \vdots\\ p_{ns}(k)-\hat{p}_{ns0}(k)\end{pmatrix} \quad ②$$

$$\rho_{\phi_k,FFP(k)}=\frac{cov(\phi_k,FFP(k))}{\sigma_{\phi_k}\cdot\sigma_{FFP(k)}} \quad ③$$

$\hat{p}_{nsf_{np}}(k)$: pressure at sensor ns when f_{np} leakage occur in k time
$\hat{p}_{ns0}(k)$: pressure at sensor ns for normal status
f: leakage (in flow unit)

3.2 Water quality failure

- **Contaminant spreads in the network depending on the pipe flow**



3.4 Enhancing Security

- **How can cyber attacks affect water systems?**
  - "Cyber incidents can affect water system operations with potentially significant adverse effects to public health and the environment"

- Interfere with operation of water treatment plant by over- or under-dosing
- Unauthorized changes to programmed instructions in system process
- Reduce the pressure flows of water into fire hydrants
- Overflow of untreated sewage into public water ways or streets
- Disabling alarm threshold, which could delay detection of intrusion of water contamination
- Shut down the water distribution
- Steal classified or proprietary information used by governments or private corporations and sell the information for gain

(Source: EPA, Chang and Shinozuka (2004))

4. Emergency Response Plan

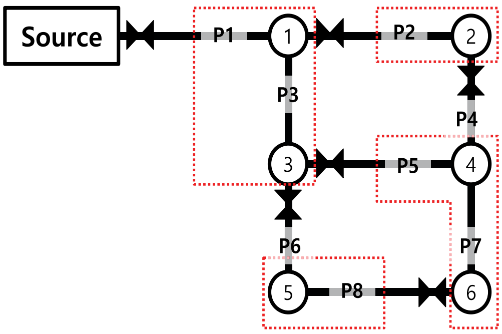
1. Overview of Emergency Response
2. Isolation
3. Maintenance
4. Adaptive operation

4.1 Overview of Emergency Response

	Physical Threats	Contamination Threat	Cybernetic threats	Interconnected infrastructure threats
Emergency Response	▪ Open emergency storage reservoirs ▪ Isolate or pressurize network sectors ▪ Ration water or prioritize nodes for continued service ▪ Install temporary bypass pipes	▪ Event detection ▪ Source identification ▪ Adaptive sampling ▪ Flush hydrants ▪ Warn consumers to change water use ▪ Isolate network sectors ▪ Boost disinfection	▪ Event detection	▪ Change WDS operation
Recovery	▪ Schedule and allocate crews for repairs	▪ None identified	▪ None identified	▪ Restore power systems elements

4.2 Isolation

- **Generally, the isolated area is different from the interrupted area, and the smallest portion of a water distribution system that can be isolated by closing isolation valves is defined as a segment**



Segment No.	Included Pipes	Included Nodes
Seg 1	P1, P3	N1, N3
Seg 2	P2	N2
Seg 3	P6,P8	N5
Seg4	P5, P7	N4, N6

4.2 Isolation

- **Segment identification (Jun and Loganathan 2007)**

Node-Arc Matrix

Connection among nodes and pipes (connected: 1, not connected: 0)

	P1	P2	P3	P4	P5	P6	P7	P8
Source	1	0	0	0	0	0	0	0
N1	1	1	1	0	0	0	0	0
N2	0	1	0	1	0	0	0	0
N3	0	0	1	0	1	1	0	0
N4	0	0	0	1	1	0	1	0
N5	0	0	0	0	0	1	0	1
N6	0	0	0	0	0	0	1	1

Valve Deficiency Matrix

	P1	P2	P3	P4	P5	P6	P7	P8
Source	0	0	0	0	0	0	0	0
N1	1	0	1	0	0	0	0	0
N2	0	1	0	0	0	0	0	0
N3	0	0	0	0	1	1	0	0
N4	0	0	0	1	1	0	1	0
N5	0	0	0	0	0	1	0	1
N6	0	0	0	0	0	0	1	0

If node-arc matrix and valve location matrix having same values at the same location, then 0 otherwise 1

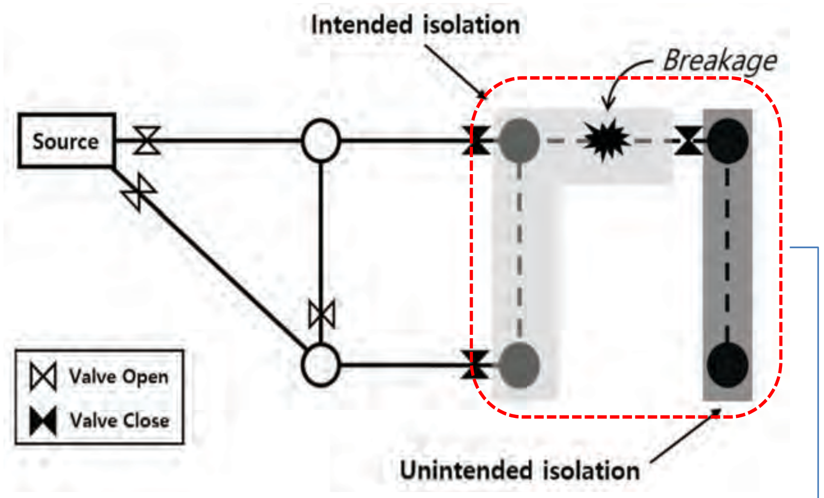
Valve Location Matrix

	P1	P2	P3	P4	P5	P6	P7	P8
Source	1	0	0	0	0	0	0	0
N1	0	1	0	0	0	0	0	0
N2	0	0	0	1	0	0	0	0
N3	0	0	0	0	1	1	0	0
N4	0	0	0	0	0	0	0	0
N5	0	0	0	0	0	0	0	0
N6	0	0	0	0	0	0	0	1

Existence of valves between two node and pipe (yes: 1, no: 0)

4.2 Isolation

- **Isolation is necessary but has undesirable side-effect**



Intended isolation area
– the service suspension area—in which the water supply, along with the broken pipe, is cut off

Unintended isolation area
– the area where water supply is unintendedly cut off from the water source because of isolating the intended isolation area

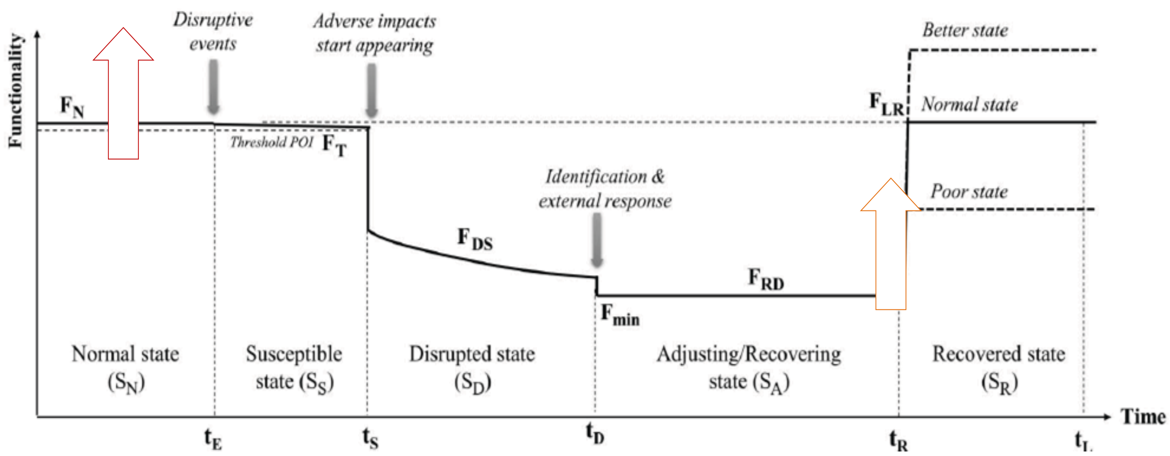
Area suffering from demand unsatisfaction

Unintended isolation cannot be estimated with demand driven analysis

Source: Choi & Kang (2020)

4.3 Maintenance

- **Pipe maintenance (replacement/repair) can be done pre- and post-failure events**
  - Pre-failure maintenance focuses on betterment of functionality
  - Post-failure maintenance focuses on back to normal (recovery)



Pre-failure maintenance

***Pipe roughness coefficient (Sharp and Walski 1988)**

$$R_j = 18.0 - 37.2log\left(\frac{e_0+at_j}{Dia_j}\right),$$

Reset installation time t_j to 0

Post-failure maintenance

Not necessary to modify pipe roughness coefficient

4.3 Maintenance

- **Recovery from multiple failure**

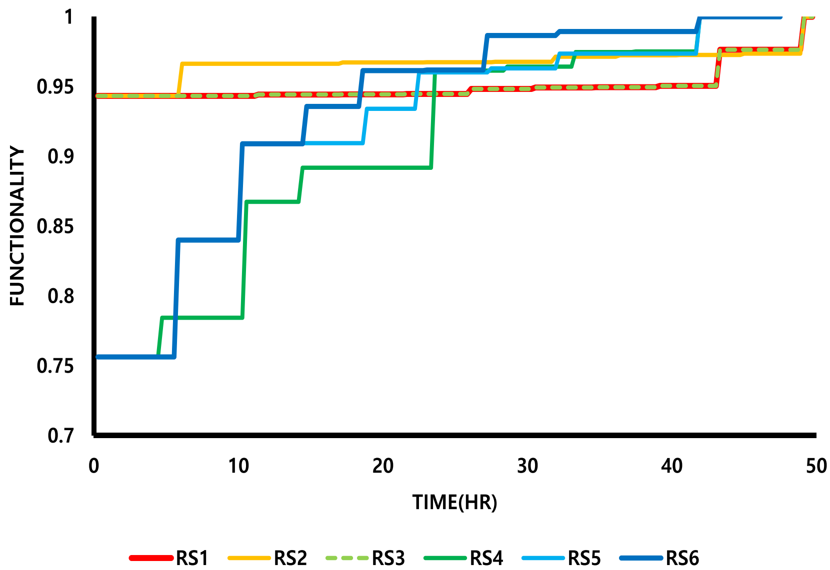
Simple way to consider pipe repair time

$$T_r = 6.5D^{0.285}$$

T_r is repair time in hour and D is diameter in inches

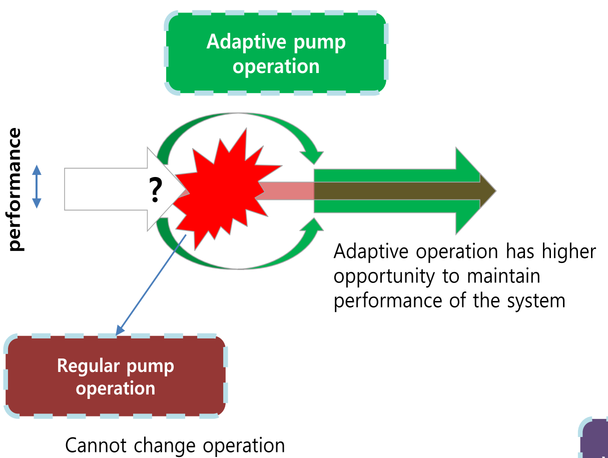
(Walski & Pelliccia, 1982)

Recovery from multiple failure

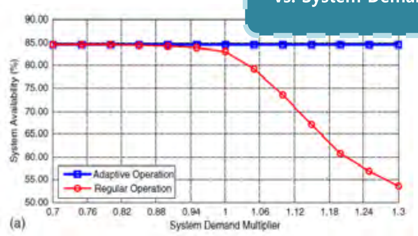


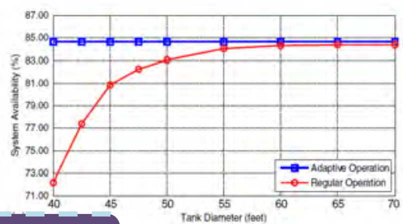
4.4 Adaptive operation

- **If a system fails to supply water with adequate pressure, the water utility would take action to respond**
  - Switching on additional pumps as a short-term remedy
  - Maintaining a higher water level in storage tanks as a long-term strategy



vs. System Demand





vs. Storage Tank Size

5. Tools for Resilience Assessment

1. Overview
2. WNTR
3. REVAS.net
4. EPANET-MSX
5. EPANET-CPA
6. TEVA-SPOT

5.1 Overview

- Modeling tools for emergency management of water distribution systems

Software	Description	Threat type	Hydraulic simulation	Risk assessment	Mitigation	Response and recovery
EPANET	Hydraulic and quality modeling	C,P	O	-	-	-
EPANET-MSX	Multispecies modeling	C	O	-	-	-
EPANET-RTX	Integration with SCADA	C	O	-	-	-
TEVA-SPOT	Contamination simulation and sensor placement	C	O	O	O	-
WST	Response actions to contamination	C	O	-	O	O
CANARY	Event detection	C	-	-	-	O
WNTF	Disaster events and network resilience	P, II	O	O	-	O
Giraffe	Disaster events and network resilience	P, II	O	O	-	-
REVAS.net	Disaster events and network resilience	P, II	O	O	-	-
epanetCPA	Cyber-physical attacks	Cy, II	O	O	-	-

Note: C = contamination; P = physical; II = interconnected infrastructure; and Cy = cybernetic infrastructure.

Source: Berglund et al. (2020)

5.2 WNTR

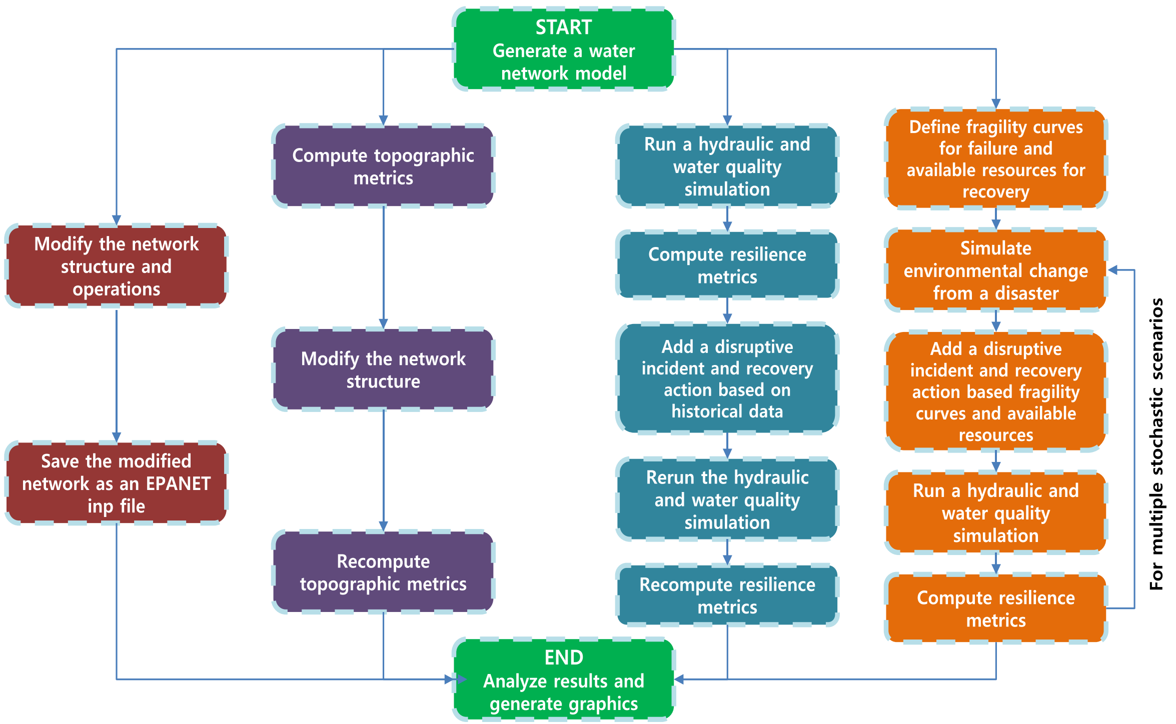
▪ Water Network Tool for Resilience

- WNTR integrates hydraulic and water quality simulation, a wide range of damage and response options, and resilience metrics into a single software framework, allowing for end-to-end evaluation of water network resilience

- WNTR includes capabilities to:
  - Generate water network models
  - Modify network structure/operation
  - Add disruptive incidents, response/repair/mitigation strategies
  - Simulate network hydraulics and water quality using pressure dependent demand or demand-driven hydraulic simulation
  - Run probabilistic simulations using fragility curves for component failure
  - Compute resilience using topographic, hydraulic, water quality/security, and economic metrics
  - Analyze results and generate graphics

5.2 WNTR

▪ Workflow



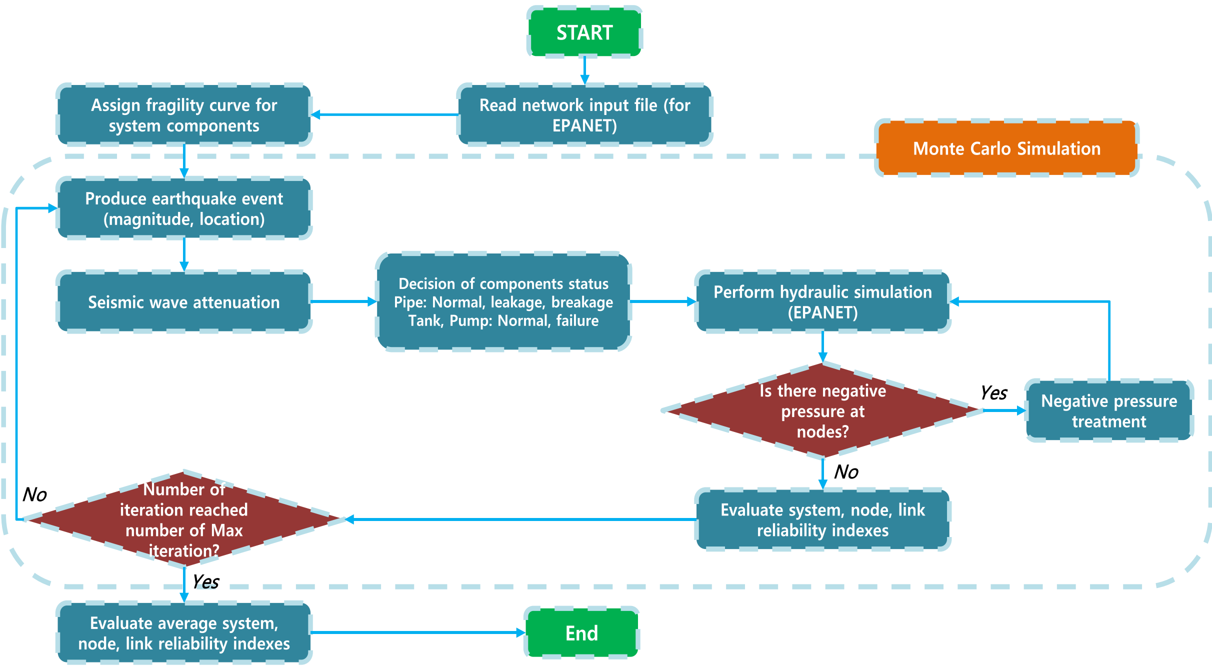
5.3 REVAS.net

- **Reliability evaluation model for seismic hazard for water supply network (REVAS.NET)**
  - Composed of several modules, including a system information/configuration interface, hypothetical earthquake generator/simulator, and hydraulic simulator (Yoo et al. 2016)

- REVAS.net includes capabilities to:
  - Generate earthquake events with random magnitude and location and consider seismic wave attenuation
  - Equipped with Monte Carlo simulation to estimate the probabilistic seismic reliability
  - Determine the failure status of tank and pump by fragility curve
  - Determine the probability for breakage and leakage status of pipe
  - Hydraulic analysis using EPANET

5.3 REVAS.net

- **Reliability evaluation model for seismic hazard for water supply network (REVAS.NET)**



5.4 EPANET-MSX

- **An extension to the original EPANET that allows it to model any system of multiple, interacting chemical species**
  - MSX stands for Multi-Species Extension

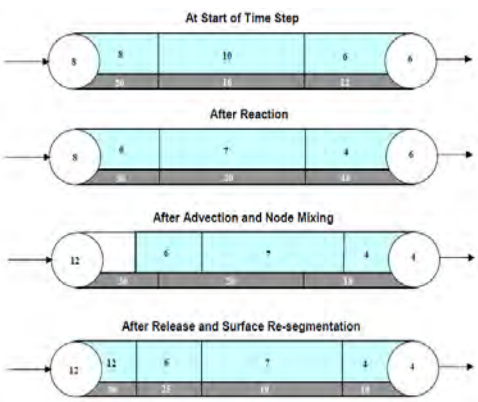
- EPANET-MSX includes capabilities to:
  - Generate earthquake events with random magnitude and location and consider seismic wave attenuation
  - Equipped with Monte Carlo simulation to estimate the probabilistic seismic reliability
  - Determine the failure status of tank and pump by fragility curve
  - Determine the probability for breakage and leakage status of pipe
  - Hydraulic analysis using EPANET

5.4 EPANET-MSX

- **An extension to the original EPANET that allows it to model any system of multiple, interacting chemical species (Shang et al. 2008)**
  - MSX stands for Multi-Species Extension

Reaction kinetics

- Advective transport in pipes
- Mixing at pipe junction
- Mixing in storage nodes



4-step water quality transport method

① **React**: Apply reaction dynamics within each pipe segment and storage tank over the time step to compute new concentrations throughout the network.

② **Advect**: Within each pipe, compute the flow volume transported over the time step and transfer this amount of volume and its associated bulk species mass from the pipe's leading segments into accumulated mass and volume totals at the downstream node.

③ **Mix**: Compute new bulk species concentrations at each node based on its accumulated mass and volume inputs from the advection step as well as any external sources.

④ **Release**: Create a new segment at the upstream end of each pipe whose size equals the pipe's flow volume and whose bulk species concentrations equal that of the upstream node

5.4 EPANET-MSX

- **An extension to the original EPANET that allows it to model any system of multiple, interacting chemical species (Shang et al. 2008)**
  - MSX stands for Multi-Species Extension

Example of EPANET-MSX input file

```
[TITLE]
Two-Source Chlorine Decay

[OPTIONS]
AREA_UNITS     FT2
RATE_UNITS     HR
SOLVER      RK5
TIMESTEP     300
ATOL      0.01
RTOL      0.001

[SPECIES]
BULK     T1     MG     0.01     0.001  ;Source 1 tracer
BULK     CL2    MG     0.01     0.001  ;Free chlorine

[COEFFICIENTS]
CONSTANT     K1     1.3     ;Source 1 decay coeff.
CONSTANT     K2     17.7    ;Source 2 decay coeff.

[TERMS]
K      (K1*T1 + K2*(1-T1))

[PIPES]
RATE     T1      0          ;T1 is conservative
RATE     CL2     -K*CL2     ;CL2 has first order decay

[SOURCES]

[QUALITY]
;Initial conditions (= 0 if not specified here)
NODE     River     T1     1.0
NODE     River     CL2    1.2
NODE     Lake      CL2    1.2
```

Setting parameters and analysis options

Define multiple species

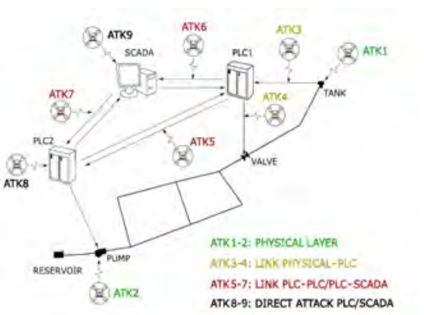
Define bulk decay rates for sources

Calculate bulk decay rates for pipes and tanks

Define initial quality values

5.5 EPANET-CPA

- **An objective-oriented MATLAB toolbox (Shang et al. 2008)**
  - Extends EPANET's features to explicitly include a cyber-layer
  - Exposes it to the user to allow rapid development of plausible attack scenarios
  - Allows users to design attack scenarios and simulate the corresponding hydraulic response of water networks



Add a cyber-layer made of sensors, actuators, multiple programmable logic controllers (PLC) and SCADA system to EPANET's physical network

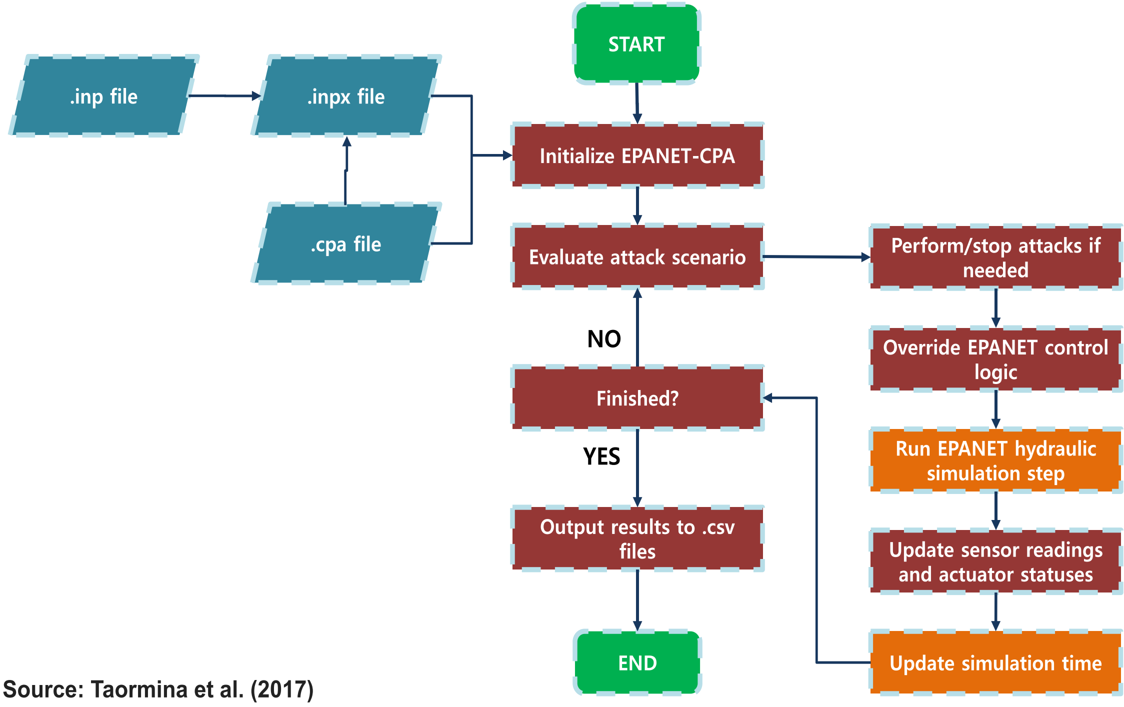
Threats considered

- Deception attacks (manipulation of measurements and control signals)
- Denial-of-service (DoS) of communication channels
- Eavesdropping and replay attacks
- Alteration of control statements
- Physical attacks to sensors
- Physical attacks to actuators

Source: Taormina et al. (2017)

5.5 EPANET-CPA

▪ Workflow



Source: Taormina et al. (2017)

5.6 TEVA-SPOT

▪ Threat Ensemble Vulnerability Assessment and Sensor Placement Optimization Tool (TEVA-SPOT)

- TEVA-SPOT allows a user to specify a wide range of modeling inputs and performance objectives for contamination warning system design

- Further, TEVA-SPOT supports a flexible decision framework for sensor placement that involves two major steps: a modeling process and a decision-making process
  - The modeling process includes (1) describing sensor characteristics, (2) defining the design basis threat, (3) selecting impact measures for the CWS, (4) planning utility response to sensor detection, and (5) identifying feasible sensor locations.

- TEVA-SPOT provides a convenient interface for defining and computing the impacts of design basis threats

5.6 TEVA-SPOT

- **Threat Ensemble Vulnerability Assessment and Sensor Placement Optimization Tool (TEVA-SPOT)**

- TEVA-SPOT was designed to model a wide range of sensor placement problems
  - For example, TEVA-SPOT supports a number of impact measures, including the number of people exposed to dangerous levels of a contaminant, the volume of contaminated water used by customers, the number of feet of contaminated pipe, and the time to detection

- Response delays can also be specified to account for the time a water utility would need to verify a contamination incident before notifying the public

- Finally, the user can specify the feasible locations for sensors and fix sensor locations during optimization
  - This flexibility allows a user to evaluate how different factors impact the CWS performance and to iteratively refine a CWS design

6. Conclusion

1. Enhancing Modeling Approaches
2. Summary

6.1 Enhancing Modeling Approaches

▪ Improvements to hydraulic and water quality software

- Ability to alter hydraulics mid simulation to better represent response scenarios
- Ability to compute reasonable results during abnormal operating conditions and system failure
- Ability to support fast initialization from previous results, as well as "snap-shots" from which a series of scenarios could be run
- Mathematical models of reaction dynamics for accurate water quality analysis
- Use of pressure driven or demand driven models when most appropriate
- Connections to field (SCADA) data to enable real time application of results
- Ability to propagate uncertainty through a single simulation (rather than requiring separate scenario runs)

6.1 Enhancing Modeling Approaches

▪ Improvements to network models and model applications

- Improvements to network models
    - Updated, validated utility network models to ensure accuracy and usability of results
    - Access to field (SCADA) data in order to improve model predictions
- Improvements to model applications
    - Set of scenarios to represent realistic disaster impacts and responses, including pipe breaks, pump failures, power outages, control valve failures, insufficient storage capacity, multiple stresses occurring at the same time, fire-fighting conditions, and water quality failures
    - Set of scenarios to represent realistic mitigation and response strategies that water utilities might employ to reduce consequences of disasters
    - Incorporation of uncertainty

6.2 Summary

- **Resilience is and will be an important criteria for water utilities**

- The goal of a resilient system is to minimize the magnitude and duration of disruption
- As multiple uncertainties are associated to resilience assessment, it requires multiple simulations especially conjunction with uncertainty analysis
- There are limited stand-alone resilience assessment tools, computer programming is necessary for resilience assessment
- Different strategies are needed to detect different identification of abnormality and mitigation for different disruption scenarios

Thank you very much