The Reliability, Efficiency and Treatment Quality of Centralized versus Decentralized Water Infrastructure[1]

Dr Qilin Li, Associate Professor, Civil & Environmental Engineering, Rice University

Dr. Leonardo Duenas-Osorio, Assistant Professor, Civil & Environmental Engineering, Rice University

Dr. Alireza Yazdani, Post-Doctoral Research Associate, Civil & Environmental Engineering, Rice University

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I. SUMMARY

This report provides an overview of the activities carried out so far to study and quantify the effects of network topology on the performance of Water Distribution Systems. In particular, this report elaborates on the topological analysis of the City of Houston (COH) water distribution system and its comparison against benchmark real water distribution systems of Colorado Springs in the US, Yorkshire Water Richmond in the U.K. and Kumasi town in Ghana. The undertaken analysis is viewed as an enabling step towards quantifying the effects of morphing existing network topology into more sustainable configurations, and developing a framework for the joint assessment of network reliability, energy-efficiency and water quality in urban water infrastructure systems.

II. ACTIVITIES AND PROGRESS

Water Distribution Systems consist of several components including the water supply source(s), treatment plants, transmission elements, storage facilities, distribution components and consumer sites. Such systems may be represented and studied as (typically large) spatial networks of nodes (e.g. sources, sites, and junctions) which are interconnected by links (e.g. trunk mains, pipes, valves, pumps). The efficiency, reliability and robustness of water distribution systems largely depend on connectivity, reliability, performance and physical and hydraulic attributes of system components. This work employs some advanced and emerging tools and techniques from Graph Theory and Complex Networks to quantify the topology of water distribution networks and describe the interplay between topology and performance in both water quality and quantity terms. Performance is quantified with engineering-based modeling tools such as EPANET, a software from the U.S. Environmental Protection Agency that enables hydraulic and water quality behavior modeling within pressurized pipe networks [1].

In this work, a number of benchmark water distribution systems have been studied to establish a reference on typical values for topological metrics in real systems. These include water distribution networks of: i) the City of Houston (COH) in the U.S., ii) Colorado Springs (CS) in the U.S., iii) Yorkshire Water Richmond (YWR) in the U.K., and iv) Kumasi town (KUM) in Ghana (Figure 1). Out of these four networks, the three latter networks have been previously studied and analyzed from the perspective of hydraulic performance and/or topological reliability (please see [2-3] and references therein for details). However, in our knowledge, this is the first attempt to study the structure and performance of the COH water distribution network by using a variety of complex network techniques and measurements viewed as the topological indicators of performance and robustness (Table 1).

The available data (as GIS or EPANET file formats) have been explored and analyzed to quantify the global (network-level) and local (network subsystem-level) structure and connectivity patterns of the studied networks. The obtained values have been viewed as topological indicators of performance and interpreted toward qualities such as system efficiency, redundancy, fault-tolerance and robustness. This analysis is regarded as an opportunity to gain invaluable insight into the interplay between the topology and performance of the COH water distribution system by comparing it

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against other networks (Table 2) that are recurrently studied and cited in the literature. To this end, some of the specifications and the results related to the topological analysis of the COH water distribution network have been highlighted and presented here (Tables 3-4, Figure 2). The work on the full characterization of the role of network topology in reliability, energy-efficiency and robustness of water distribution systems is part of ongoing efforts.

III. PROJECT OUTPUT, DISSEMINATION AND PLANNED ACTIVITIES

This reported work has completed a preliminary phase focused on the topological assessment of the City of Houston water system. A short list of the ongoing or planned activities includes:

i. The analysis of the minimally connected (Minimum Spanning Tree) and maximally connected (Greedy Triangulation) versions of these networks (COH, CS, YWR and KUM) to identify system performance boundaries based on the connectivity limits of the network [4].
ii. The quantification of the effects of morphing existing water infrastructure systems into decentralized and hybrid layouts for different levels of physical intervention in terms of miles of new pipelines, number of pumping stations, water tanks and treatment sites.
iii. A comparison of the investigated topological metrics against those available through EPANET modeling of water distribution networks such as energy consumption and water quality indicators.
iv. Dissemination and publication of the results of this project in leading academic journals, and leveraging the project to obtain external funding from federal agencies, EPA and NSF.

Some additional venues for the dissemination of this ongoing research include:

i. An abstract accepted for presentation at PSAM11/ESREL 2012 International Conference in Probabilistic Safety Assessment, special session on Vulnerability of Critical Infrastructure, Helsinki, Finland. A full paper will be submitted by end of January 2012 for review and publication in the conference book.
ii. A presentation of the early results of this project has been made at the Rice University Department of Civil and Environmental Engineering's CEVE Seminar Series held on November 21, 2012.
iii. A meeting with the City of Houston Water Utility Resilience Research Group is expected to take place in January 2012. This meeting is regarded as a venue for presenting the analysis of the COH water distribution network and seeking feedback as well as an opportunity for gaining further support for this project from the COH water utility managers.

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Figure 1 EPANET view of City of Houston **COH** (top left), Colorado Springs **CS** (top right), Yorkshire Water Richmond **YWR** (bottom left), Kumasi **KUM** (bottom right)

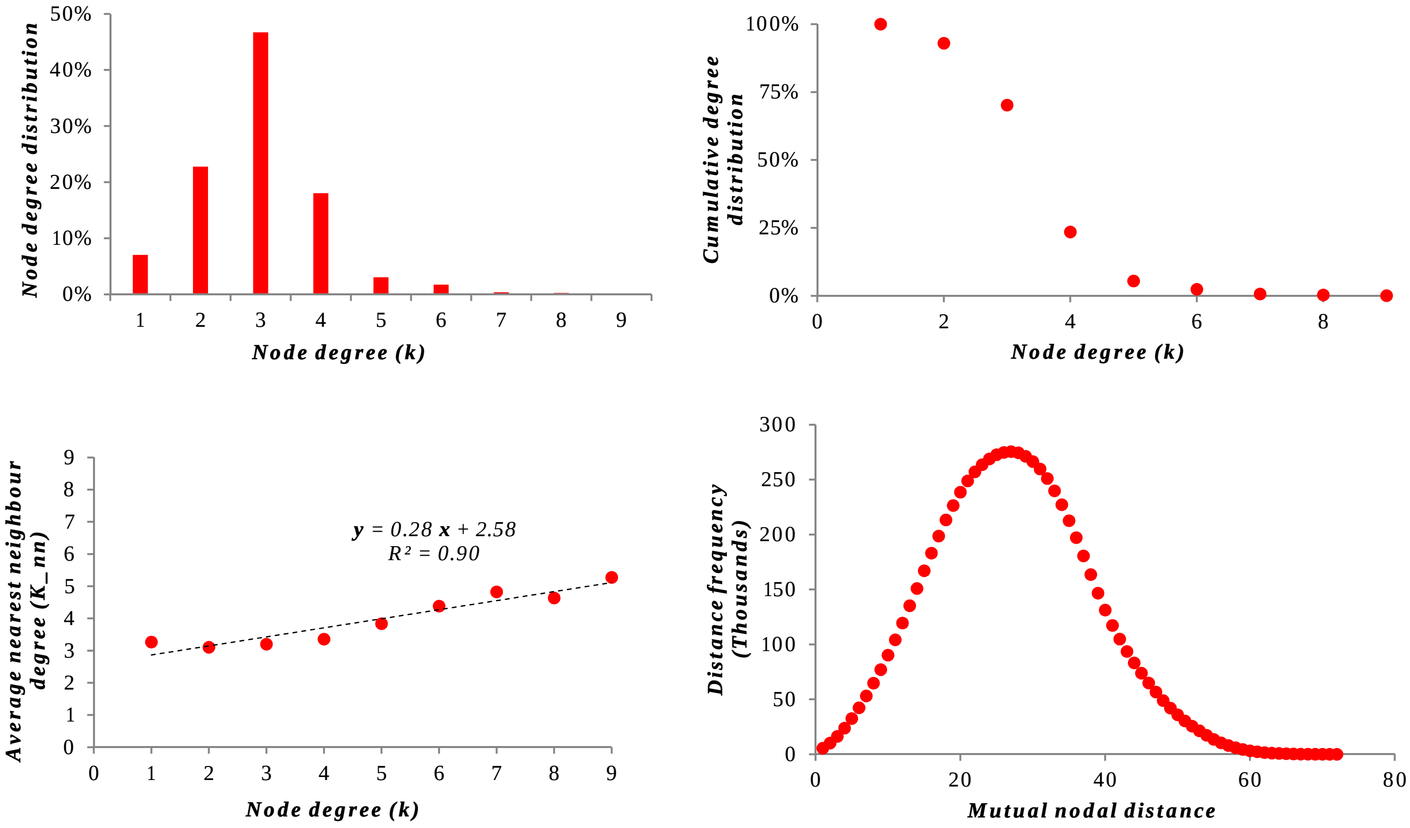

Figure 2 The representation of the COH water distribution network node degree histogram (top left), cumulative degree distribution (top right), average nearest degree distribution (bottom left), and distance distribution (bottom right).

Table 1 Measurements to quantify and study the effects of network topology on performance

Metric(s)	**Type**	**Definition**	**Quantifying**
Algebraic connectivity $a(G)$	Global	Second smallest eigenvalue of network Laplacian representing how well-connected a network is.	Robustness, Optimal-connectivity
Articulation points D_{ap} /bridges/ Cut-sets	Local	Nodes/links/collection of components whose removal disconnects network	Robustness, Optimal-connectivity
Average degree $<k>$, Max degree M, min degree m, degree distribution	Global	Average/Max/min number of links adjacent to a node and the probability distribution of the degree sequence	Connectivity, node criticality, vulnerability (e.g. power law, Poisson)
Average path length l , Graph diameter d	Global	Average/maximum number of links traversed along the shortest paths for all pairs of network nodes	Efficiency/ Cost of construction and maintenance
Central point dominance b	Global	Average value of difference between centrality of most central node and all others	Efficiency, Vulnerability to failure of central nodes
Average pipe length a_l	Global	Average geographical distance between nodes/sites	Efficiency/ Cost of construction and maintenance
Critical ratio of random breakdown f_c	Global	Percentage of random node breakdown that renders network topology defragmented	Vulnerability, Sensitivity to random component failures
Demand-adjusted entropic degree	Local	A generalized connectivity measure to incorporate node degree, base demand and distribution of adjacent pipes' capacity	Connectivity, node criticality, vulnerability
Meshedness r_m, Clustering coefficient c_g, Number of loops of any size ***loops***	Global	The ratio of general (transitive triangles) loops to all possible loops	Redundancy through alternative supply paths
Node (link) betweenness centrality, node/link capacity	Local	Number of shortest paths from all nodes (links) to all others that pass through that node (link), node/link capacity	Component criticality, Redundancy , Reliability
Node (Edge) connectivity κ (μ)	Global	Minimum number of nodes (edge) to remove to disconnect network	Vulnerability, Sensitivity to component failures
Topological efficiency e_g	Global	Average value of the reciprocals of the shortest paths	Efficiency/ Reachability

Table 2 Detailed global topological measurement of the City of Houston water distribution network compared against benchmark water distribution networks

Description	Metric	COH	CS	YWR	KUM
Number of nodes	n	3926	1786	872	2799
Number of links	m	5801	1994	957	3065
Algebraic connectivity (second smallest eigenvalue of graph Laplacian)	$a(G)$	2.26E-04	2.43E-04	6.09E-05	9.40E-05
Average degree ($2m/n$)	$<k>$	2.96	2.23	2.19	2.19
Average path length	l	27.23	25.94	51.44	33.89
Average pipe length (m)	a_l	574.2	187.12	633.09	316.20
Betweenness centralization (central point dominance)	b	0.3463	0.42	0.56	0.45
Closeness centralization	c	0.0359	-	-	-
Critical ratio of random breakdown ($1- 1/(<k^2>/<k>)-1$)	f_c	0.57	0.42	0.32	0.37
Density of articulation points	D_{ap}	0.11	0.44	0.52	0.42
Edge connectivity	μ	1.00	1	1	1
Global topological efficiency	e_g	0.0227	0.054	0.034	-
Graph diameter	d	72	69	135	120
Link density ($2m/(n*n-1)$)	q	0.0008	0.0001	0.0001	0.0003
Link per node (m/n)	d	1.48	1.12	1.1	1.1
Max node degree	M	9	4	4	4
Min node degree	m	1	1	1	1
Meshed-ness coefficient	r_m	0.239	0.0586	0.0495	0.0477
Node connectivity	κ	1.00	1	1	1
Number of loops of any size ($m-n+1$)	$loops$	1,876	209	86	267
Clustering coefficient (density of transitive triangle)	c_g	0.048	0.0009	0.0402	0.0154

Table 3 Classification of components in the COH water distribution network

Number of nodes	***Number of links***
Junctions :3821	*Pipes :5514*
Reservoirs :43	*Pumps:159*
Tanks :62	*Valves :128*

Table 4 Node degree distribution and average nearest neighbor degree distribution of the COH water distribution network

Node Degree	***Node degree frequency***	***Degree distribution***	***Cumulative degree distribution***	***Average nearest neighbor degree (K_nn)***
1	*276*	*7.03%*	*100.00%*	*3.27*
2	*894*	*22.77%*	*92.97%*	*3.11*
3	*1834*	*46.71%*	*70.20%*	*3.20*
4	*708*	*18.03%*	*23.48%*	*3.36*
5	*120*	*3.06%*	*5.45%*	*3.84*
6	*68*	*1.73%*	*2.39%*	*4.38*
7	*14*	*0.36%*	*0.66%*	*4.83*
8	*10*	*0.25%*	*0.31%*	*4.64*
9	*2*	*0.05%*	*0.05%*	*5.28*