



GRAPH VULNERABILITY ANALYSIS OF CHOLA IRRIGATION NETWORKS IN KUMBAKONAM AND THIRUVAIYARU REGIONS

R. Sundareswaran, Sir Sivasubramaniya Nadar College of Engineering, India (sundareswaranr@ssn.edu.in)
M. Shanmugapriya, Sir Sivasubramaniya Nadar College of Engineering, India (shanmugapriyam@ssn.edu.in)
K. Sathish Kumar, Sir Sivasubramaniya Nadar College of Engineering, India (sathishkumark@ssn.edu.in)
Dharunya Sundararajan, Sir Sivasubramaniya Nadar College of Engineering, India (dharunya2110907@ssn.edu.in)
Smruthi Pradeep, Sir Sivasubramaniya Nadar College of Engineering, India (smruthi2110345@ssn.edu.in)
Abinaya Sureshbabu, Sir Sivasubramaniya Nadar College of Engineering, India (abinaya2110414@ssn.edu.in)

ABSTRACT

The Cholas set up a well-organized and efficient water management system as the foundation of their agricultural-based economy. The water supply system of the Chola Empire was elaborately planned, specifically to the geography of the land and the crops that were grown over their extensive kingdom. This was primarily carried out by strategically bifurcating the Kaveri River, which was a fundamental component of their state. Their measures also included building new dams and checks along the riverbanks to control the flow and to hold back the surplus water in the rainy season. Water distribution systems (WDSs) are complex sets of many interconnected junctions and pipelines (canals and dams/lakes in our context). The reliability and resilience of these systems mainly rely on their network configuration, which makes detailed analysis vital for proactive failure detection and sustained operational performance regardless of the season. Within this paper, the graph vulnerability parameters are utilized for gauging the structural integrity of the WDS, thereby providing a better understanding of how different parameters influence system strengths and how much the Cholas were able to factor these in.

Keywords: Chola Water Distribution Systems, Kaveri River Network, Graph theory, Vulnerability parameters.

1. INTRODUCTION

The Cholas were among the most prominent Tamil dynasties of ancient South India, renowned for their effective administration and exceptional achievements in irrigation engineering. Rising to power in the early Common Era, they transformed the Kaveri river basin through advanced hydraulic interventions, notably by dividing the river to form the Kollidam channel (Figure 1) for flood regulation and controlled water diversion. This enabled gravity-based irrigation that converted arid regions such as Thanjavur into highly productive agricultural land. Their water management system combined interconnected tanks and ponds with a hierarchical canal network, distributing water equitably from main supply channels to regional and village-level canals while maintaining continuous flow to prevent stagnation. Temporary bamboo-and-mud check dams provided seasonal flood control, supported by specialised administrative bodies overseeing storage and distribution. Major reservoirs such as Veeranam Lake and Cholagangam Lake further demonstrate the dynasty's expertise in large-scale water regulation, sediment control, and drought resilience, with lasting agricultural and urban benefits. The Kallanai Dam (Grand Anicut), constructed in the 2nd century AD, remains a remarkable example of durable hydraulic design, effectively regulating river flow for irrigation and flood management. Its sustained functionality, studied by modern engineers and later enhanced during the colonial period, has earned it recognition as a UNESCO World Heritage Site, underscoring the Cholas' enduring legacy as master hydraulic engineers.



Figure 1: Kollidam River and a Canal feeding the Katchamangalam Dam

Graph theory provides a systematic approach for representing and studying interconnected systems by modelling their components as nodes and the relationships between them as links. This framework has become widely used for analysing complex infrastructures such as transport corridors, communication systems, and water distribution or irrigation networks. Classical concepts, including Eulerian circuits played a foundational role in the development of graph theory and topological analysis. Another important measure is the crossing number, which quantifies edge intersections in a graph. Networks with zero crossings are planar, while higher crossing numbers indicate non-planar layouts. In irrigation and pipeline systems, reducing crossings simplifies construction, lowers maintenance demands, and improves reliability by minimising interference and flow disturbances.

Representing water infrastructure as a graph allows reservoirs, junctions, and pumps to be treated as nodes, with canals or pipes modelled as weighted edges reflecting length, capacity, or cost. This abstraction enables the application of optimisation tools such as shortest-path and flow-allocation algorithms to improve delivery efficiency and meet demand requirements. Recent research has shown that combining graph-theoretic indicators with hydraulic parameters offers more realistic insight than purely topological or hydraulic approaches, particularly in assessing vulnerability and leakage behaviour in water distribution systems.

Several studies have adopted this integrated perspective. Ulusoy et al. proposed a hydraulically informed metric, Water Flow Edge Betweenness Centrality, to identify critical pipes influencing overall network resilience. Dunn and Wilkinson demonstrated that incorporating flow information into centrality measures improves prediction of system responses to node failures. Agathokleous et al. reported strong correlations between hydraulic performance indices and network centrality measures, while Di Nadro et al. applied eigenvector-based metrics to support strategic supply management. Giudicianni et al. introduced a vulnerability framework based on fractal properties to assess network robustness under hazard scenarios, even when detailed system data are unavailable. Similar graph-based approaches have also been extended to drainage networks to locate structurally critical elements.

More recently, Kim et al. developed a node-based adjacency matrix technique to identify vulnerable segments and unintended isolations within water distribution systems, providing a clear representation of connectivity. Tzatchkov et al. presented graph-theoretic algorithms for sectorising large water networks into smaller operational units, enabling the identification of disconnected nodes and evaluation of source contributions. Their AutoCAD-integrated implementation has been successfully applied in urban water systems to improve operational control and reduce water losses.

2. LITERATURE REVIEW

2.1 Irrigation System Of The Chola Empire

Reconstructing the original Chola irrigation networks with precision is inherently challenging due to the passage of time. As noted by Dr. V. Selvakumar, Head of the Department of Maritime History and Marine Archaeology at Tamil University, Thanjavur, many Chola-era canals and water bodies now lie 1–3 metres below ground level. Although the Cholas maintained detailed administrative records on palm leaves, copper plates, and stone inscriptions, translating these texts into a complete hydraulic network is practically feasible. Dr. M. Bhavani of the Department of Epigraphy and Archaeology, Tamil University, identifies key obstacles, including the vast volume of manuscripts, restricted access to archival materials, and significant changes in script, dialect, and terminology over nearly two millennia.

Consequently, this study relies primarily on modern irrigation system data documented in A Structural Study of Irrigation Structures in Thanjavur District by R. Malliga, recognising that unavoidable data gaps must be addressed through informed extrapolation. These gaps were cross validated using archaeological findings compiled by Dr. Mani Maran in “தமிழரின் நீர் மேலாண்மை”. Additional historical context was drawn from established works,

including *The Cholas* by K.A. Nilakanta Sastri, *Ancient Irrigation Technology: Sluice Technology in Tamil Nadu* by K. Rajan, and *Irrigation Systems of India* by K. Srinivasan.

2.1.1. Kaveri River

The Kaveri River (also spelled Cauvery) is one of the major rivers in South India, revered for its cultural, historical and economic significance. Originating from the Talakaveri in the Brahmagiri hills of the Western Ghats in Karnataka, the river flows through the states of Karnataka and Tamil Nadu before emptying into the Bay of Bengal. Stretching over ~800 km, it plays a vital role in supporting agriculture, drinking water supply and hydroelectric power generation. The river forms the fertile Cauvery Delta, often referred to as the “Rice Bowl of Tamil Nadu.” Several ancient and modern irrigation structures, such as the Kallanai (Grand Anicut) and Mettur Dam, have been built across the river, making it one of the most harnessed rivers in India for agricultural purposes since the Chola Period.

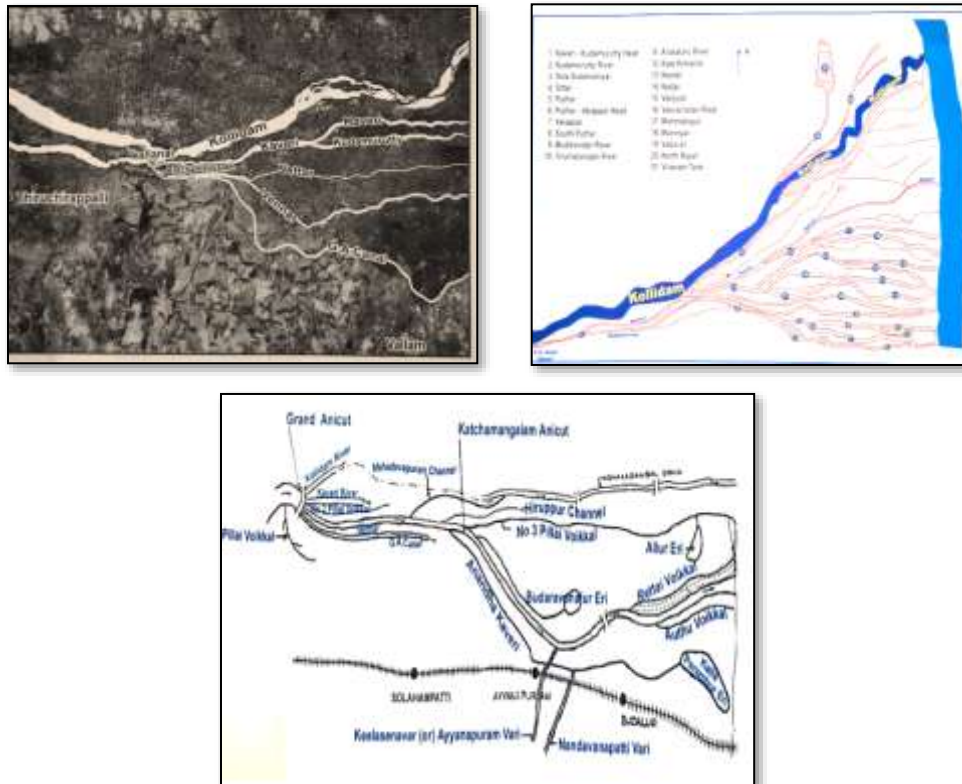


Figure 2: The Kaveri Delta

2.1.2. Kallanai Dam

Kallanai Dam (Figure 3), also known as the Grand Anicut, is one of the oldest irrigation dams in the world, constructed approximately 2,000 years ago. It is built across the Kaveri River in the Tiruchirappalli (Trichy) district of Tamil Nadu, South India. Kallanai is recognized as the fourth-oldest water-diversion structure in the world and the oldest in India that is still operational. The dam was originally constructed under the reign of King Karikalan of the Chola Dynasty around 150 AD. Its primary purpose was to divert the waters of the Kaveri River to the fertile delta region for irrigation through an intricate canal system. The dam divides the Kaveri River into four streams: Kollidam Aru, Kaveri, Vennaru and Puthu Aru. The Kallanai Dam was constructed with architectural precision, allowing clear visibility of the structure from multiple vantage points. The dam measures approximately 329 metres (1,079 ft) in length, 20 metres (66 ft) in width and 5.4 metres (18 ft) in height. Its unique construction involves embedding massive stones in the Cauvery River to divert water toward the fertile delta region. The primary function of the dam was to regulate the flow of the Cauvery, retaining sufficient water for irrigation while allowing excess water to be diverted into the Coleroon River through the Ullar River. During the 19th century, the dam underwent significant modifications under British administration. In 1804, Captain Caldwell, a military engineer, was assigned the task of improving irrigation in the delta region. After examining the structure, he discovered that most of the water was flowing into the

Kollidam branch, leaving only a limited supply for irrigation. To rectify this, Caldwell proposed raising the height of the dam. Consequently, additional stone layers were placed on the structure, increasing its capacity and enhancing water regulation effectiveness.



Figure 3: Kallanai Dam

2.1.3. High dynamic range map of Kumbakonam and Thiruvaiyaru taluk

The following maps (Figure 4) and Table 1 display the base layouts of various taluks in the Thanjavur district of Tamil Nadu, highlighting important geographic and hydrological features such as rivers, canals, tanks, villages, blocks and watershed polygons.

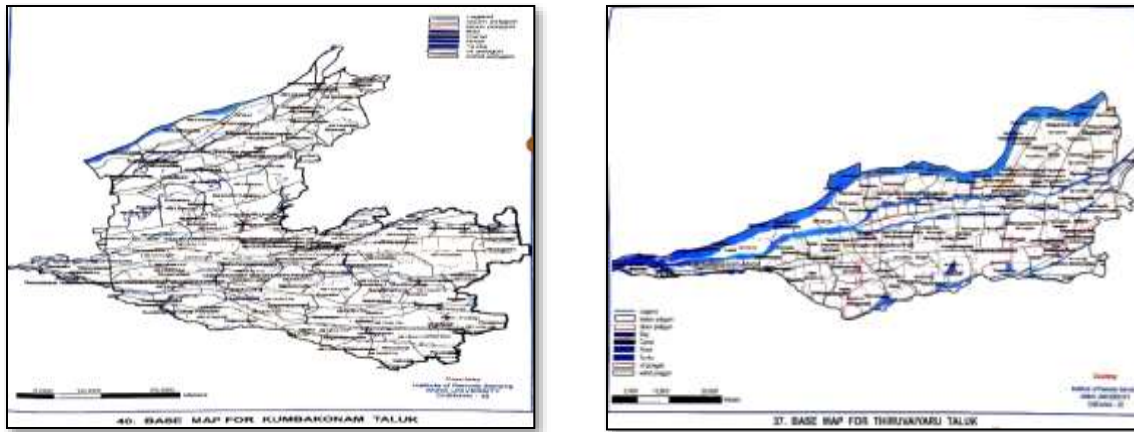


Figure 4: High Dynamic Range Map of Kumbakonam and Thiruvaiyaru Taluk (Source: Institute of Remote Sensing)

| Table 1. District Base Map Descriptions | |
|---|--|
| Taluks | Description |
| Kumbakonam Taluk | Kumbakonam features elongated village clusters following the region’s rivers and canal systems. Tanks and bays are distributed, predominantly along the north and east, providing reliable water sources for farming. The extensive canal grid underscores this taluk’s importance for both irrigation and transport, supporting traditional agrarian economies. |
| Thiruvaiyaru Taluk | The Thiruvaiyaru map is distinctive for its thin, elongated shape, oriented along the major Katchamangalam Anicut and adjacent rivers. Village clusters line the river and canal banks, benefiting from direct access to water. Several tanks are strategically positioned to maximize agricultural yield and watershed polygons support effective drainage and flood management strategies. |

3. MATERIAL AND METHODS

3.1 WDN And Graph Model

A Water Distribution Network (WDN) delivers water from sources such as reservoirs, tanks, or wells to domestic, industrial, and agricultural consumers and consists of nodes connected by pipes, canals, or channels. Such systems can be represented as graphs, where vertices correspond to junctions, reservoirs, or storage units and edges represent flow paths weighted by physical attributes like length, capacity, or hydraulic characteristics, enabling efficient analysis of flow behaviour, optimisation, and vulnerability. In this study, the distribution system is modelled as a simple undirected graph $G = (V, E)$ ⁷, with V denoting nodes and E denoting connections, and standard graph measures such as degree, connectivity, distance, and diameter used to characterise network structure. Building on the sensitivity-based graph-hydraulic framework proposed by Meriem Adraoui et al. for leak detection in closed-pipe systems, which combines weighted hydraulic parameters and clustering techniques to identify vulnerable zones, a similar methodology is applied here to Chola-era canal networks. Key adaptations are introduced to reflect the open-channel nature of canals, ensuring that the modified hydraulic parameters appropriately capture flow behaviour in historical irrigation systems.

3.2 CENTRALITY MEASURES IN GRAPHS

Centrality measures are quantitative indicators used to identify the most important or influential nodes in a network represented in Figure 5. They help assess the structural significance of nodes in terms of connectivity, control, or communication efficiency within a graph. Some important definitions for the concepts used throughout the paper are listed below:

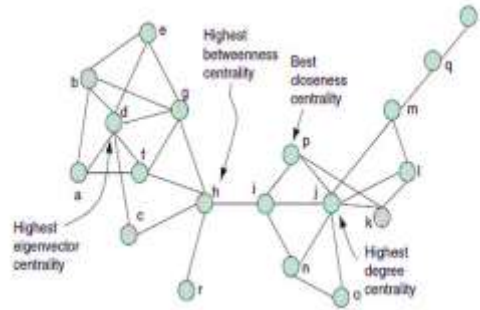


Figure 5: Centrality measures

3.2.1 Degree centrality (d_c): It measures the importance of a node based on the number of direct connections (edges) it has with other nodes. In a directed graph, it includes in-degree (incoming edges) and out-degree (outgoing edges). Higher degree indicates higher local influence. In other words, it is the number of canals diverging from a source. A high degree on centrality indicates that a node has a higher influence over the water irrigation system.

$$d_c(v) = \sum_{u \in V} p(u, v)$$

where $p(u, v)$ are the elements of the adjacency matrix, indicating a connection between nodes u and v .

3.2.2 Betweenness centrality (b_c): It quantifies how often a node lies on the shortest paths between pairs of other nodes. Nodes with high betweenness act as bridges or control points for flow within the network. It signifies the node's control over the irrigation system highlighting its criticality for the flow of water throughout the irrigation system.

$$b_c(v) = \sum_{s \neq v \neq t \in V} \frac{\sigma_{st}(v)}{\sigma_{st}}$$

where σ_{st} is the shortest path between s and t and $\sigma_{st}(v)$ is the number of times those path cross through node v .

3.2.3 Closeness centrality (c_c): It measures how close a node is to all other nodes in the network, calculated as the reciprocal of the total shortest path distance from that node to all others. If a node has relatively higher centrality than other nodes it means that this source of water can reach the end user quicker than the other sources of water. Higher closeness indicates faster access to information across the network.

$$c_c(v) = \frac{1}{\sum_{u \neq v} d(v, u)}$$

where $d(v, u)$ is the shortest path distance between nodes v and u .

3.2.4 Eigenvector centrality (e_c): It assigns importance to a node based not only on the number of connections it has, but also on the importance of the nodes to which it is connected. Nodes connected to other highly influential nodes receive higher centrality scores.

$$e_c(v) = \frac{1}{\lambda} \sum_u A_{vu} e_c(u)$$

where A_{vu} is the adjacency matrix element, λ is the largest eigenvalue of the adjacency matrix. These centrality measures are widely applied in network-based studies including water distribution systems to identify critical nodes, optimize flow, improve system resilience and support informed decision-making.

3.3 Kaveri Basin: Network Representation And Structural Properties

The Kaveri basin, despite its extensive reach and intricate branching, is structurally vulnerable to the loss of a small subset of nodes that form the backbone of canal distribution. This finding provides quantitative validation of long-standing historical observations that emphasize the centrality of major anicuts and regulators in the Chola irrigation system. The graphical analysis confirms that the hydraulic design prioritised efficient conveyance rather than redundancy and that systemwide stability depended heavily on maintaining the integrity of a few nodal points. These insights offer a critical foundation for understanding the functional logic of the network and form the basis for subsequent comparative evaluations with other basin systems.

4. RESULTS AND DISCUSSION

4.1 Heatmap Centrality Results of the Kumbakonam Canal Network

4.1.1 Network reconstruction and structural properties

The extracted Kumbakonam irrigation network is shown in Figure 6. In this representation, nodes correspond to individual canals, while edges represent the water-flow connections between canals. From the original image-based extraction, a total of 148 nodes and 137 edges were detected. After isolating the largest connected component to ensure structural consistency, the final network used for analysis consists of 117 canal nodes and 125 flow edges.

The network exhibits a core periphery structure, where a densely connected central region distributes water to multiple peripheral canal chains. Such a structure is hydraulically efficient but structurally vulnerable to failures occurring at the transition points between the core and peripheral sub-networks.



Figure 6: Extracted Kumbakonam canal network.

4.1.2 Degree Distribution and Network Heterogeneity

The degree distribution of the Kumbakonam network is presented in Figure 7 on a log–log scale. The distribution shows a right-skewed pattern in which most canal nodes possess low degree, while a small number of canals exhibit relatively higher degree.

This behaviour indicates a heterogeneous flow network, where most canals act as local distributors while a few canals function as major redistribution channels. Such heterogeneity is a key prerequisite for the emergence of super-spreader nodes, as identified by heatmap centrality.

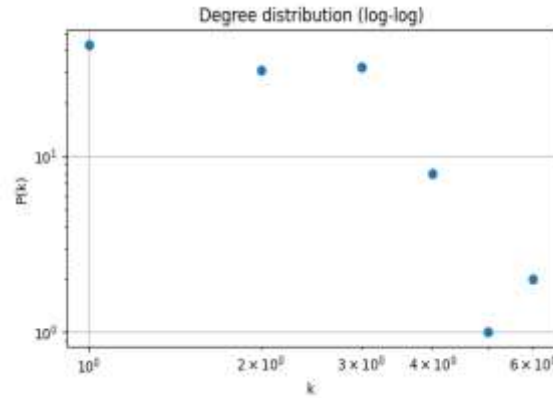


Figure 7: Degree distribution of the Kumbakonam canal network on log–log scale

4.1.3 Identification of Super-Spreader Canals Using Heatmap Centrality

Heatmap centrality was computed for all canal nodes using the difference between the farness of each node and the average farness of its neighbouring nodes. Nodes with high negative heatmap values were classified as structurally vulnerable or super-spreader canals, as they exert dominant control over shortest water-flow paths.

Table 2. Top 10 Structurally Vulnerable Canals in the Kumbakonam Network (Heatmap Ranking)

| Node | Heatmap |
|------|----------|
| 71 | -70.6 |
| 119 | -62.1667 |
| 4 | -59.6667 |
| 38 | -59 |
| 40 | -59 |
| 51 | -59 |
| 79 | -58 |
| 11 | -55 |
| 7 | -39.6667 |
| 49 | -39.6667 |

4.1.4 Interpretation of Heatmap and Classical Centrality Measures

The Top 10 canals listed in Table 2 exhibit the most extreme negative heatmap values in the entire Kumbakonam network, confirming that these canals function as super-spreaders of water flow and structural influence. These vulnerable canals are not necessarily those with the highest degree; instead, their dominance arises from their strategic placement along shortest transmission paths. A strong correspondence is observed between heatmap centrality and betweenness centrality, indicating that the vulnerable canals also serve as hydraulic bottlenecks through which a large fraction of water flow must pass. The eigenvector centrality values further confirm that these canals are embedded within the spectral core of the network and are connected to other influential canals. The weaker correlation between degree and heatmap confirms that vulnerability in the Kumbakonam network is governed more by flow positioning than by simple connectivity, highlighting the added value of heatmap centrality over classical metrics.

Table 3. Top 10 Structurally Vulnerable Canals in the Kumbakonam Network

| Node | Betweenness | Eigenvector | Degree | Closeness |
|------|-------------|-------------|--------|-----------|
| 71 | 0.570765 | 0.549655 | 6 | 0.115884 |
| 51 | 0.534633 | 0.440864 | 6 | 0.115538 |
| 84 | 0.521289 | 0.375394 | 5 | 0.115538 |

| | | | | |
|----|----------|----------|---|----------|
| 95 | 0.511994 | 0.246166 | 4 | 0.114738 |
| 89 | 0.508546 | 0.233188 | 4 | 0.113725 |
| 87 | 0.501949 | 0.203069 | 4 | 0.11295 |
| 80 | 0.496402 | 0.203069 | 4 | 0.111538 |
| 69 | 0.493703 | 0.182035 | 4 | 0.110266 |
| 59 | 0.482759 | 0.182035 | 4 | 0.109228 |
| 79 | 0.472264 | 0.172301 | 4 | 0.105551 |

4.1.5 SI Spreading Model Validation of Vulnerable Canals

To validate the spreading dominance of the heatmap-identified vulnerable canals, a Susceptible–Infected (SI) spreading model was simulated on the Kumbakonam network. In this model, the Top-10 canals identified by each centrality measure (degree, eigenvector, closeness, betweenness and heatmap) were used as initial infected seeds. Each simulation was repeated 100 times and the average cumulative infection function ($F(t)$) was computed. The resulting SI spreading dynamics are shown in Figure 8.

The results show that heatmap-based and betweenness-based seeding produce the fastest early-stage growth of ($F(t)$), confirming that vulnerable canals identified using heatmap centrality act as efficient propagation accelerators. Degree-based seeding also leads to rapid saturation, while eigenvector-based seeding shows comparatively slower early-stage diffusion. This validates that heatmap centrality is dynamically predictive, not merely a structural descriptor.

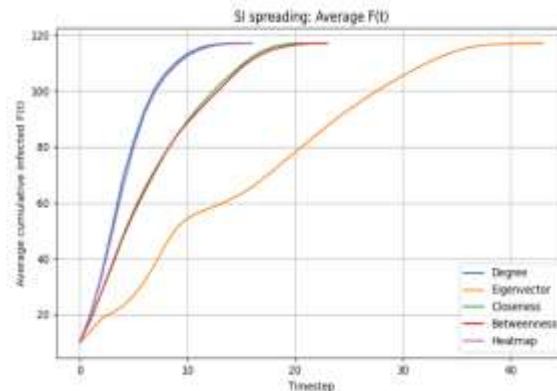


Figure 8: SI spreading dynamics for the Kumbakonam network

4.2 Heatmap Centrality Results Of The Thiruvaiyaru River–Canal Network

4.2.1 Network Reconstruction and Structural Properties

The extracted Thiruvaiyaru irrigation network is shown in Figure 9. In this representation, nodes correspond to river junctions, while edges represent the irrigation canals that distribute water from the river system. From the image-based extraction, a total of 95 nodes and 112 canal segments were initially detected. After filtering and isolating the largest connected component, the final network used for analysis consists of 88 river nodes and 109 canal edges.

The extracted network exhibits a predominantly elongated, river-aligned topology, where multiple lateral canals branch from the main river spine and reconnect through secondary distributaries. This configuration produces a strong longitudinal dependency, where downstream irrigation supply is highly sensitive to disruptions at upstream river junctions.

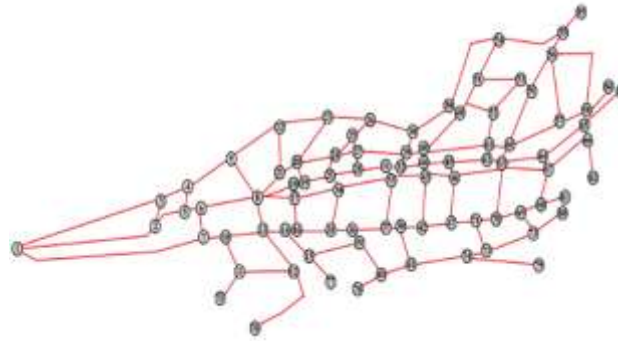


Figure 9: Extracted Thiruvaiyaru river–canal network

4.2.2 Degree Distribution and Network Heterogeneity

The degree distribution of the Thiruvaiyaru network, plotted on a log–log scale, is shown in Figure 10.

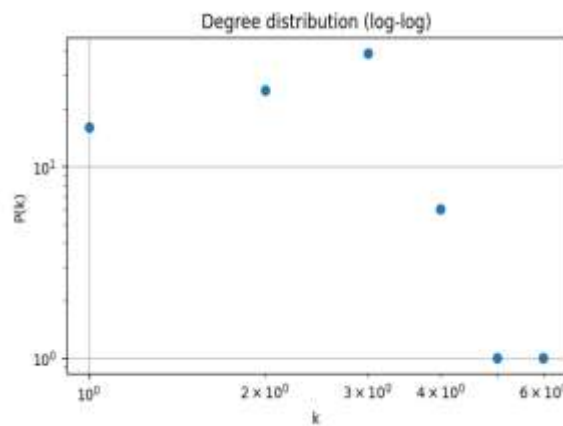


Figure 10. Degree distribution of the Thiruvaiyaru river–canal network

The distribution is right-skewed, with most river nodes having low degree (1–2), while only a small number of river junctions exhibit higher degree values (3–6). This confirms that the network is structurally heterogeneous, with a few river junctions functioning as major redistribution points. Such heterogeneity is a key prerequisite for the emergence of super-spreader nodes, as predicted by heatmap centrality theory.

4.2.3 Identification of Super-Spreader River Nodes Using Heatmap Centrality

Heatmap centrality was computed for all river nodes using the difference between the farness of each node and the average farness of its neighboring nodes. River nodes with high negative heatmap values were classified as structurally vulnerable or super-spreader nodes, as they exert dominant control over the shortest water-flow transmission paths. The Top-10 most vulnerable river nodes identified using heatmap ranking are listed in Table 4.

| Table 4. Top 10 most vulnerable river nodes | |
|--|----------------|
| Node | Heatmap |
| 71 | -55.8333 |
| 13 | -44.6 |
| 72 | -41 |
| 32 | -40.75 |
| 14 | -39.25 |
| 28 | -39 |
| 31 | -34.5 |
| 67 | -28.6667 |
| 83 | -28.3333 |

| | |
|----|-----|
| 85 | -28 |
|----|-----|

4.2.4 Interpretation of Heatmap and Classical Centrality Measures

The Top 10 river nodes listed in Table 5 exhibit the most extreme negative heatmap values in the entire Thiruvaiyaru network, confirming that these nodes function as super-spreaders of hydraulic influence. These river junctions are not necessarily those with the highest local connectivity; rather, their dominance arises from their strategic placement along the shortest canal transmission paths. A strong correspondence is observed between heatmap centrality and betweenness centrality, indicating that the vulnerable river nodes also act as hydraulic bottlenecks, through which a large fraction of irrigation flow must pass. The eigenvector centrality values further indicate that these nodes are embedded within the spectral core of the river–canal system, confirming their global structural importance. The weaker correspondence between degree and heatmap centrality confirms that vulnerability in the Thiruvaiyaru network is governed more by flow positioning than by mere connectivity, demonstrating the additional explanatory power of heatmap centrality beyond classical measures.

Table 5. Top 10 Structurally Vulnerable Canals in the Thiruvaiyaru Network

| Node | Degree | Eigenvector | Betweenness | Closeness |
|------|--------|-------------|-------------|-----------|
| 71 | 6 | 0.377244 | 0.510132 | 0.210145 |
| 13 | 5 | 0.255649 | 0.48278 | 0.209639 |
| 14 | 4 | 0.247695 | 0.442795 | 0.205674 |
| 28 | 4 | 0.246405 | 0.441703 | 0.202797 |
| 31 | 4 | 0.2168 | 0.436759 | 0.193333 |
| 32 | 4 | 0.212404 | 0.301902 | 0.1875 |
| 72 | 4 | 0.210338 | 0.29738 | 0.186695 |
| 82 | 4 | 0.201353 | 0.27095 | 0.184713 |
| 1 | 3 | 0.200676 | 0.234162 | 0.18125 |
| 2 | 3 | 0.191209 | 0.138042 | 0.18125 |

4.2.5 SI Spreading Model Validation of Vulnerable River Nodes

To validate the dynamic dominance of the heatmap-identified vulnerable river nodes, a Susceptible–Infected (SI) spreading model was simulated on the Thiruvaiyaru network. In this model, the Top 10 nodes identified by each centrality measure (degree, eigenvector, closeness, betweenness and heatmap) were used as the initial infected seeds. Each simulation was repeated 100 times and the mean cumulative infection function (F(t)) was computed.

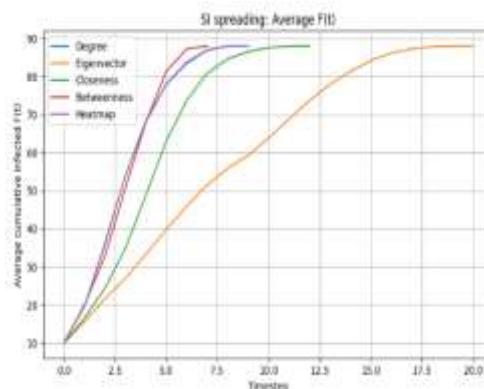


Figure 11. SI spreading dynamics for the Thiruvaiyaru network

The results show that heatmap-based and betweenness-based seeding led to the fastest early-stage growth of (F(t)), confirming that the river junctions identified as vulnerable also act as the most efficient transmission accelerators. Degree-based seeding also results in rapid saturation, while eigenvector-based seeding exhibits comparatively slower early-stage diffusion. This confirms that heatmap centrality is dynamically predictive, not merely a static structural descriptor.

5. CONCLUSION

The study demonstrates that Chola-era irrigation networks can be effectively analysed using modern graph-theoretic measures of centrality and vulnerability. Analysis of reconstructed networks from the Kumbakonam and Thiruvaiyaru taluks reveals a system designed for efficient and adaptable water flow, with hierarchical canal structures and influential nodes playing key roles in distribution, particularly in Kumbakonam. The application of the SI spreading model confirms the effectiveness of centrality-based heatmaps in identifying flow-accelerating components. These results highlight the advanced engineering principles underlying Chola irrigation systems and show that their structural behaviour aligns closely with that of contemporary water distribution networks, offering a quantitative framework for studying heritage water infrastructure.

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