Complex networks theory for water distribution networks modelling and resilience assessment. An explorative analysis

GitHub: IreneBa26

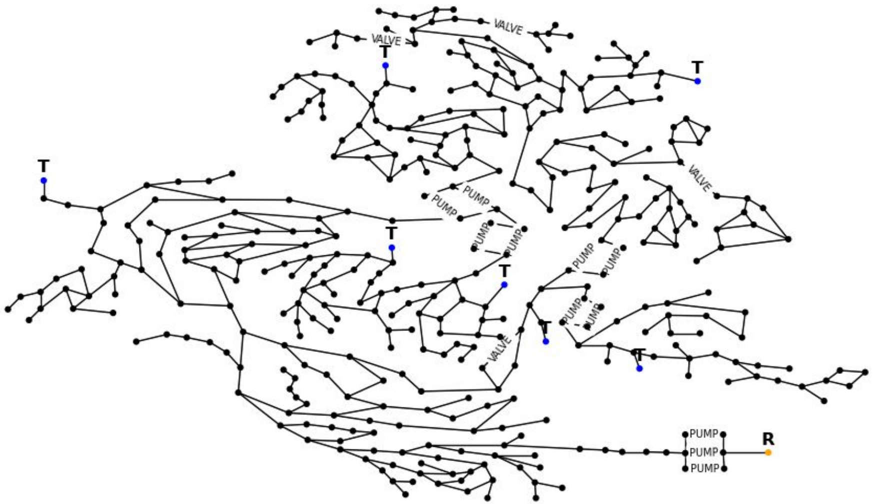
Introduction & Overview

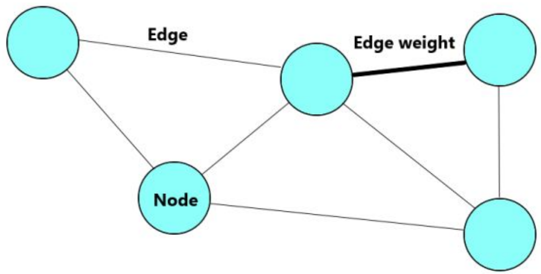
What is Complex Network Theory (CNT)? [1]

- Side branch of Graph Theory
- Focus on **interactions** and relationships among individuals
- Non-trivial topological features

Why Water Distribution Networks? [2]

- **Complex structure**
- Tanks, reservoirs and demand points → **Nodes**
- Pumps, valves and pipes → **Edges**
- **Edge weights:** interactions characterization





[1] Watts & Strogatz (1998)
[2] Yazdani & Jeffrey (2012)

Aims and Objectives

Research questions:

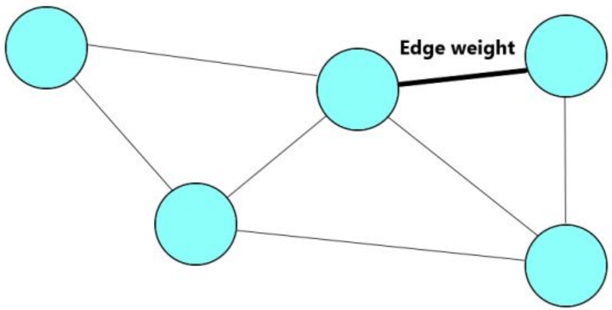
- What are the most suitable criteria to model and analyze a water distribution network as a **complex graph**?
- Under which **conditions** could CNT metrics represent a hydraulic network?
- Could CNT reduce the **computational effort** required for water network resilience assessment?

↓

Topology-based surrogate model

Review of Literature

- **Edge weights** - Different methodologies/techniques for **best** system calibration:
    - Simulation-based parameters (flow, head, pressure, demand)
    - Structural parameters (pipe length, diameter length, node elevation)

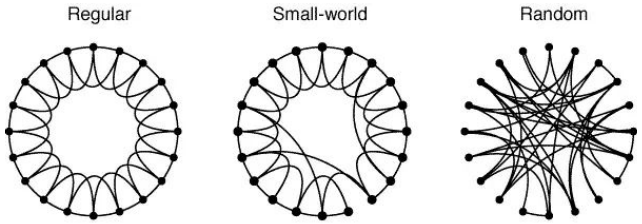


Pipes length as edges weight [3]

[3] Sitzenfrei et al. (2019)

Review of Literature

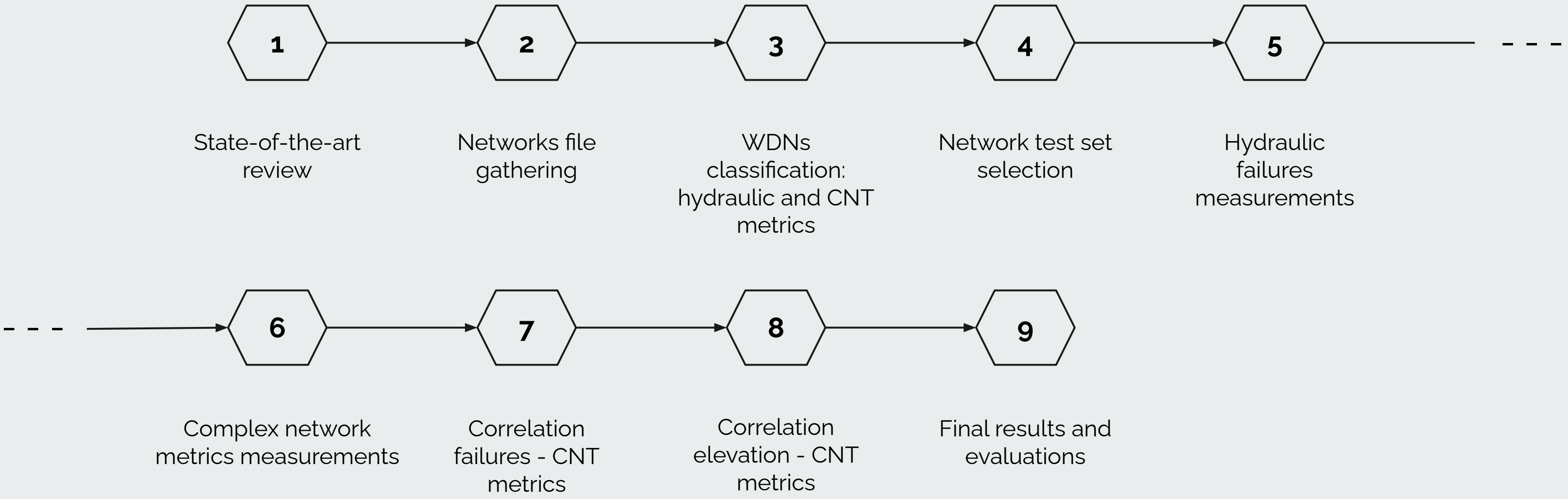
- **Small world effect** [1]**:** highly clustered network where most nodes are not neighbours of one another but can be reach from every other node with a **short path** → Small world coefficient **σ > 1**
    - **locally and globally efficient**
    - **robust to targeted attacks**
- **Resilience assessment - unsatisfied water demand** [4]:
    - **Failure duration**: average duration of node failure
    - **Failure magnitude**: severity of water shortage: the percentage of unmet water demand



Source: Watts and Strogatz (1998)

[1] Watts & Strogatz (1998)
[4] Zhan et al. (2020)

Implementation flowchart



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WDNs classification: hydraulic and CNT metrics

Network test set selection

Methods

WDNs classification

Numbers of nodes, edges, reservoirs, tanks, pumps, valves, junctions, pipes and size of the network (total pipes length)

Small world coefficient (σ > 1)

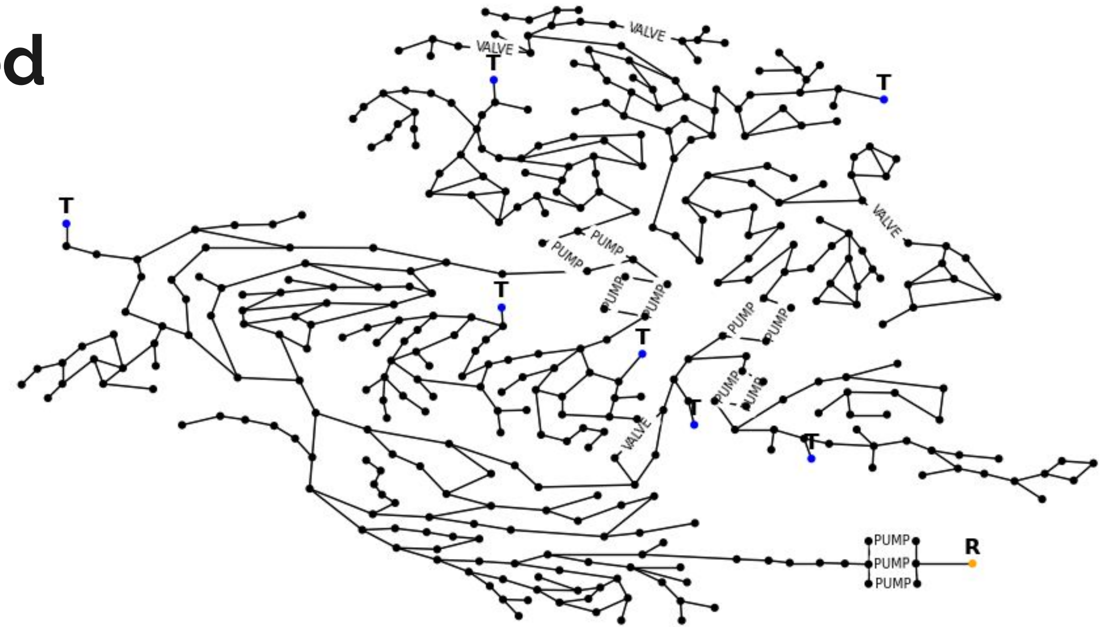
Network name	σ median
Anytown	1.7
C-town	5,05
MOD	2.9
KL	20.37
ky1	2.42
ky2	10.52
ky3	3.58
ky4	17.05
ky5	4,91
ky6	5,76

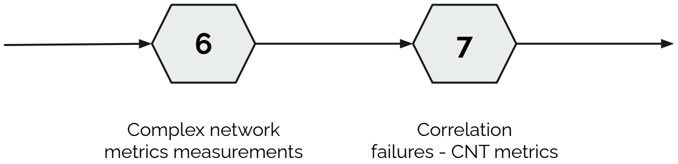
Network name	σ median
ky7	4,89
ky8	12,29
ky9	14,93
ky10	5,26
ky11	10,87
ky13	17,53
ky14	4,34
ky15	4,5
RuralNetwork	3.04
ZJ	0,81

Test set selection

Network name	Nodes	Edges	Reservoirs	Tanks	Pumps	Valves	Junctions	Pipes	Length (m)
C-town	396	444	1	7	11	4	388	429	56738.77
MOD	272	317	4	0	0	0	268	317	71806.11
Net3	97	119	2	3	2	0	92	117	65750.96
KL	936	1274	1	0	0	0	935	1274	252497.77
ky6	548	647	2	3	2	1	543	644	123202.96

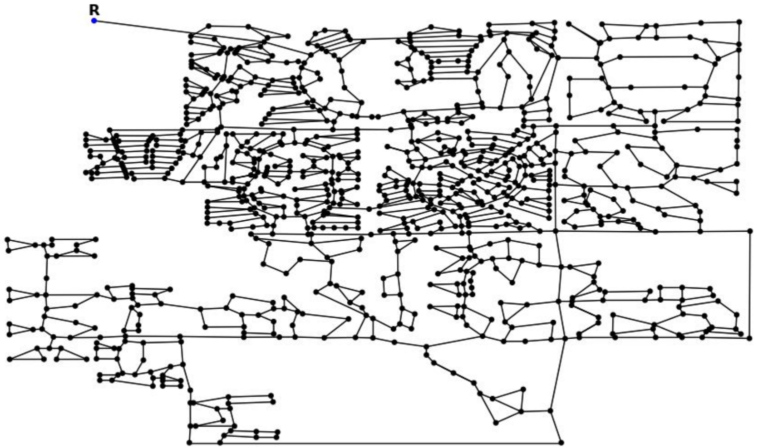
Network-referred analysis





Results

KL network



Comparison CNT metrics - failures values

- Small world property

Average failure duration

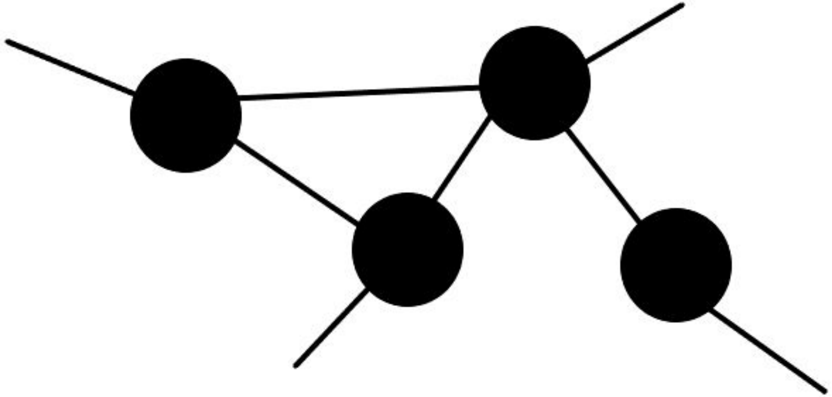
Name	10-th percentile [h]	50-th percentile [h]	90-th percentile [h]
C-town	3.91	53.2	112.75
MOD	13.16	72.09	134.15
KL	10.96	47.61	**93.61**
Net3	0.1	37.59	**88.46**
Ky6	9.09	57.54	135.67

Name	APL [m]	σ
C-town	3487.32	5.08
MOD	3323.78	2.9
KL	**4117.58**	**20.37**
Net3	5496.40	2.03
Ky6	3290.52	5.76

Average failure magnitude

Name	10-th percentile [%]	50-th percentile [%]	90-th percentile [%]
C-town	$1.6 \cdot 10^{-5}$	0.000177	0.000397
MOD	$4 \cdot 10^{-6}$	$5.8 \cdot 10^{-5}$	0.000317
KL	$2 \cdot 10^{-6}$	$2.5 \cdot 10^{-5}$	**0.000067**
Net3	$1 \cdot 10^{-6}$	0.00011	0.000574
Ky6	$1.3 \cdot 10^{-5}$	$6.7 \cdot 10^{-5}$	0.000277

Node-referred analysis



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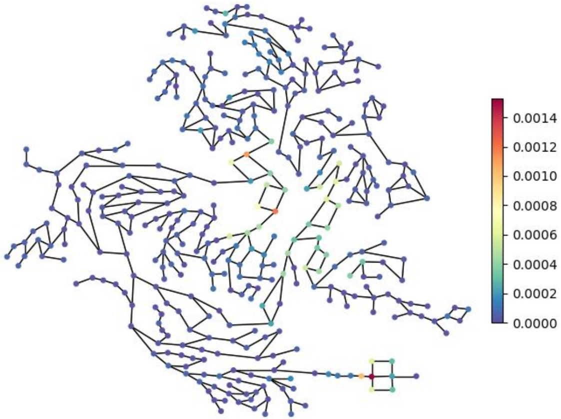
Correlation
failures - CNT metrics

Results

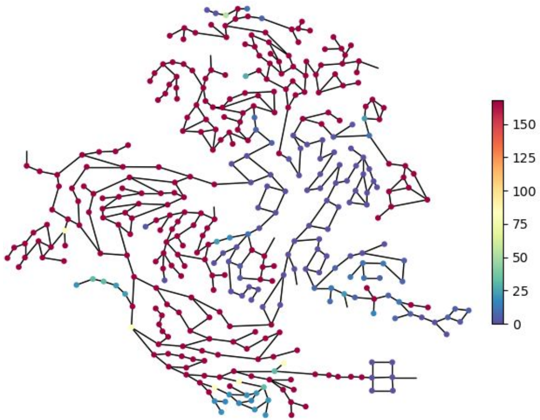
Correlation CNT metrics - Failure duration

- Closeness centrality: Nodes which are closest to all other nodes

C-town: Closeness centrality



Failure duration 90-th percentile



10-th percentile					
Name	**BCE**	**Node degree**	**Closeness centrality**	**Clustering coeff**	**EIG**
C-town	-0.031	0.047	-0.039	-0.027	-0.015
MOD	0.02	-0.03	**-0.159**	-0.036	**0.154**
KL	-0.123	-0.095	**-0.223**	0.112	0.091
Net3	-0.114	-0.091	-0.021	-0.029	-0.018
Ky6	0.031	0.015	-0.006	-0.05	-0.024

50-th percentile					
Name	**BCE**	**Node degree**	**Closeness centrality**	**Clustering coeff**	**EIG**
C-town	-0.127	0.01	**-0.138**	0.11	-0.059
MOD	0.085	0.02	**-0.258**	-0.106	**0.150**
KL	**-0.171**	**-0.208**	**-0.174**	0.088	0.023
Net3	-0.115	-0.025	-0.066	-0.134	-0.086
Ky6	**0.158**	-0.055	-0.039	-0.056	-0.07

90-th percentile					
Name	**BCE**	**Node degree**	**Closeness centrality**	**Clustering coeff**	**EIG**
C-town	0.166	0.033	**-0.348**	0.054	0.032
MOD	**0.192**	0.014	**-0.232**	-0.091	0.066
KL	**-0.331**	**-0.251**	**-0.140**	0.081	-0.011
Net3	0.015	-0.07	**-0.117**	-0.108	**-0.154**
Ky6	0.085	**-0.128**	-0.039	-0.033	**-0.183**

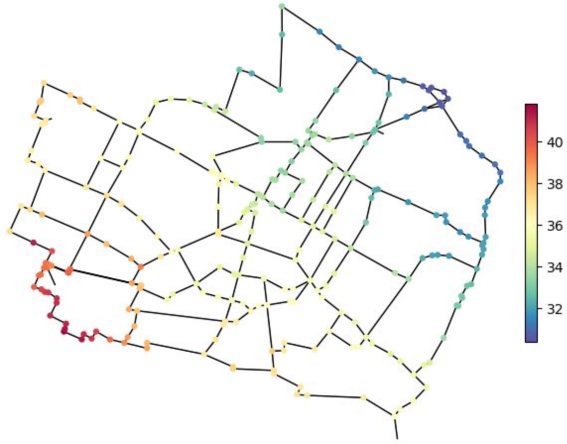
Correlation elevation - CNT metrics

Results

Correlation node elevation - CNT metrics

Name	BCE	Node degree	Closeness centrality	Clustering coeff	EIG
C-town	-0.049	0.034	0.059	**0.199**	**-0.118**
MOD	-0.038	-0.029	**-0.814**	**-0.212**	0.08
KL	0.002	-0.098	**-0.137**	0.034	**0.123**
Net3	**-0.297**	**-0.153**	**0.504**	**-0.122**	-0.068
Ky6	**0.140**	-0.049	-0.012	-0.003	-0.067

MOD: Elevation



Closeness centrality

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Final results and evaluations

Conclusions

What are the most suitable criteria to model and analyze a water distribution network as a **complex graph**?

- Exclusive characterization - few metrics → **not enough** accuracy
- **Small world** property **may** have direct implications with network resilience and robustness
- **Correlation** between closeness centrality - failure duration - node elevation

Under which **conditions** could CNT metrics represent a hydraulic network?

- **Confirmed** previous literature discoveries
- **Nodes elevation** plays an important role in surrogate modelling

Could CNT reduce the **computational effort** required for water network resilience assessment?

- CNT does not require simulation, therefore it's computational efficient. Yet, a "general rule" was not found with our correlation analysis

Future studies

- Discoveries to be tested on **different** types of WDNs
- Edge weights to be calibrated including **other structural parameters** (nodes elevation, water flow, operational status)
- Simulation parameters → more **calibrated** and specific on each WDNs

References

[1] Watts, D. J. & Strogatz, S. H. Collective dynamics of 'small-world' networks. nature 393, 440–442 (1998).

[2] Yazdani, A. & Jeffrey, P. Water distribution system vulnerability analysis using weighted and directed network models. Water Resources Research 48 (2012).

[3] Sitzenfrei, R., Oberascher, M. & Zischg, J. Identification of network patterns in optimal water distribution systems based on complex network analysis in World Environmental and Water Resources Congress 2019: Hydraulics, Waterways, and Water Distribution Systems Analysis (2019), 473–483.

[4] Zhan, X., Meng, F., Liu, S. & Fu, G. Comparing performance indicators for assessing and building resilient water distribution systems. Journal of Water Resources Planning and Management 146, 06020012 (2020).