Measuring Response and Recovery Behavior of Urban Water Networks

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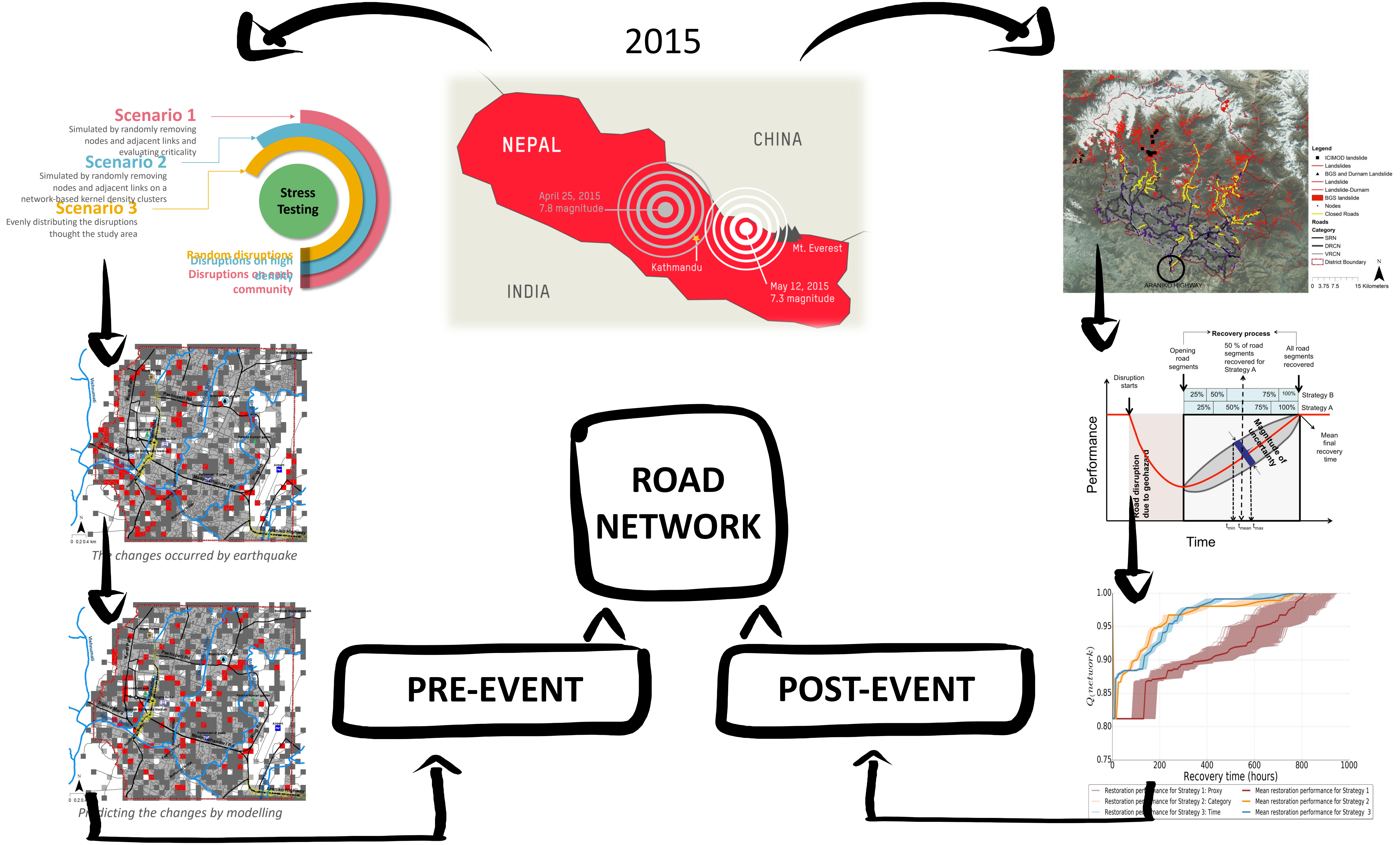
https://nazliyoncaaydin.com/

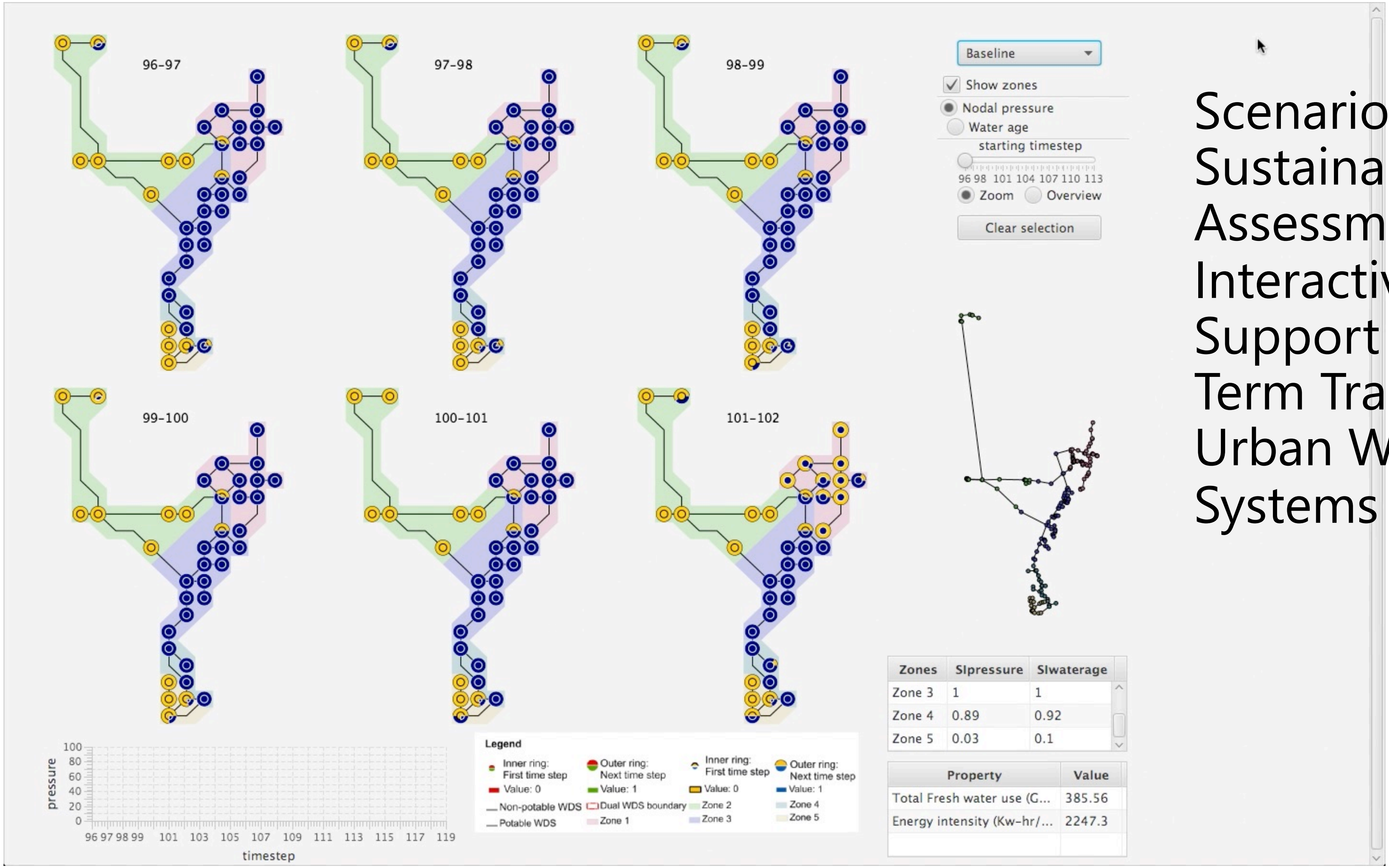
Resilience is the capacity of a system to sustain its functions and become better – through absorbing, adapting and self-organizing – under conditions of chronic stresses, abrupt shocks or disruptive innovations

- **Pre-event***
- What can go wrong?
- What are the consequences?
- How to maintain awareness?
- Can we detect "outlier events"?
- How to best protect a system?

- **Post-Event ***
- How to best re-stabilize a system?
- How to best rebuild a system?
- How to best reconfigure a system?
- How to adapt in the longer run?

* Hans Heinimann (2017). "FRS Agency Interaction"


2015
NEPAL
CHINA
INDIA
April 25, 2015
7.8 magnitude
Kathmandu
Mt. Everest
May 12, 2015
7.3 magnitude
Scenario 1
Simulated by randomly removing nodes and adjacent links and evaluating criticality
Scenario 2
Simulated by randomly removing nodes and adjacent links on a network-based kernel density clusters
Scenario 3
Evenly distributing the disruptions thought the study area
Stress Testing
Random disruptions
Disruptions on high density
Disruptions on community
The changes occurred by earthquake
Predicting the changes by modelling
ROAD NETWORK
PRE-EVENT
POST-EVENT
ARANIKO HIGHWAY
Recovery process
Disruption starts
Performance
Time
Mean final recovery time
Strategy A
Strategy B
Recovery time (hours)
Mean restoration performance for Strategy 1
Mean restoration performance for Strategy 2
Mean restoration performance for Strategy 3

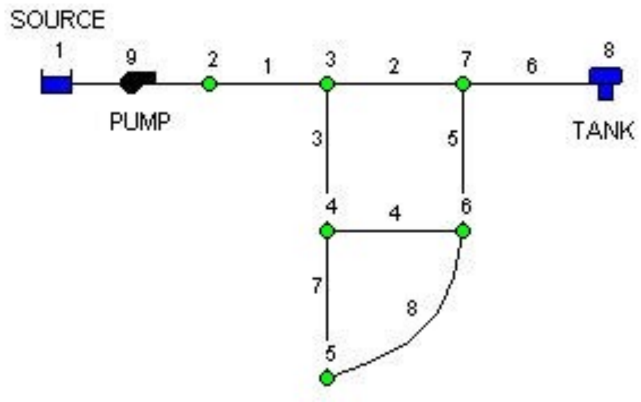


Scenario-Based Sustainability Assessment to Provide Interactive Decision Support for the Long-Term Transition of Urban Water Supply Systems

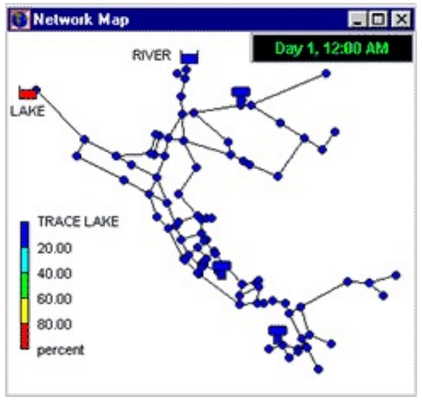
WATER NETWORKS

https://epanet22.readthedocs.io/en/latest/2_quickstart.html

https://www.epa.gov/sites/production/files/2015-03/epanet.gif



- Water distribution network variables:
  - Nodes
  - Edges



INPUTS

Time-dependent

Table 2.1 Example Network Node Properties

Node	Elevation (ft)	Demand (gpm)
1	700	0
2	700	0
3	710	150
4	700	150
5	650	200
6	700	150
7	700	0
8	830	0

Table 2.2 Example Network Pipe Properties

Pipe	Length (ft)	Diameter (inches)	C-Factor
1	3000	14	100
2	5000	12	100
3	5000	8	100
4	5000	8	100
5	5000	8	100
6	7000	10	100
7	5000	6	100
8	7000	6	100

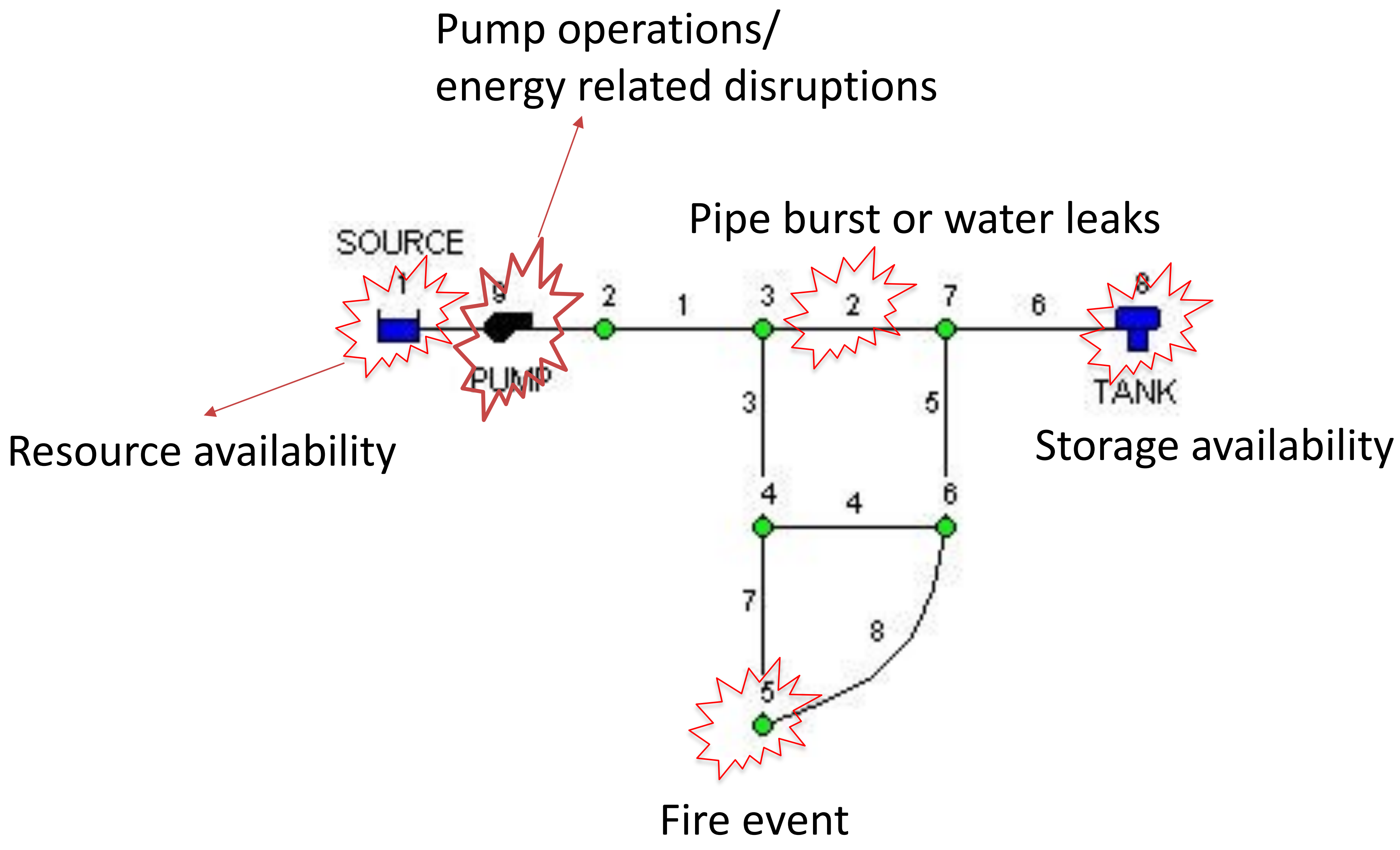
OUTPUTS

Network Table - Links

Link ID	Flow GPM	Velocity fps	Headloss ft/Kft	Status
Pipe 1	617.42	1.29	0.80	Open
Pipe 2	382.51	1.09	0.69	Open
Pipe 3	159.91	1.02	1.00	Open
Pipe 4	29.34	0.19	0.04	Open
Pipe 5	-90.09	0.57	0.34	Open
Pipe 6	292.42	1.19	1.03	Open
Pipe 7	55.58	0.63	0.57	Open
Pipe 8	-44.42	0.50	0.38	Open

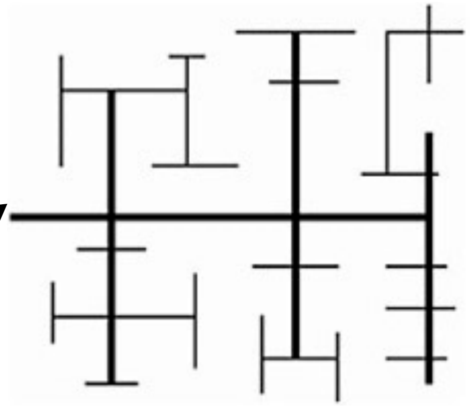
WATER NETWORKS DISRUPTIONS

https://epanet22.readthedocs.io/en/latest/2_quickstart.html



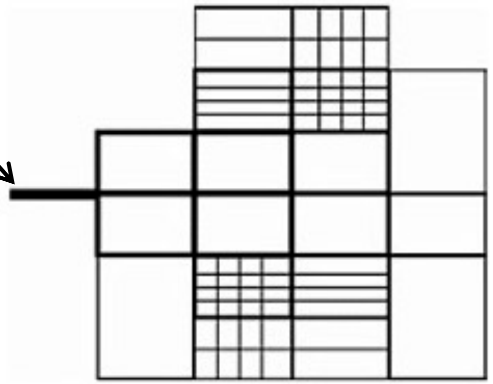
Topology of water networks

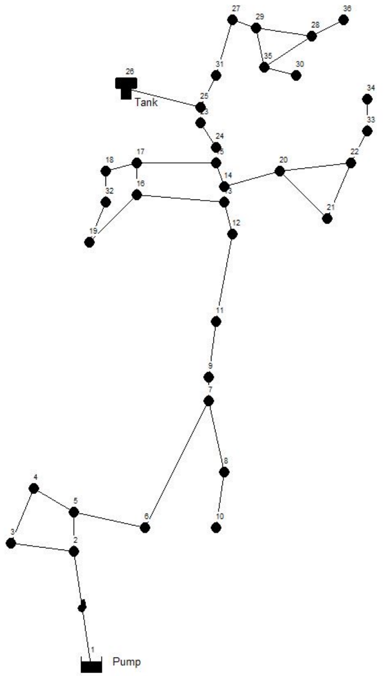
Simulation-based hydraulic performance evaluation to investigate systems capability to cope with shocks.

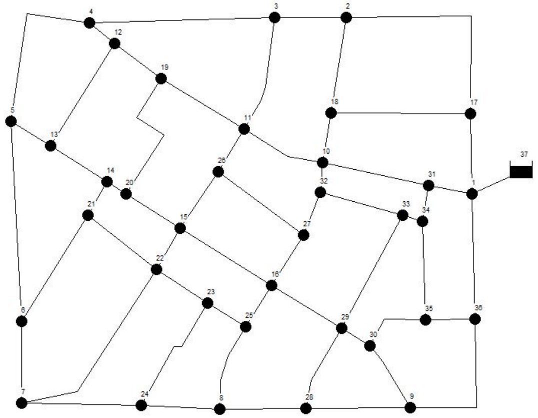


Topology 1

Topology 2



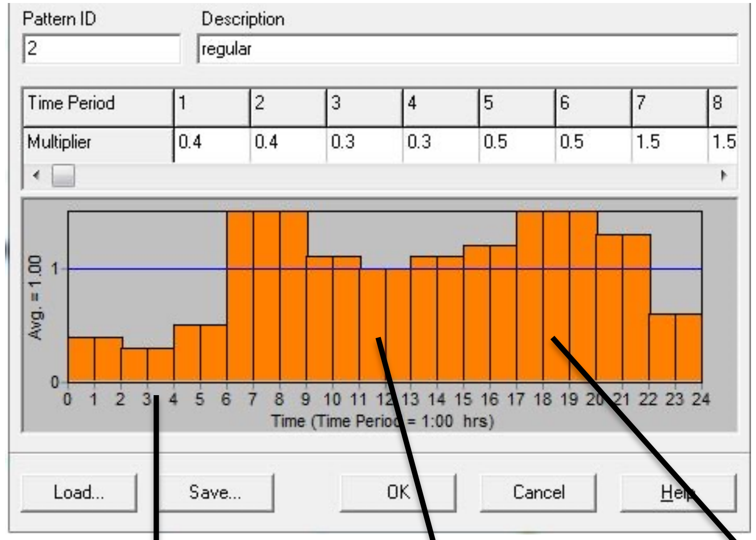




Demand variation and operation range

Simulation-based hydraulic performance evaluation to investigate systems capability to cope with shocks.

Demand variation

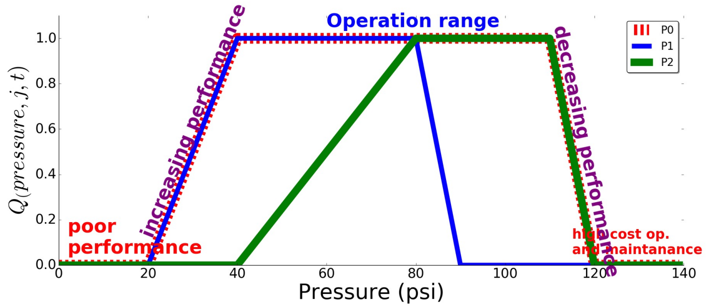


Min. Demand

Base demand

Peak Demand

Operation range



Pressure Performance (psi)	P0	P1	P2
P_{min}	20	20	40
P_{max}	120	90	120
Operation range	40-110	40-80	80-110

Demand variation and operation range

Simulation-based hydraulic performance evaluation to investigate systems capability to cope with shocks.

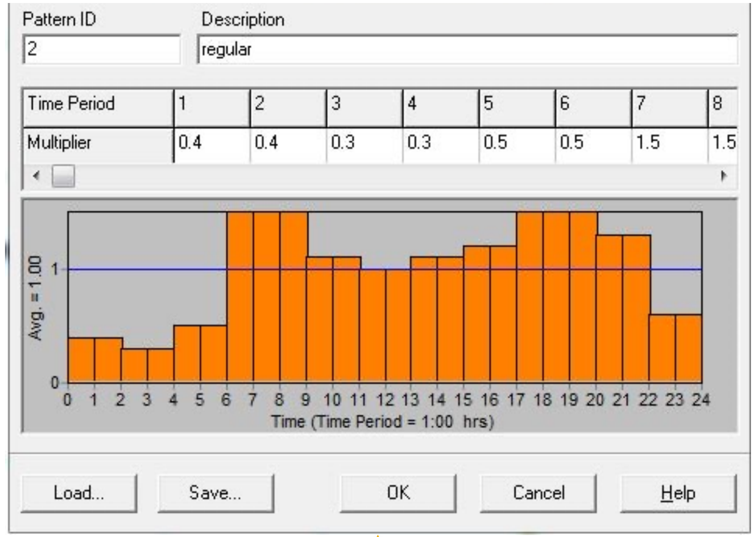
Identify critical location

Disruption simulation

Performance Evaluation

Excess demand simulation representing fire flow

Demand variation

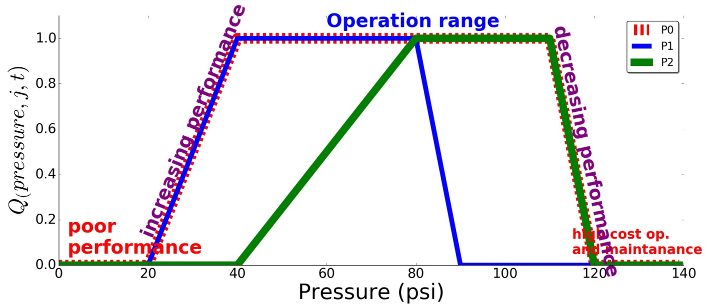


$$Q_{pressure,t} = \sum_{j=1}^{NJ_i} w_{j,t}\, Q_{pressure,j,t}\, \frac{D_{j,t,satisfied}}{D_{j,t}}$$

$$w_{j,t} = \frac{D_{j,t}}{\sum_{j=1}^{NJ_i} D_{j,t}}$$

Fire flow (2000 GPM-3 hours)

Operation range



Pressure Performance (psi)	P0	P1	P2
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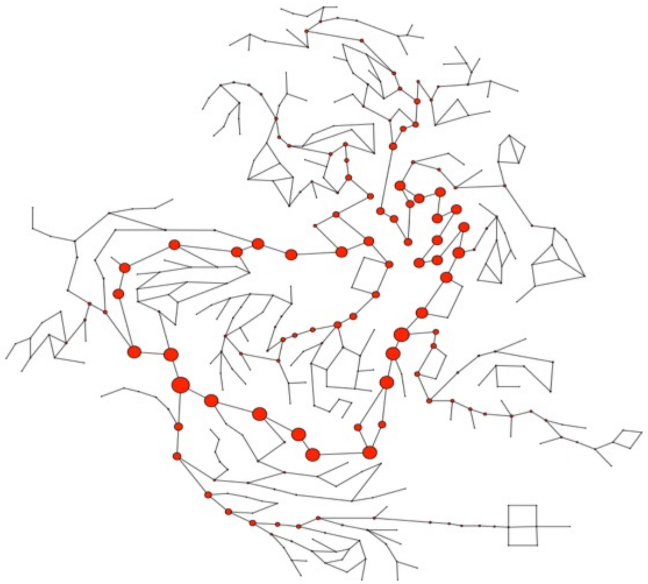
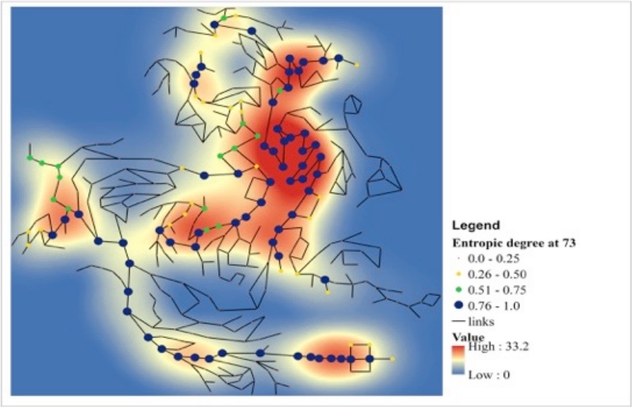
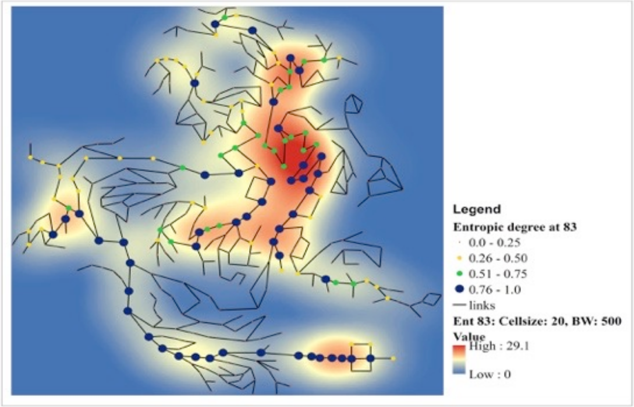
Finding a correct Measure of Performance (MOP) for water networks



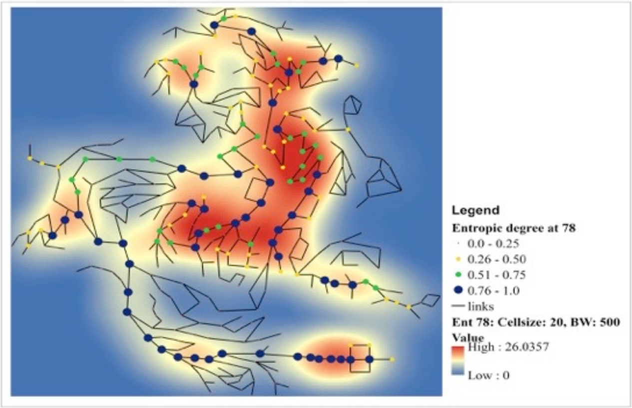
Betweenness centrality
c-town network



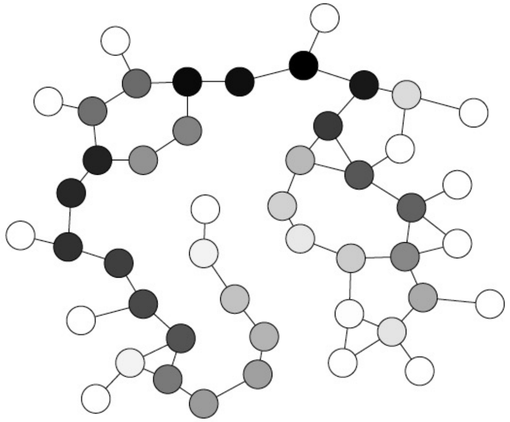
Time step 78

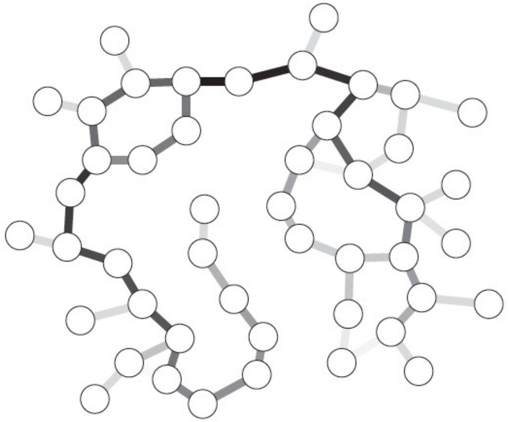


Time step 73



Time step 83





Node Betweenness

Edge Betweenness

Both node and edge betweenness centralities defined by is defined as the number of shortest paths passing through a node while routing between all other node pairs **

$$B_x = \sum_{i=1}^{n} \sum_{j=i+1}^{n} \frac{n_{ij}(x)}{n_{ij}}$$

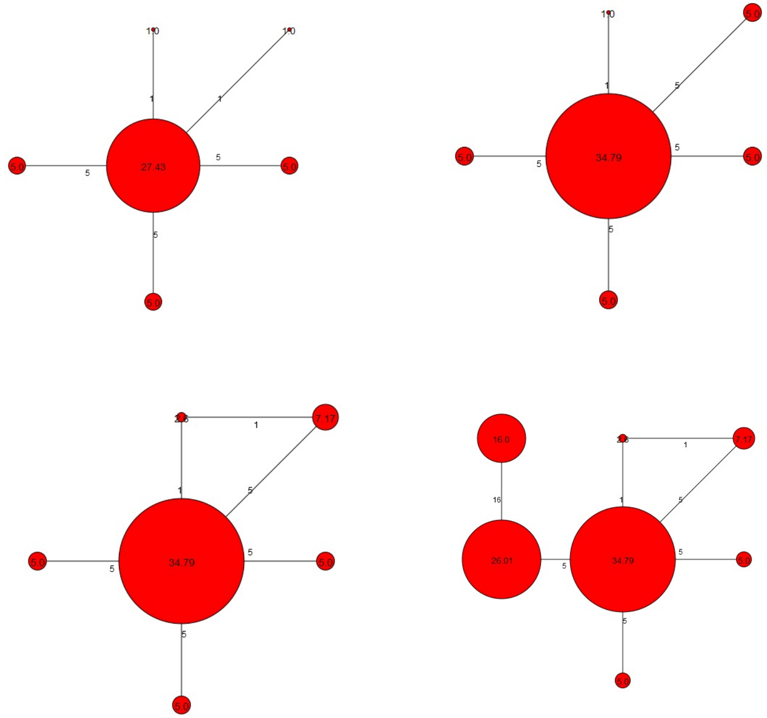
n_{ij} is the total number of shortest paths between nodes i and j, while $n_{ij}(x)$ represents the amount of time node x was used

*Node and edge betweenness figures are adapted from: Wang, W., Tang, C. Y. (2013). "Distributed Computation of Node and Edge Betweenness on Tree Graphs." 52nd IEEE Conference on Decision and Control, December 10-13, 2013. Florence, Italy.

**Newman MEJ (2010) Networks: an introduction. Oxford University Press, Oxford

*** Bompard, E., Pons, E., and Wu, D. (2013). "Analysis of the structural vulnerability of the interconnected power grid of continental Europe with the Integrated Power System and Unified Power System based on extended topological approach." International Transactions on Electrical Energy Systems, 23(5), 620-637.

Entropic Degree



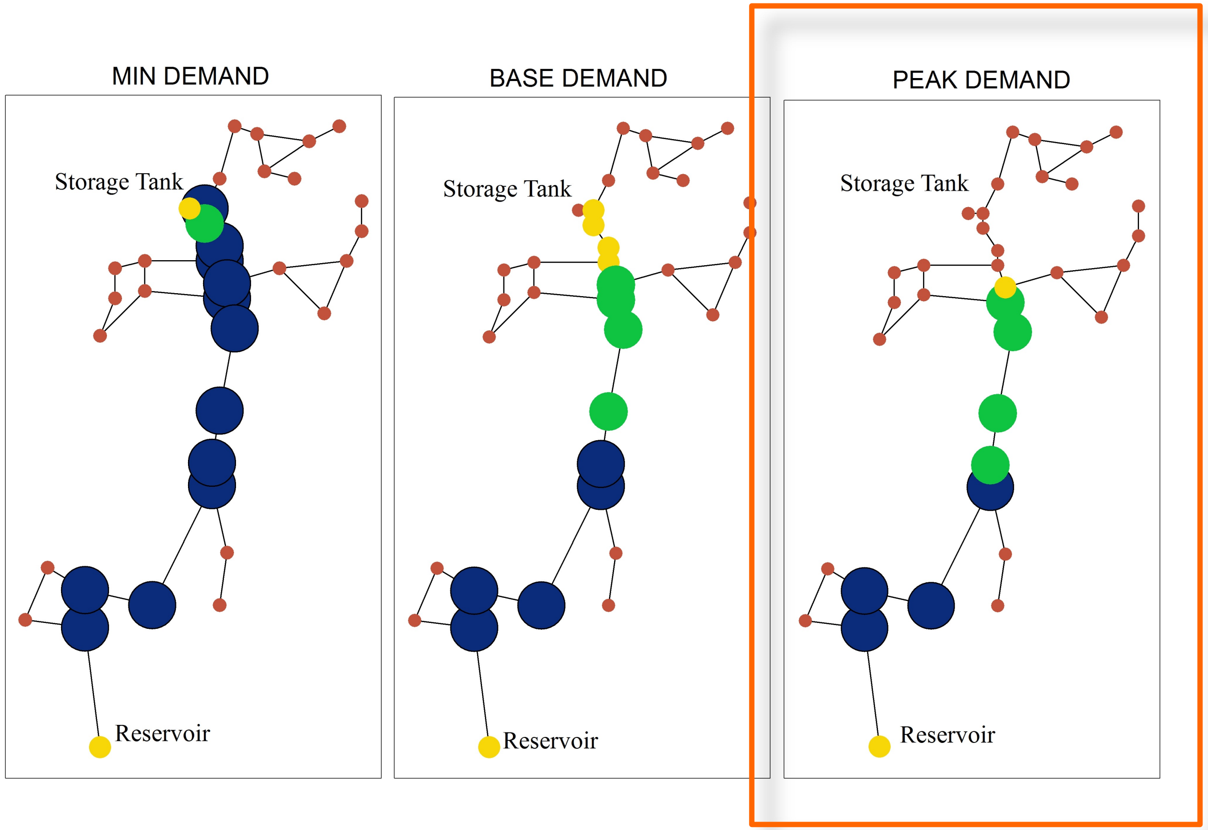
$$k_i^w = (1 - \sum_{j=1}^{N_B} p_{ij} \log p_{ij}) \sum_{j=1}^{N_B} w_{ij}$$

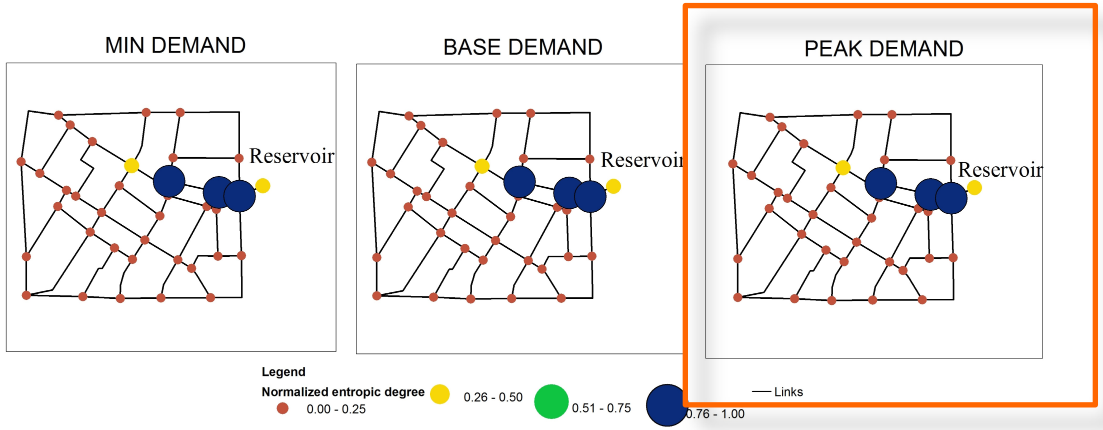
$$p_{ij} = w_{ij} \Big/ \sum_{j=1}^{N_B} w_{ij}$$

$$p_{ij} = normalized\ weight$$

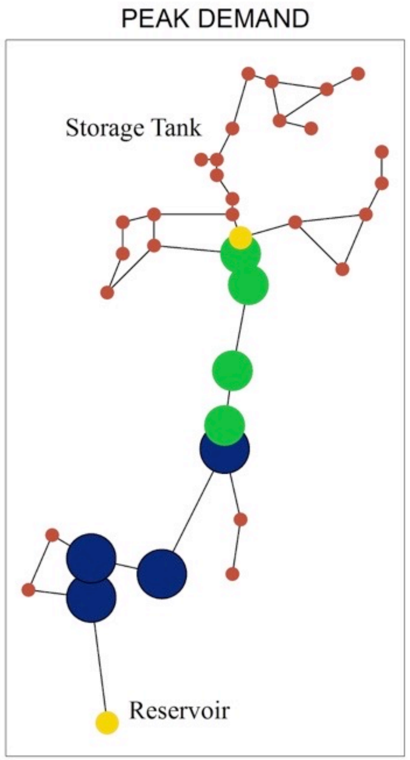
Results

- Time dependent criticality analysis

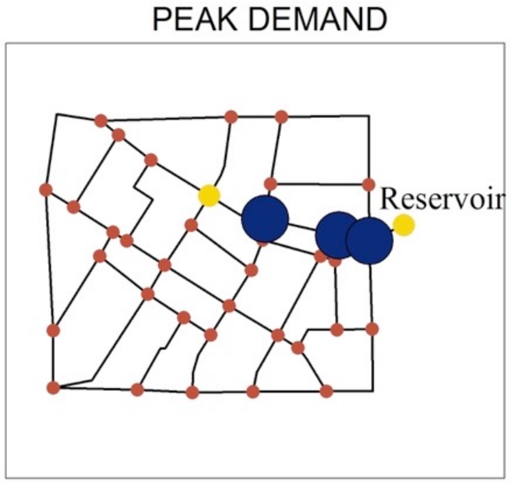


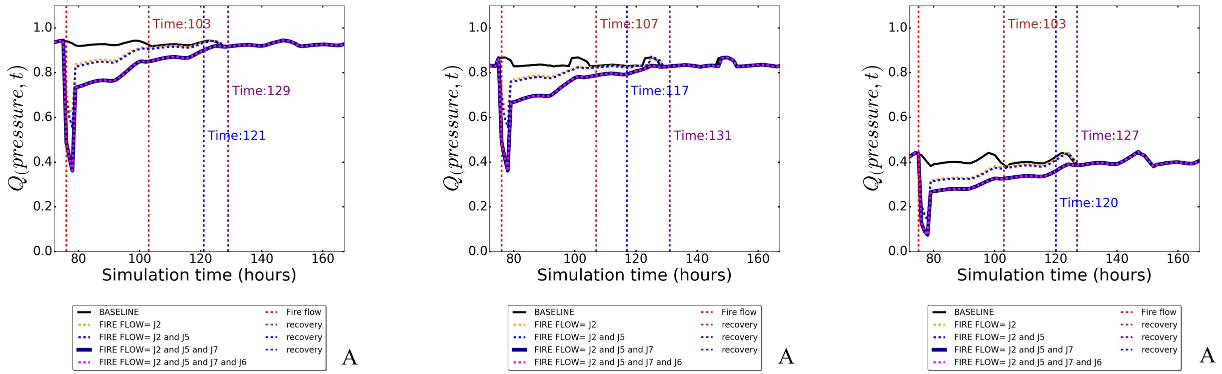


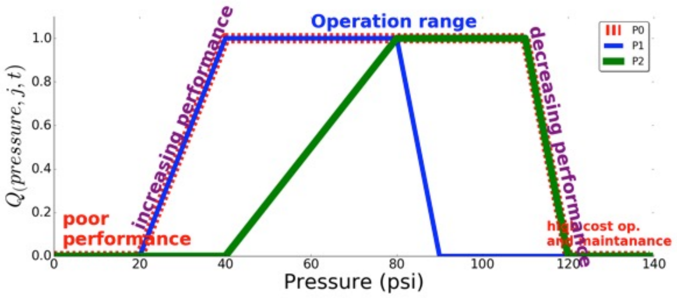
Topology 1



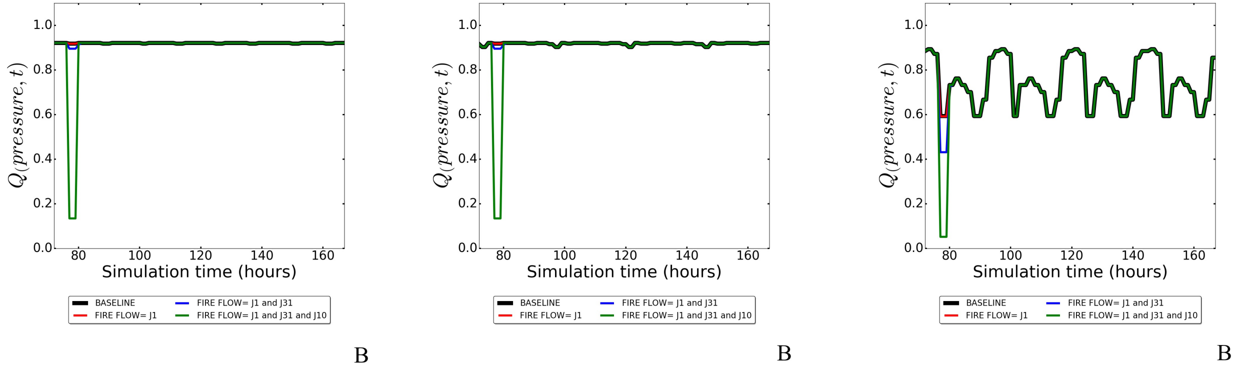
Topology 2







Recovery performance under different operation regimes



Quantitative Assessment of System Response During Disruptions: An Application to Water Distribution Systems

Beatrice Cassottana, Nazli Yonca Aydin and Tang Loon Ching

B. Cassottana, N. Y. Aydin, and L. C. Tang, "Quantitative Assessment of System Response during Disruptions: An Application to Water Distribution Systems," Journal of Water Resources Planning and Management, vol. 147, no. 3, 2021, doi: 10.1061/(asce)wr.1943-5452.0001334.

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Quantitative Assessment of System Response During Disruptions: An Application to Water Distribution Systems

- Capturing the relationship between key factors that influence *performance loss and recovery*
- Identify groups of scenarios that the system exhibits similar response behaviors and that can be easily labeled
- Support decisions to improve WDS resilience before and during a disruption

Quantitative Assessment of System Response During Disruptions: An Application to Water Distribution Systems

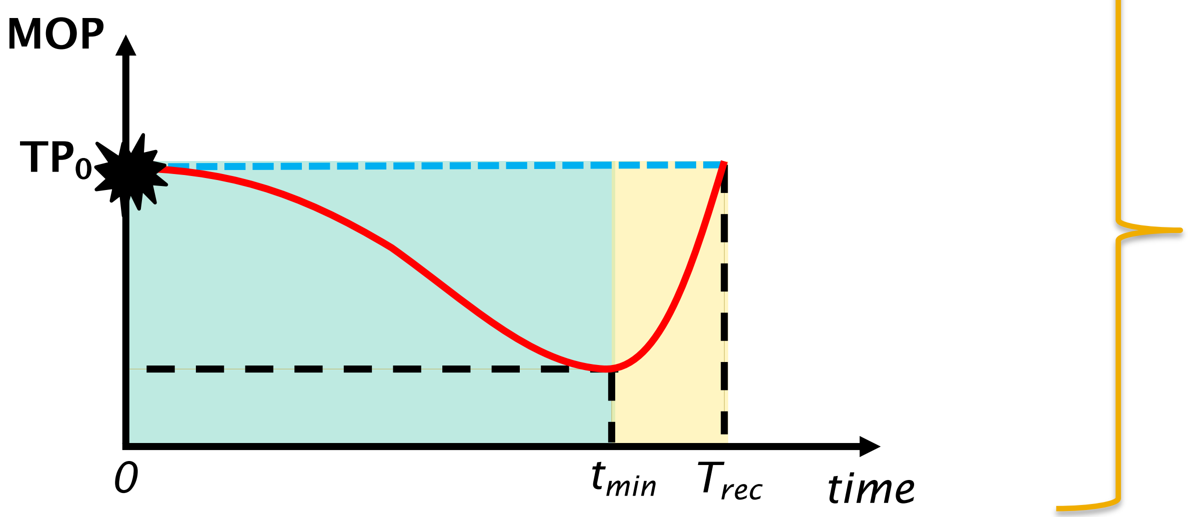
- Two benchmark water networks are considered: **Net3 and C-Town**
- An **n-1 analysis** is conducted, where one node at a time is disrupted by simulating a water leakage
- Systems dynamics are simulated and the **average satisfied demand** computed as

$$\mathrm{MOP}(t) = \frac{1}{n}\sum_{i=1}^{n} \frac{d_i(t)}{D_i(t)}$$

where n is the number of nodes, d_i and D_i the satisfied and expected demand of node i

Quantitative Assessment of System Response During Disruptions: An Application to Water Distribution Systems

- Single component failures in water networks such as water leakage etc.
  - Slower performance loss
  - Faster recovery



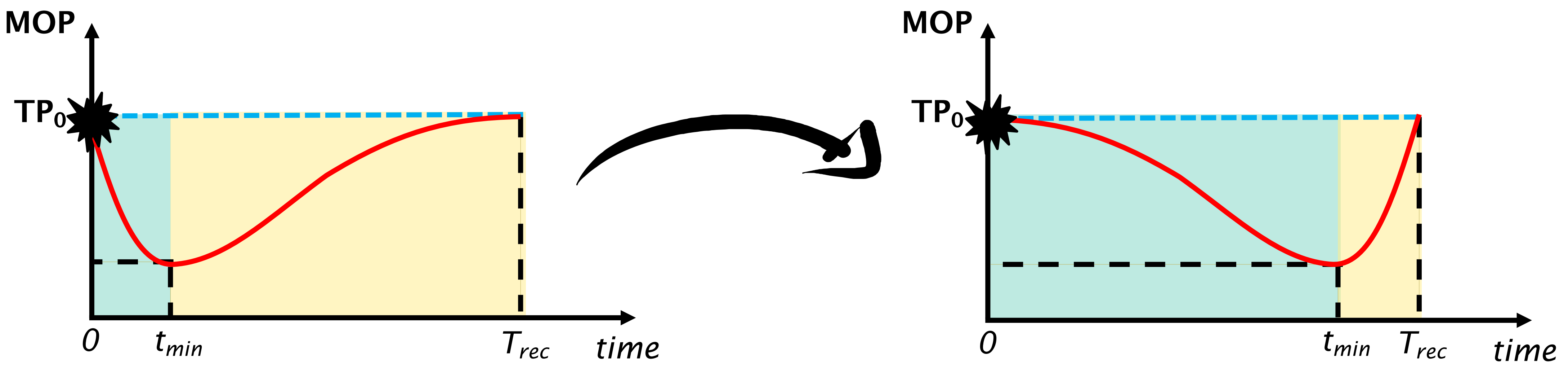
This is due to the existing reserve capacity in the system i.e., storage tanks

https://riskcenter.ethz.ch/events/seminar-series/frs-lunch-resilience-seminars.html

Recovery Modelling for Water Distribution Systems

- Existing recovery functions (***hybrid and gamma recovery functions***) can only represent fast losses and slower recovery

- We develop the **beta family of recovery** functions with **enhanced versatility** and physical interpretation and apply it to identify critical components of a WDS



Recovery Modelling for Water Distribution Systems

The beta family of recovery functions

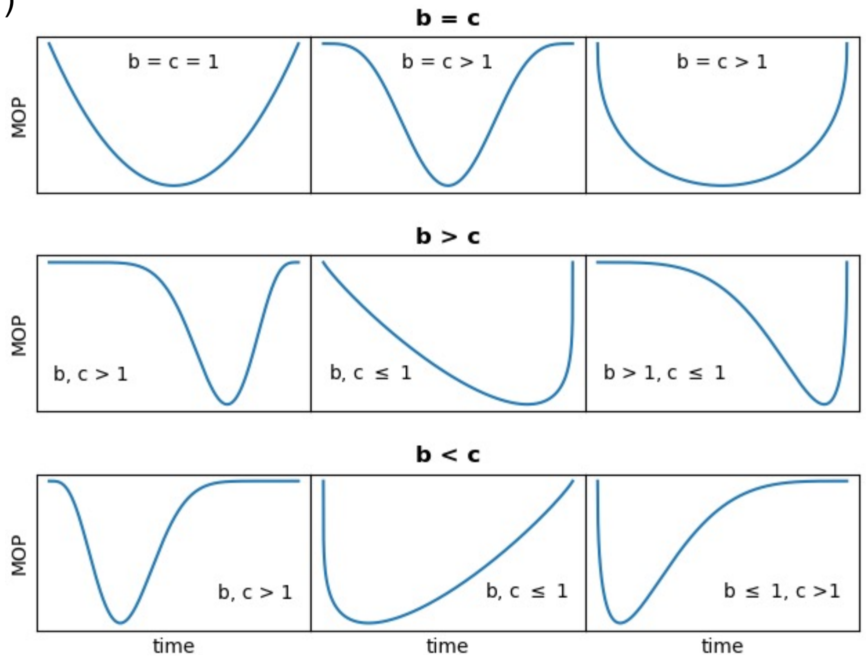
$$\mathrm{MOP}(t) = \mathrm{TP}_0 - a\,\frac{(b+c)^{b+c}}{b^b c^c}\left(\frac{t}{\nu}\right)^b\left(1-\frac{t}{\nu}\right)^b$$

with $0 \leq t \leq \nu$

1) **Versatility**: although it assumes constant target performance, it can represent symmetric and asymmetric recovery processes

2) **Physical interpretation**: *a* characterizes the max performance loss, *b* the performance loss rate, *c* the recovery behaviour, and ν the time to recovery

(1)



(2)

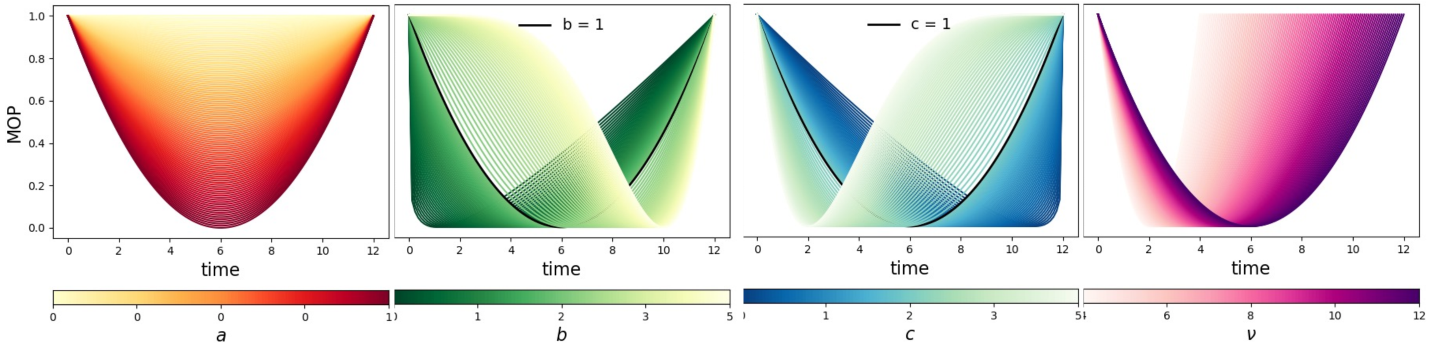
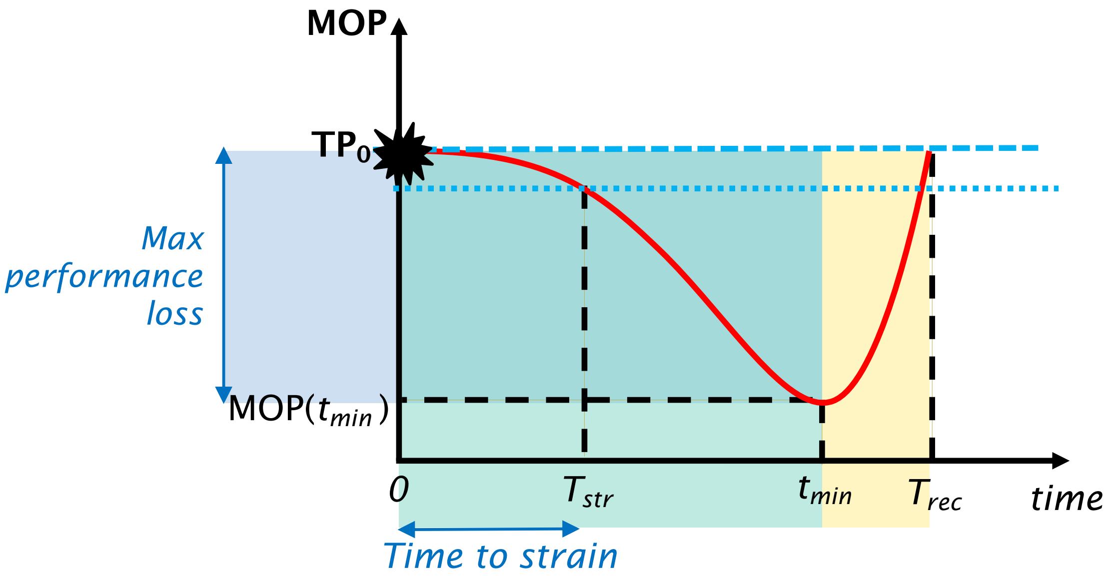


Figure 1: Symmetric (*b* = *c*) and asymmetric recovery processes (*b* ≠ *c*) represented by the beat family
Figure 2: Effects of parameter *a, b, c* and ν on the beta family

Node clustering

➢ The q most critical nodes are selected based on *the total performance loss (Δ)*



➢ The q nodes are clustered according to the estimated parameters $\boldsymbol{a_i}$ **and** $\boldsymbol{b_i}$

(since the recovery capabilities are fully determined by the simulation inputs, parameters c_i and ν_i are not considered for the analysis)

➢ The resulting clusters shows a similar recovery process under disruption scenarios

➢ Reminder:

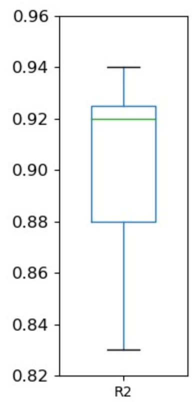
✓ ***a*** characterizes the max performance loss

✓ ***b*** the time to strain

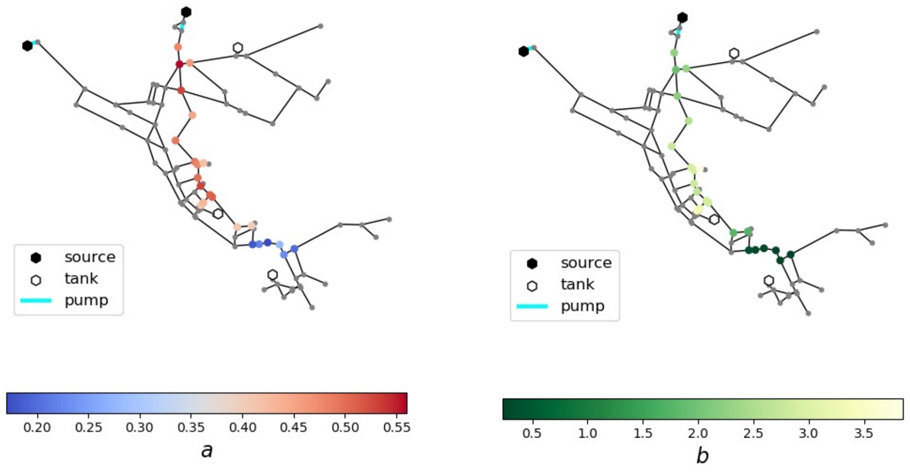
Results

- Some degree of correlation is observed between parameters *a* and *b*
- Two characteristic recovery processes are identified

(1)



(2)



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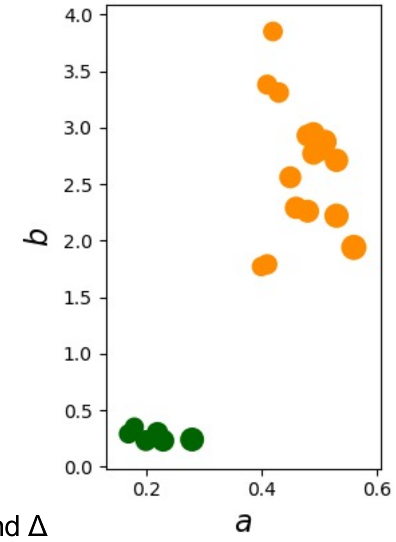
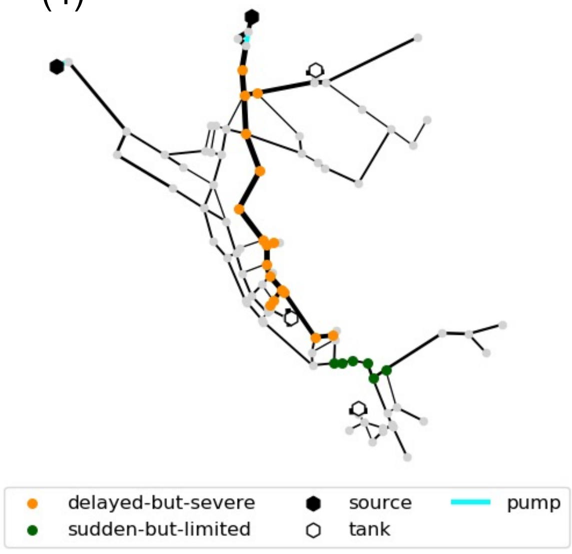


(4)



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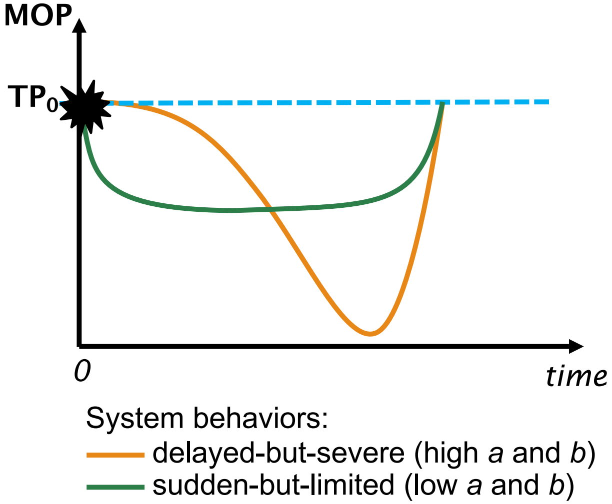
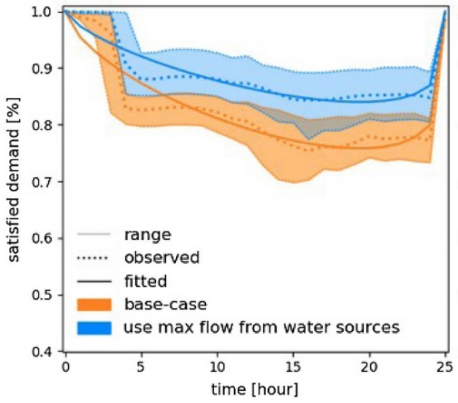


Figure 1: Goodness of fit (R^2)
Figure 2: Topology of *Net3*, nodes are coloured according to *a*, *b*, and Δ
Figure 3: Results of the *k-means* algorithm
Figure 4: Topology of *Net3*, nodes are coloured according to *cluster*
Figure 5: Identified characteristic recovery processes

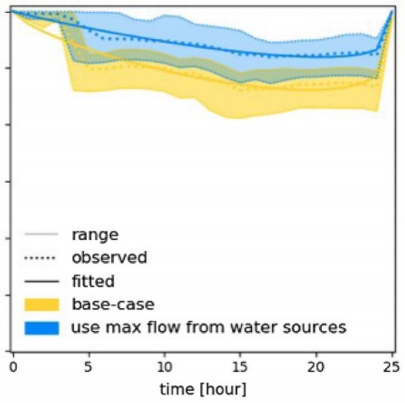
Results

Resilience strategies

- Two strategies are implemented, namely using the max available flow from (i) water sources or (ii) water tanks
- Their effects is evaluated on the two identified clusters using the beta recovery functions fitted to the MOP associated to the min, max, and median Δ of a cluster

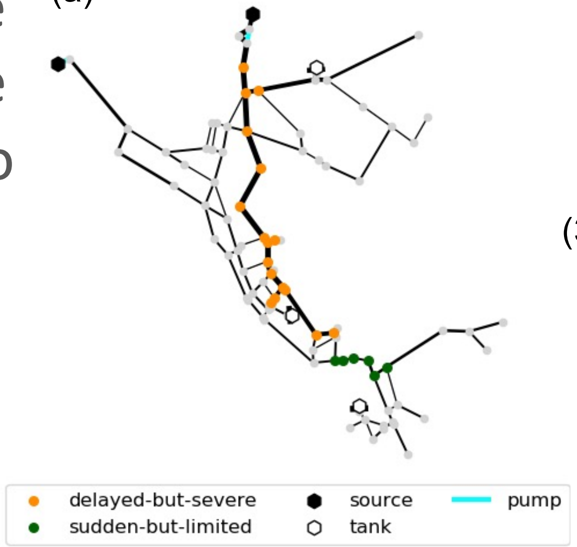


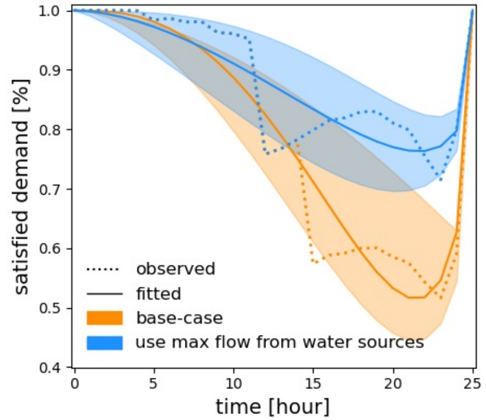
(1)



(2)

(a)





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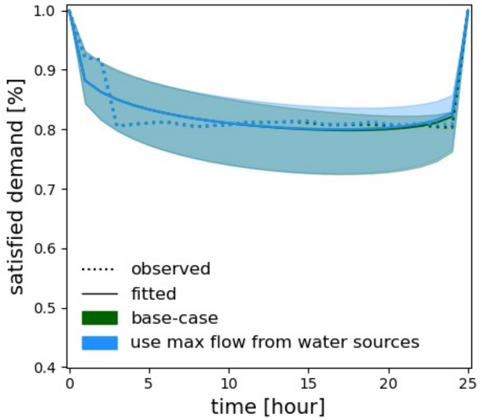
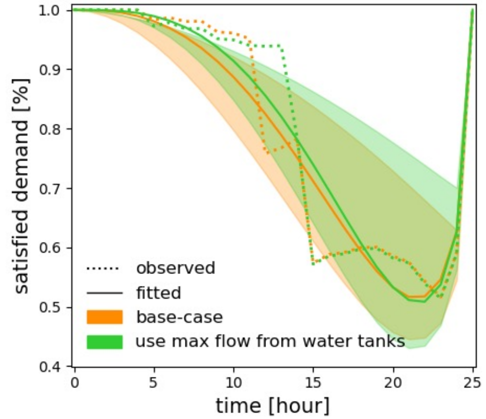


(4)



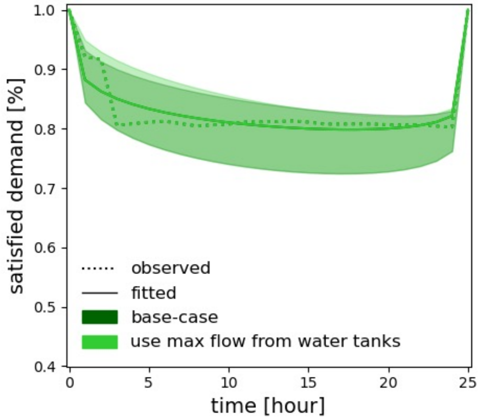
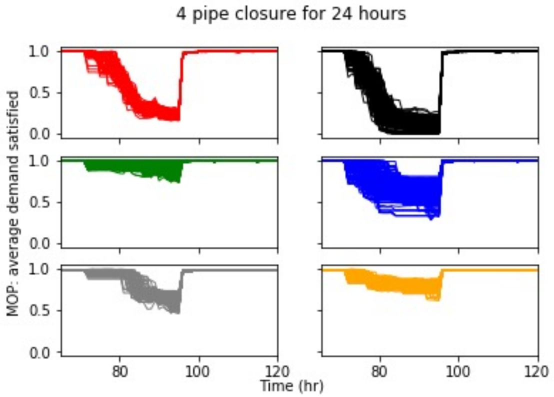
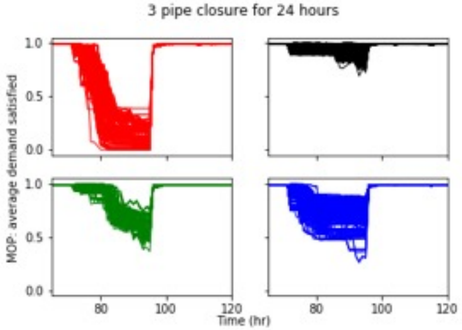
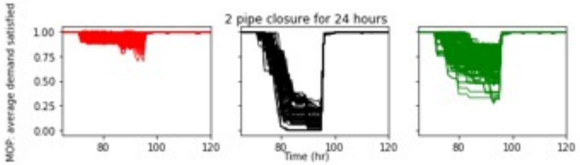


Figure a: Topology of *Net3*, nodes are coloured according to *cluster*
Figure 1: Fitted functions, strategy (i), cluster ‘delayed-but-severe’
Figure 2: Fitted functions, strategy (i), cluster ‘sudden-but-limited’
Figure 3: Fitted functions, strategy (ii), cluster ‘delayed-but-severe’
Figure 4: Fitted functions, strategy (ii), cluster ‘sudden-but-limited’

Emerging response behavior





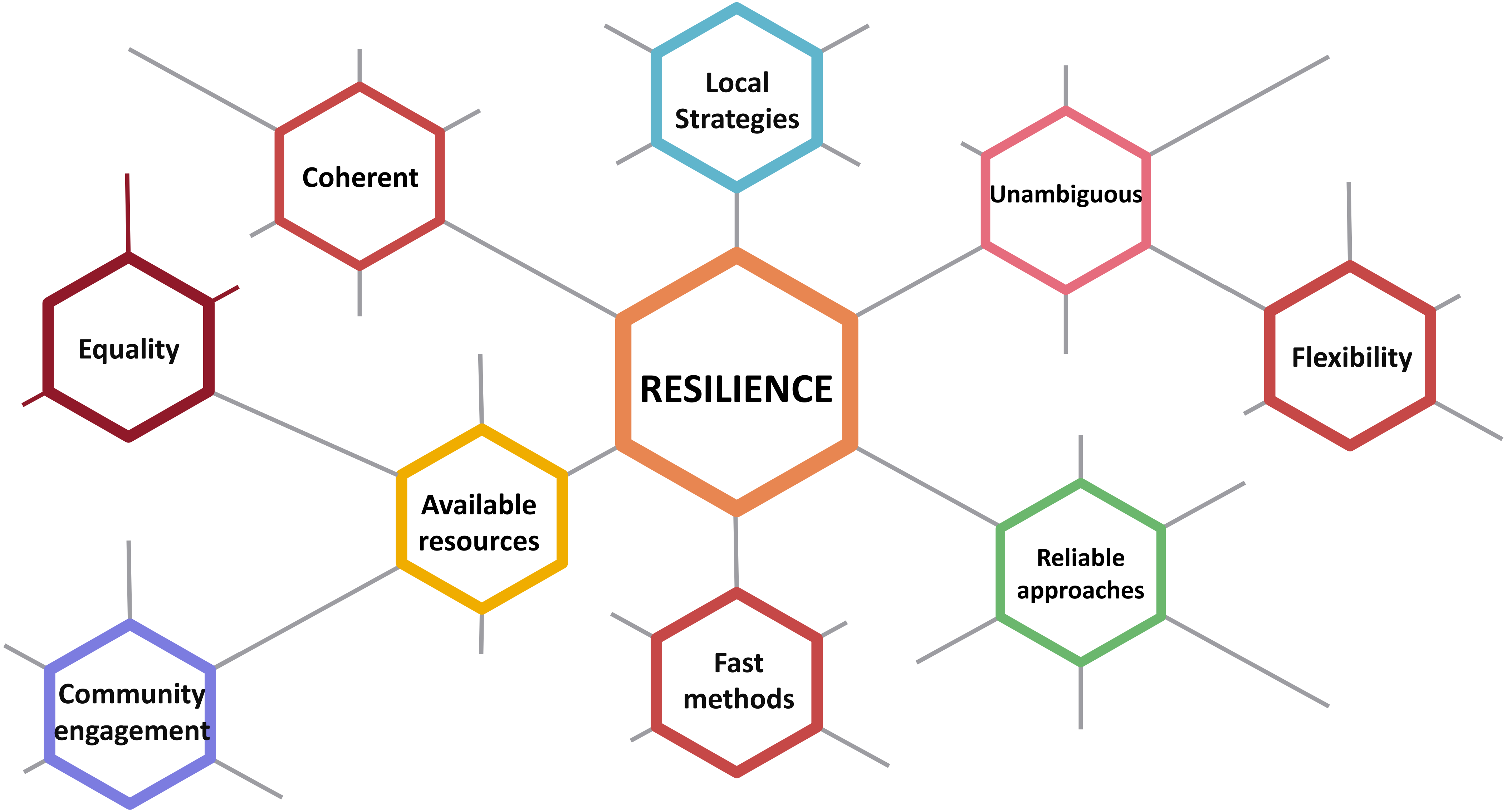


2 pipes

3 pipes

4 pipes

What do we need for building resilience?



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