Water Network Topography for the State of Texas

A Scale Free Network

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Abstract

This technical report examines the Texas water network using a dataset from the Texas Water Use Survey administered by the Texas Water Development Board. It contributes to the literature in three ways. First, it provides an empirical strategic social network analysis (SNA) of the water flow in Texas through 6,675 nodes, comprising water sources and systems via more than 7,858 relationships (how water moves through the system). The findings indicate that the Texas water network exhibits scale-free characteristics, with highly connected hubs. The hub structure suggests that the concentration of security resources on hubs will provide the highest return on investment and maximize resilience and robustness in the network. Additionally, we conducted a key player analysis, and we identify a set of water sources and systems whose removal disconnects or significantly fragments the network. We suggest that focusing protection resources on these would most effectively enhance overall water network resilience.

Contents

Introduction

Water constitutes one of, if not, *the* most important critical infrastructure (CI) sectors in the state of Texas. It provides a critical need for human consumption, and myriad critical infrastructure sectors depend on it, such as the public health and energy sectors.[1] Water's criticality to humans is matched by its criticality to other sectors such as critical manufacturing, chemical production, and energy generation processes.[2] Thus, understanding the vulnerability of the water sector is a homeland security imperative.

One useful methodology for identifying strengths and vulnerabilities in a critical infrastructure system is network analysis. That is, network analysis allows us to map how water systems are interconnected, pinpoint critical nodes in a web of relationships, and assess — through a series of visual and statistical techniques — how disruptions in one part of the network could cascade across the broader system. Thus, an assessment of the resilience and robustness of the Texas water infrastructure through a network lens is valuable for homeland security enterprise planning.

This technical report will first discuss the history and key contemporary issues in water distribution in Texas. It will then provide an overall description of the data sources used to construct a representation of the Texas water network. This technical report also provides a general overview of the network via social network analysis (SNA). Rapid visualization and context for the whole network is important for conveying network structure. Figure 1 below shows, the main component of the overall Texas water flow network.

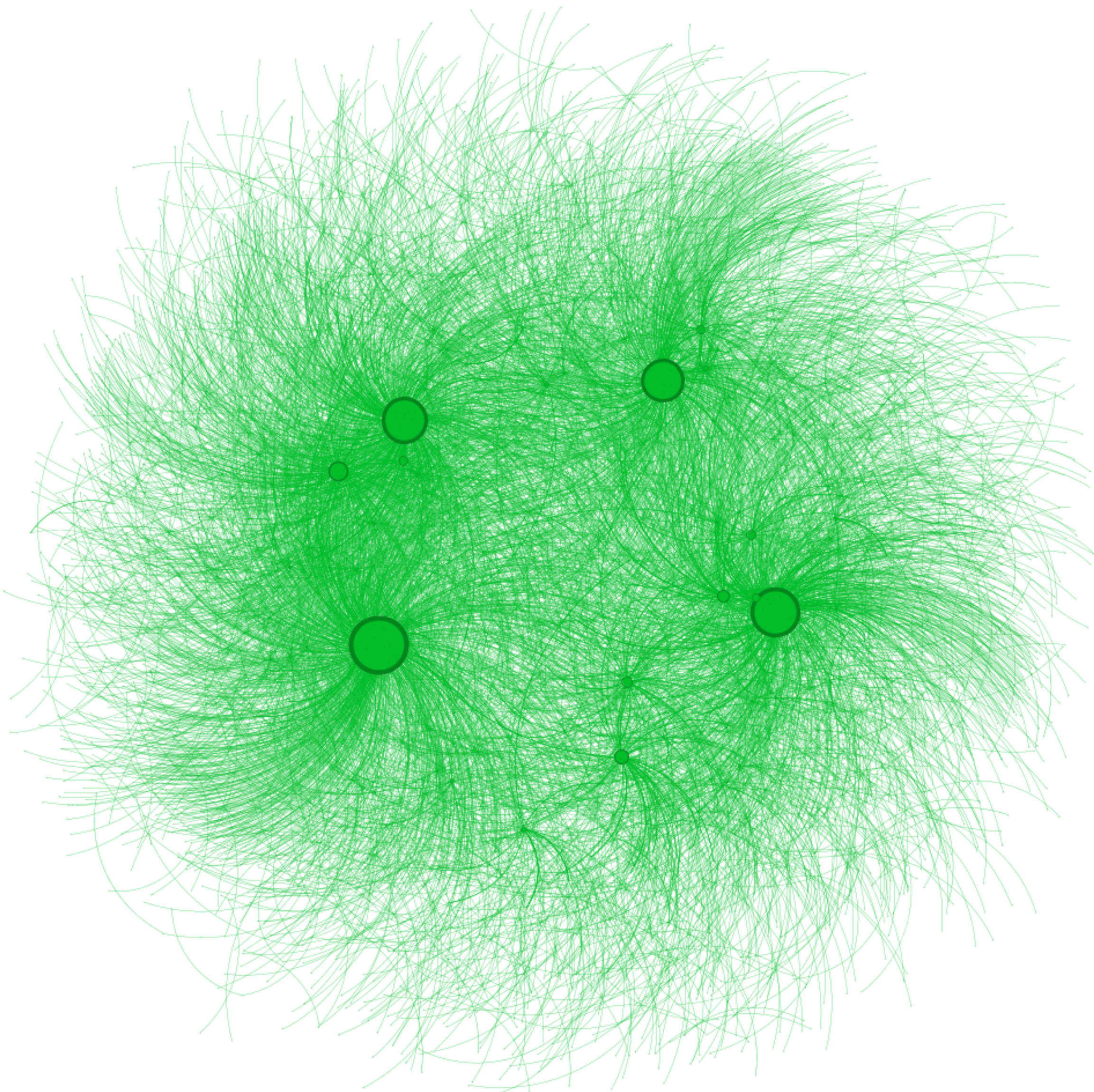

Figure 1. Texas Water Network Main Component with Nodes Sized on Out Degree Centrality and Water Sources in Green

After examining the overall network structure, we then turn to the identification of key sets of nodes whose removal would be highly disruptive, potentially fragmenting the network.[3] This fragmentation has tangible real-world consequences: thousands of homes and entire cities could go without water and could disrupt other interdependent systems, e.g. critical machining or electrical systems.[4]

In this paper, we propose running some important foundational statistical tests to better characterize the network's vulnerabilities. Scale-free networks tend to be more resilient to random attacks or failures.[5] Thus, determining if the network is scale free is useful for understanding the Texas Water Network's level of vulnerability to different types of threats.

First, we test whether the Texas water network exhibits a scale-free structure. This concept, pioneered by Albert-Laszlo Barabási, describes networks organized around a small number of highly connected hubs, which confer the network's resilience to random failures but make it vulnerable to targeted attacks.[6] Based on various statistical tests, we find that the state of Texas water network's node degree distribution follows a power law, the defining feature of scale-free networks. Thus, we quantify how the network is indeed a scale free network and the degree to which this property holds.[7]

Second, given that the Texas water system is indeed a scale-free network, we can then leverage other statistical tests to identify its vulnerability to targeted attacks. That is, the network's dependence on a few key nodes can cause it to be subject to failure or fragment when these sets are removed, a phenomenon that does not commonly occur in random networks.[8]

While centrality metrics are commonly used to identify nodes with social power in the network based on their position, they do not provide an optimal set of actors that when removed, would disconnect the network or maximally fragments the flow or resources.[9] In contrast, the key player problem (KPP) pioneered by Borgatti,[10] was designed to determine which optimal *set of nodes* would fragment the network if removed. The purpose of applying KPP is to pinpoint key sets of nodes and allow for the allocation of security resources more strategically; thus, making the Texas water delivery network safer. In essence, this set of nodes allows us to simulate an adversarial attack and allocate protection resources accordingly.

Literature Review

Water infrastructure in the state of Texas is critically important to the health and safety of all Texans. According to the National Infrastructure Advisory Council (NIAC) Water Resilience report of 2016, "the majority of the population is served by a small percentage of mostly large or very large systems."[11] Being served by a few large systems reflects population distributions, not necessarily the topological structure of the water network. However, the physical and operational connections between systems would determine if the network is organized as a scale-free system. The potential prevalence of hubs in the water sector makes network-based analyses particularly relevant for identifying critical nodes and potential vulnerabilities, in line with the existing priorities in existing government reports and the academic literature on infrastructure networks.

Water Sector Interdependence

The water sector is critical not just because of the important services it provides to users as a basic human need, but because of its interdependence with other sectors. The water sector has been identified as one of four "lifeline sectors" due to its criticality to all CI sectors and importance in mitigating regional disasters; with the other sectors being communications, energy, and transportation.[12] For example, if water service is lost, hospitals have limited capacity to continue functioning in the absence of water service. This leads immediately to degraded services after two hours.[13]

A 2016 NIAC report finds that twelve major critical infrastructure sectors suffer degradation of their capacities to function within hours of water loss. These sectors which depend on water include: the chemical and hazardous materials industry which would suffer a 67-99% degradation after 8 hours of water loss; the transportation and command facilities sector is degraded 34-66% after 8 hours of water loss; wastewater treatment degrades 1-33% after five hours; electrical generation plants degrade 67-99% after four hours; and Agricultural and Food production is degraded 67-99% after 4 hours, etc. Water also is critical to the communications and information technology sector because of the importance of water in equipment cooling.[14]

Conversely, water systems are dependent upon other sectors, especially the energy sector. For example, with a loss of electricity, pumping stations and other facilities in water systems shut down; thus, degrading the capacity of the water sector. While the water sector has emergency generators, long-term power outages can overwhelm these redundant systems. The water sector is also dependent on the chemical sector because chemicals are required for the operation of water facilities. Without the transportation sector, water sector employees cannot get to work, nor can important chemicals be delivered.[15]

Cyber Threats

Water services are comprised of three elements: physical, human, and increasingly cyber.[16] With increasing use of information technology and control systems the water sector has become more efficient, but also more vulnerable to cyber-attack.[17] According to a November

2024 security assessment, drinking water systems serving 193 million people in the United States faced exposure to cyberattacks. The Environmental Protection Agency (EPA) identified 97 water systems with critical or high-risk vulnerabilities that served 26.6 million people. In comparison, 211 systems with medium or low-risk vulnerabilities provided water to over 82.7 million people.[18] The EPA, through its enforcement alert in May 2024, established that 70% of water utilities failed to meet standards aimed at stopping cyberattacks on their systems. According to the EPA, water utility cyberattacks are increasing in frequency and intensity.[19]

Workforce Challenges

The Texas water sector suffers from workforce challenges. According to a report based on survey data conducted by the Houston Advanced Research Center for the Texas Water Foundation, found that a majority of utilities surveyed (63%) "reported that their organization was experiencing workforce related challenges."[20] Survey respondents identified key issues such as "talent attraction, providing competitive wages, talent retention, and staffing shortages within their organizations."[21] A 2025 report from Jobs for the Future also identified other issues related to water infrastructure workforce issues in Texas. Rural communities suffered a brain drain of talent to larger metro areas. The report also identified a "silver tsunami of retiring operators, increasing demand due to the state's growing population, rising operational costs, noncompetitive wages, and a dwindling pool of qualified replacements."[22]

According to the American Water Works Association (AWWA) *State of the Water Industry 2024 Executive Summary*, AWWA forecasts that one-third of water utility workers will retire this decade. In the published 2024 AWWA Executive Summary, workforce issues rank in the top 10 issues facing the water sector.[23] The creation of employee training strategies, competitive pay plans, and academic ties to hire and retain staff who maintain our water systems is needed.[24]

Legal Issues: Rule of Capture, Pricing, Allocation

Texas law presents unique challenges to critical infrastructure protection (CIP) for the water sector, as local legal principles complicate the governance of water use. Water law faces three main challenges: the Rule of Capture principles, water price structures, as well as water allocation systems among different sectors.

Under Texas groundwater law, landowners can extract and use groundwater underneath their property without worrying about next-door well disruptions through the "Rule of Capture" principle. In 1904, Houston & Texas Central Railway Co. v. East established Texas Supreme Court doctrine that let landowners use all their groundwater freely even if it emptied neighboring wells.[25]

Water prices in Texas depend on whether water comes from a surface or ground source, as well as the intended use and the regional policies. The state monitors surface water rights through permits that define the permitted amounts and end uses. Under the Rule of Capture system, groundwater prices stay decentralized, which leads to unequal water expense levels.[26] Local water providers and governments set prices for their customers to pay for fixing and maintaining water systems, in addition to water treatment and delivery services. Surface water users receive preferential rates in the industry because of past practice and their crucial dependence on irrigation for farming. Water shortages demand that we rethink pricing designs to motivate water savings while guaranteeing everyone equal access to this resource and maintaining our treatment systems.[27]

Water usage in Texas agriculture makes up a substantial amount of all water consumed in the state. Large agricultural water use creates problems with fairly sharing limited water supplies between farming areas and retail and commercial users. Agricultural users receive first choice on water rights because of their historical rights, which create problems for modern cities when drought hits. Meeting farming water needs with other uses requires a thoughtful strategy that looks at how water helps both prosperity and food safety, and future growth.

Importance of Water Infrastructure in Texas

Texas's water network includes reservoirs and treatment plants that work alongside pumps and underground reservoirs to provide drinking water to millions of citizens and businesses. The Edwards Aquifer supplies drinking water to its two million users and delivers groundwater directly to Texas's farming and industrial operations. [28] The current water infrastructure of the state needs substantial improvements. In 2020 the Texas Tribune reported that Texas lost 136 billion gallons of water because its aging water infrastructure needed updating and maintenance work.[29]

Economic Implications

Texas's economic growth depends on its water supply networks. According to Texas 2036 researchers, the state will face a 4.7 million acre-feet water deficit under extreme drought conditions by 2030, representing one-quarter of 2020 water usage totals. The resulting water shortage will harm Texas's economy until proper investment happens in water systems and conservation.[30]

Network Analysis for Critical Infrastructure

Although the application of network analysis to critical infrastructure remains limited, existing studies underscore its potential for identifying systemic vulnerabilities. Ted G. Lewis of the Naval Postgraduate School (NPS), for example, has long used network analysis to identify vulnerabilities in critical infrastructure and has spearheaded network analysis for critical infrastructure protection (CIP) education.[31] He argues that CI efforts often focus on a “single point audit” of a single node like a powerplant, but resources would be better served by assessing CI as a network which allows for the identification of critical nodes and links.[32]

Similarly, scholars such as Albert et al. 2004 found in their paper *Structural Vulnerability in the North American Power Grid* that the August 2003 black out could best be understood as a network failure and understanding the network's global properties or structural features was key to explaining why a highly interconnective and generally robust network could suffer such a catastrophic failure. They found betweenness centrality was a proxy for the potential electrical load on a particular node and simulated the removal of key nodes and the effect on the grid. They suggest that a more decentralized local system of power generation might be the only economic mechanism to change the hub-based network structure that created the vulnerabilities of cascading failures.[33]

Boccoletti et al. (2006) focus on complex networks which they define as

> networks whose structure is irregular, complex and dynamically evolving in time, with the main focus moving from the analysis of small networks to that of systems with thousands or millions of nodes, and with a renewed attention to the properties of networks of dynamical units.[34]

Here again we see Boccoletti et al. (2006) echoing the same points made by Lewis on the importance of understanding network structure.

Barabási's work on scale-free networks has also been extended to critical infrastructure systems, emphasizing the vulnerability of key hubs.[35] Scale-free networks which are organized around key hubs of high centrality are resilient to accidental failures, but are vulnerable to coordinated simultaneous attacks.[36] Thus, identifying a scale-free network in critical infrastructure allows for the immediate identification of key nodes to devote protective/defensive resources. But are all networks really scale free? This is the question raised by Broida et al. (2019) who find that many networks that appear scale-free at first blanche, are not when scrutinized with more sophisticated statistical measurements.[37] This study aims to contribute to this literature by applying network analysis to the Texas water infrastructure based on a network of surveyed water systems and one of the key contributions of this report is to test the scale-free nature of the Texas water network.[38]

Methodology

We derived the data for the Texas Water Network (TWNet) using the 2022 data set from the Texas Water Use Survey (WUS), administered by the TWDB. The WUS conducts an annual survey of 4500 public water systems and 3000 industrial facilities.[39] Clarifications on survey structure, data, and data quality were obtained through consultation with the Texas Water Development Board and Texas Water Foundation.

When constructing the network, we opted to simplify the network graph to remove parallel arcs and self-loops. By doing this, each pair of nodes is connected by at most one arc, and no node points to itself. This simplification aligns with the structural focus of the paper. That is, our primary concern is identifying which nodes play a key role in network structure, and retaining parallel arcs or self-loops would obscure node importance by inflating connection counts rather than reflecting true structural relationships (e.g., structural importance based on betweenness).

The Texas WUS dataset allowed for the creation of a directed waterflow network between water sources, water systems, purchasing entities or sales. For a more detailed discussion of the underlying data, please see the Institute for Homeland Security companion report introducing the TWNet online visualization tool.

With our data set in hand, we then performed our network analysis using standard SNA statistical and visualization software including UCINET, networkx, UCINET (Key Player subprogram), Gephi for visualization, and the powerlaw Python package to test whether the network's degree follows a power law distribution, which would indicate consistency with scale-free structure.[40] From there, the paper provides the key set of players whose removal would significantly fragment the network and use other metrics to identify hubs whose removal would disrupt the network.

Exploratory Analysis of The Texas Water Network

We begin our exploratory network analysis of the Texas water network data by assessing the topography of the overall network. The network is fairly large at 6,675 nodes and unique edges 7,758 edges or relationships. It should noted that this analysis excluded repeated ties and self-loops. It is a directed network which considers the directional flow of water. Table 1 below contains key network topography metrics that network analysts typically assess in any exploratory analysis.

Network Topography Metric	Overall Network
Nodes	6,675
Edges	7,758
Average Degree	2.3545
Degree Centralization	0.122
Out-Degree Centralization	0.122
In-Degree Centralization	.0013
Density	0.0002
Weakly Connected Components	60
Diameter	11
Average Clustering Coefficient	.0554
Average Path Length	2.122

Table 1. Whole Network Topography Metrics for the Texas Water Network (Output UCINET).

We found a decentralized network (0.122-degree centralization on a scale of 0-1) with interesting properties. The lack of centralization globally around a handful of nodes is due to the disconnected nature of this network, as noted here by the 60 weakly connected components.[41] Even within a connected component, the diameter of 11 signifies that it would take 11 steps to get across a single component. Altogether, this suggests a network that would be difficult to traverse and even connected components are not particularly centralized around a handful of nodes.

The Texas water network is sparse, with a density of 0.0002 on a 0-1 scale. This is not surprising since many Texas utility districts are far flung and use their own ground water to supply their customers. In more densely populated areas such as Houston we are more likely to see more local connectivity allowing water to flow through alternative paths in the event of random failures; thereby, increasing resilience in those areas.

The average degree, or the average number of ties of each actor in the network, is 2.354 (see Table 1 above). This can be interpreted as the average actor in the network has a little over two ties to other actors in the network. This suggests limited redundancy within the network and potential vulnerability to disruption with the removal of actors, such as the failure of utility districts or the disruption of water suppliers.

Scale-Free Network?

One of the key questions we set out to answer within this analysis is whether the Texas water network exhibits scale-free properties. This is important because scale free networks tend to be highly resilient to random failures but can be extremely vulnerable to strategic attacks.

Globally the degree distribution is highly right-skewed and heavy tailed. That is, a small subset of nodes is richer in ties, while most nodes in the network only are linked to a few others. While a visual inspection may suggest a power-law-like pattern (see the top panel of Figure 2), a formal Clauset-Shaliz-Newman statistical test indicates that the empirical distribution is plausible as a power-law model (p-value = 0.981).[42]

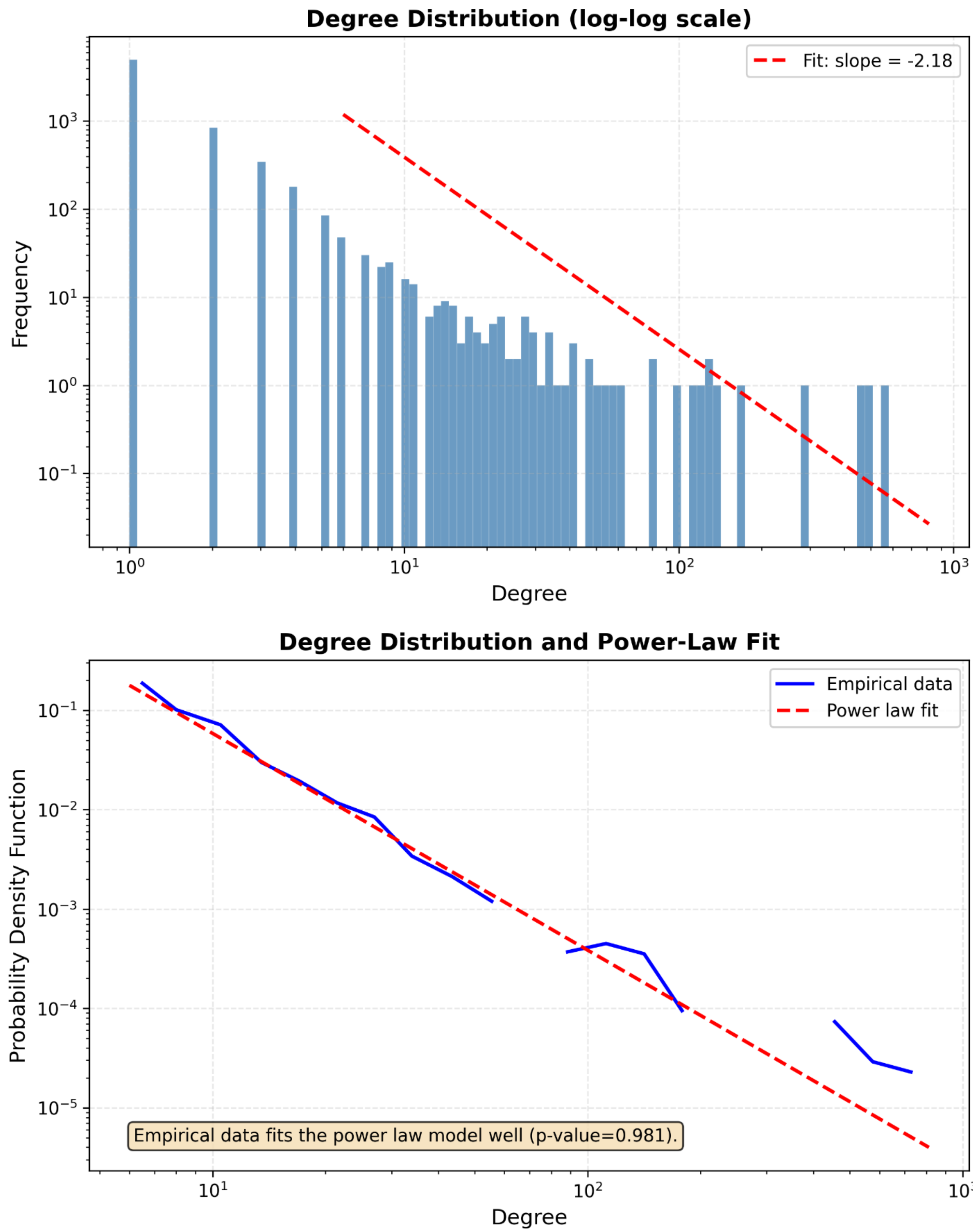

Figure 2. Degree Distribution of the Water Network

Likelihood ratio tests comparing the power law to alternative distributions reveal a more nuanced picture. That is, the power law is strongly favored over exponential, stretched exponential, and lognormal-positive distributions, but truncated power law and lognormal distributions show comparable or slightly better fits.

Taken together, this suggests the network exhibits "scale-free-ish" properties typical of real-world infrastructure networks, where physical (e.g., water is a finite resource) and geographical (e.g., nearby water sources and systems are preferred over distant ones) constraints prevent pure power-law behavior while maintaining the characteristic heavy-tailed distribution indicative of hub-dominated network structure.

Identifying Hubs

Given that the Texas Water network is indeed a scale-free network, we can now usefully identify highly connected actors based on various centrality metrics to inform policymakers and citizens where to best devote scarce protective resources.

In terms of betweenness centrality, a brokerage metric, the top five nodes were: (1) City of Houston, (2) Dallas Water Utility, (3) Mount Houston Road MUD, (4) City of Grand Prairie, (5) City of Fort Worth. These are large city water systems which deliver water to other smaller cities and public water systems. Thus, their identification in the betweenness centrality metric hubs is logical.[43]

Identifying Key Players (Sets)

Stephen P. Borgatti developed an algorithm that can identify a set of key players whose removal would maximize network fragmentation.[44] The algorithm evaluates two metrics of fragmentation. The first, equals the proportion of all pairs of actors that are not tied to one another. The second, distance-weighed fragmentation, considers the shortest path distance between pairs of actors. In this analysis, we have utilized Borgatti's Combinatorial Optimization algorithm in UCINET using a group set size of five. That is, we searched for the set of five actors that, if removed from the network, would most fragment the network.[45] This is a more sophisticated algorithm than simply removing the most central actors from the network based on various node centrality metrics.

Key Players to Fragment the Network (Sets)

The key players to fragment the network were identified by the algorithm as: City of Houston, Carrizo-Wilcox Aquifer, Gulf Coast Aquifer, San Jacinto Basin (Source Unknown), and the Trinity Aquifer. It is notable that most of the key players identified for removal to maximally fragment or increase the distance across the network were aquifers. These are the water sources for much of the rest of the network and therefore often have the most direct ties. It should be noted that the key player metric does not consider directed data but assumes undirected data. Thus, water flow is not measured. The only key player identified that was not an aquifer was the City of Houston. Given the city's deep interconnectivity, as demonstrated by the various centrality metrics, this should not surprise us. Indeed, in terms of betweenness centrality, the City of Houston water system is the most central network. Betweenness centrality is defined as an actor that lies on the most shortest paths in the network and is often interpreted as a brokerage metric.[46]

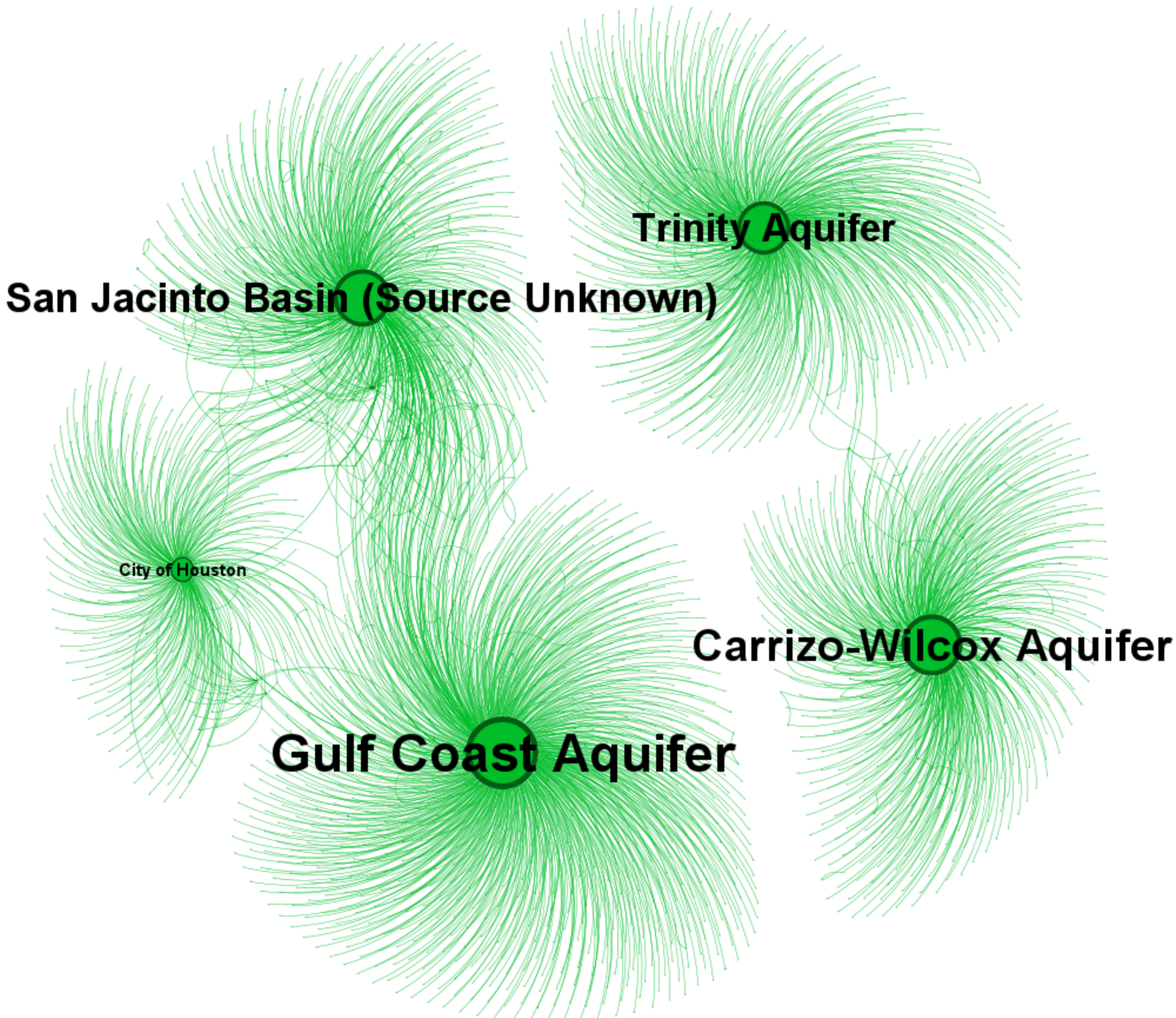

Figure 4. Ego Networks of the Five Key Players for Network Fragmentation in the Texas Water Network
Authors' Elaboration Visualization produced in Gephi and KPP Identification in UCINET

The Texas water network exhibits a baseline fragmentation of 0.06 based on Borgatti's metric. When removing the key players, fragmentation increases to 0.676, representing more than a tenfold increase in the fragmentation within the network. Thus, this section has provided multiple lists of important sets of nodes in the Texas water network that should be the focus of protective resource distribution.

Conclusions

This analysis found the Texas water network to be a decentralized and fragmented network. Nonetheless, the network was scale-free based on our goodness of fit test results aligning this analysis with the literature from Barábasi on critical infrastructure network structures. This allowed the identification of highly central nodes to devote significant protective resources to. Many of these nodes were logically large aquifers and highly connected water systems in urban areas such as Houston. This is a tangible real world finding that better informs Texas state policymakers in their efforts to more efficiently distribute scarce security resources.

Further, this report also identified sets of actors in a group of five that would maximally fragment the network if removed based on Stephen Borgatti's key player metric. This identification of a set that could maximally disrupt the network, is yet another avenue which allows security personnel and policymakers to know where to place security resources to defend critical hubs and maximize the bang for the buck on security spending.

Securing aquifers poses unique challenges given their widespread and subterranean geographic nature. Further, groundwater levels in these aquifers are largely determined by how much humans pump from them and thus how we choose to govern their use. It is beyond the scope of this study to identify all potential threats, e.g. biological attack vulnerability, and security mitigation strategies for aquifers but rather to identify the specific aquifers that play critical roles in the network of water distribution in Texas. Even if it is determined that securing aquifers is too daunting, network analysis allows us to rank all network participants according to various centralities and determine which of the actors we can more easily secure which are also central to the network.

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Disclaimer

The analysis contained within this report does not necessarily reflect views of the Texas Water Development Board, the Texas Water Foundation, or the official policy of the Institute for Homeland Security.

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