Designing Collective Action in Decentralized Wastewater Infrastructure: A Behavioral Cooperative Game-Theoretic Analysis from Rural Alabama's Black Belt

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ABSTRACT

Decentralized wastewater systems are increasingly promoted as viable alternatives to centralized infrastructure in limited-resource rural regions. However, forming stable clustered systems remains challenging due to spatial fragmentation, high infrastructure costs, and misalignment between individual household incentives and collective outcomes. Existing clustering approaches rely largely on aggregate cost assumptions and fixed-size configurations, with limited attention to household-level cost distribution and participation dynamics. This study develops a socio-technical framework integrating multi-scale Density-Based Spatial Clustering of Applications with Noise (DBSCAN) and Minimum Spanning Tree (MST) optimization to identify the most cost-effective and stable wastewater coalitions. The framework quantifies the stability gap—the difference between assigned household costs and the onsite wastewater treatment system-based defection threshold—to assess coalition viability and the need for targeted intervention. Application to rural Alabama's Black Belt shows that aggregate cost metrics often mask internal instability. Coalition viability is driven by spatial configuration and household-level cost distribution, with peripheral connections frequently exceeding the defection threshold and triggering cascading instability in the cluster. Results further demonstrate that cluster size alone does not determine economic performance; network geometry plays a dominant role in shaping both cost efficiency and stability. These findings position coalition stability as a central criterion for decentralized wastewater planning and provide responsible management entities with a decision-support framework to identify unstable participants, estimate targeted subsidies, and design adaptive clustering strategies. The proposed framework advances both theory and practice by integrating spatial analysis, engineering design, and cooperative game-theoretic principles to support sustainable and affordable infrastructure provision in limited-resource rural contexts.

INTRODUCTION

Decentralized wastewater infrastructure has emerged as a technically promising alternative to traditional centralized sewer systems, especially in limited-resource rural communities where centralized approaches are economically or technically infeasible. In rural Alabama's Black Belt, this alternative has shifted from a contextual option to an urgent necessity. The region is characterized by scattered rural settlements, persistently low household incomes, and high poverty rates—reaching up to 40% of residents below the federal poverty line in some counties—alongside limited access to municipal services (Maxcy-Brown, 2023). Challenging geological conditions compound these socioeconomic constraints: the region's dense, clay-rich soils severely restrict water percolation and render conventional septic systems technically ineffective. As a result, many households rely on failing septic systems or resort to hazardous straight piping—defined as the direct discharge of untreated wastewater directly into the environment—because advanced onsite wastewater treatment systems (OWTS) remain unaffordable for many residents (Maxcy-Brown et al., 2021). These conditions create acute public health risks, contribute to environmental degradation, and represent a long-standing infrastructural gap that has persisted in the region for decades (Bakchan et al., 2023; Maxcy-Brown et al., 2021).

Cluster-based decentralized wastewater systems have been proposed as a practical response to the technical limitations of individual OWTS and the affordability constraints faced by limited-resource rural communities (Li et al., 2024; Parkinson & Tayler, 2003; Bakchan et al., 2023). In a clustered configuration, a small group of geographically proximate households connects to a shared treatment unit, reducing overall system capital expenditures by limiting wastewater conveyance infrastructure and distributing initial capital investment expenses across multiple users (Thomas et al., 2024; Maurer et al., 2005). Contemporary modeling has significantly improved the technical cost-efficiency of these clusters (e.g., De Santi et al., 2025; Schwetschenau et al., 2023). However, a critical gap remains in understanding their socio-economic durability. In principle, this typological configuration improves economic feasibility by lowering per-household costs as participation increases. In practice, however, the transition from individual OWTS to clustered systems is not solely a technical or financial decision; it is a collective action problem (Taylor, 1987). The behavioral framing utilized here focuses on revealed economic behavior instead of stated preferences, quantifying the strategic choice to remain in or defect from a coalition based on objective financial thresholds.

Although a clustered system delivers benefits to the community as a whole, participation requires individual households to commit to upfront investments under uncertainty. Each household must decide whether to contribute without assurance that sufficient number of neighbors will also participate to keep costs affordable and the system financially viable. This uncertainty creates a strategic tension between individual incentives and collective benefits, giving rise to a *behavioral and economic (B&E) deadlock*—that is, a systemic failure in which individually rational choices prevent a collective, lower-cost solution (see Table 1). This deadlock is rooted in the strategic interactions among players seeking to maximize individual utility under uncertainty—a concept pioneered by Von Neumann and Morgenstern (1944). In the absence of a stabilizing authority, households may hesitate to commit to a cluster if they perceive a risk that others' withdrawal will leave them with a disproportionate share of the fixed costs. Under regulatory requirements, a responsible management entity (RME) serves as the mandated legal authority for decentralized wastewater systems. As identified by Bakchan & White (2024), RMEs in limited-resource rural communities, such as the Black Belt, often face significant socio-technical barriers. Within this context, the present study positions the RME as a strategic fiscal stabilizer—an entity capable of identifying and bridging financial gaps to sustain collective participation and prevent coalition collapse. This stabilizing role enables the RME to address the B&E deadlock directly through enforceable participation structures and financial risk management. Without such institutional support, households default to individual solutions, even when clustered systems would yield lower costs and improved outcomes. The community thus becomes trapped in a collectively worse outcome, often termed a Pareto-inferior result, where individually rational decisions lead to persistent environmental and public health risks (Taylor, 1987; Olson, 1965).

Table 1. Key Theoretical and Methodological Concepts for Coalition Stability in System Clustering

Construct	Definition	Application for RME Clustering Decisions
Behavioral & Economic (B&E) Deadlock	A systemic failure in which individually rational choices prevent the adoption of a collectively lower-cost solution (Barrett & Swallow, 2006; Ostrom, 1990).	Identify the behavioral and financial breaking points that prevent households from joining the cluster (i.e., signaling risk of coalition collapse).
Bird's Rule	A mathematical method (Bird, 1976) that assigns infrastructure costs based on a household's actual physical footprint (e.g., pipe length, pumping requirements).	Allocate the shared infrastructure costs fairly, ensuring no household pays for more "pipe" than they actually use, thereby reducing perceived cross-subsidization and improving participation stability.
Defection Threshold (T_i)	The maximum cost shares a participant accepts before it becomes economically rational to pursue an autonomous alternative, representing the individual rationality constraint in cost allocation games (Tijs & Driessen, 1986); here defined as the cost of installing an individual advanced OWTS.	Benchmark the cluster's cost-competitiveness; values exceeding T_i indicate high likelihood of defection, signaling a need for intervention.
Stability Gap (G_{total})	The sum of financial differences where individual fair costs exceed the defection threshold.	Quantify the exact external subsidy required to prevent coalition collapse and maintain stability.
Optimal Coalition Zone	A geospatial grouping of households in which clustered system costs remain below the OWTS benchmark and coalition stability is maintained.	Provide a data-driven map identifying where clusters are most likely to remain cost-competitive and stable.

Research Problem. The primary challenge in implementing clustered (i.e., shared) systems is the gap between individual and collective viability. This challenge is amplified by the absence of a structured framework that identifies how an RME can effectively stabilize such coalitions. In this study, the defection incentive is characterized as the strategic choice between two formal typological pathways: participation in a shared clustered system or the adoption of an individual OWTS. While straight piping persists a zero-cost default, it does not constitute a viable long-term regulatory alternative. In contexts of extreme poverty, such as the Black Belt, this decision reflects financial necessity rather than indifference to environmental or public health consequences. Policy responses have historically relied on standardized enforcement mechanisms, including fines and legal penalties. However, prior work shows that such punitive measures fail to induce participation under these conditions and may further entrench noncompliance (Kordahi & Bakchan, 2025). Environmental compliance in these settings therefore remains difficult without complementary forms of support, including capital assistance, regulatory flexibility, and institutional coordination (Kordahi & Bakchan, 2025). In the absence of such support, when the per-household cost of a clustered system exceeds the cost of installing an individual OWTS, households are more likely to defect to maintain short-term financial survival. The OWTS installation cost thus serves as the defection threshold, defining the upper bound for cluster participation and governing coalition stability (see Table 1).

A critical limitation of the still sparse literature on decentralized wastewater system clustering is the widespread reliance on an implicit assumption of constant cluster sizes, often paired with the premise that the per-household cost of joining a clustered system remains less than or equal to the cost of installing an individual OWTS (Burt et al., 2019). The literature also lacks conceptual clarity on how an RME can operationalize fair cost allocation to sustain participation. In rural landscapes with uneven housing density, constant-size assumptions exclude groups of households that fall marginally below standard clustering size thresholds, even when they are geographically proximate and technically suitable for clustered systems. Under equal cost-sharing arrangements, per-household costs in these near-threshold clusters often exceed the OWTS benchmark, rendering clustered participation noncompetitive and leading to coalition collapse before implementation. These outcomes reinforce the B&E deadlock situation, where individually rational decisions prevent collective investment even when clustered systems would yield superior outcomes.

These dynamics indicate that coalition stability must be characterized by perceived fairness in cost allocation (Eggimann et al., 2016), defined here as the alignment between a household's assigned cost and the infrastructure and connection requirements associated with its inclusion in a clustered system. This condition is difficult to satisfy in spatially heterogeneous clusters, where households differ in connection distance, terrain, or network complexity. The RME plays a vital role here as the entity responsible for managing these complex financial dynamics. Critically, the RME's role depends on its function as a systemic control mechanism. More specifically, this framework positions the RME as a technical intermediary that uses data-driven evidence to bridge the gap between external funding and local needs. By providing a transparent roadmap for subsidies, the model grants the RME the technical legitimacy needed to coordinate and sustain coalitions where formal authority is otherwise limited. When cost allocations are perceived as unfair—often due to perceived cross-subsidization within clusters—withdrawals occur, fixed costs are redistributed among fewer participants, and additional households are pushed beyond the OWTS-based defection threshold. This chain reaction initiates a cascading failure (or domino effect), further destabilizing the coalition and potentially leading to its complete dissolution. From a planning perspective, the core challenge thus shifts from whether clustering is feasible to which coalition structures are viable and how an RME can sustain them. This shift reveals a *stability gap*, defined as the difference between per-household costs implied by a given coalition structure and the OWTS cost benchmark governing defection (see Table1). Identifying optimal coalition zones, therefore, requires evaluating how alternative spatial groupings affect per-household costs, perceived fairness, and coalition stability across varying cluster sizes.

Research Question and Objectives. This study seeks to develop a heuristic-based optimization framework that identifies optimal coalition zones for decentralized wastewater infrastructure systems. The framework integrates multi-scale spatial clustering and tree-based cost allocation to quantify the stability gap and the potential impact of RME intervention. To do so, it specifically (1) evaluates all potential clustering configurations across multiple spatial density scales (varying Epsilon values) to identify feasible clusters where the average per-household cost falls below the individual OWTS benchmark, and to determine the minimum cluster size required for initial economic viability; (2) models fair cost allocation for each identified cluster using a hierarchical Minimum Spanning Tree (MST) approach to determine individual cost allocation based on actual infrastructure usage, thereby reducing perceived cross-subsidization and enhancing internal coalition stability; and (3) quantifies the stability gap for the target cluster—defined as the variance between individual fair costs and the defection benchmark—to identify unstable participants and estimate the minimum subsidy required for RME intervention to sustain participation. The proposed framework is demonstrated in rural Alabama's Black Belt, specifically Wilcox and Lowndes counties.

METHODS and DATA

Socio-Technical Optimization Framework. This study employs a socio-technical optimization framework that integrates automated geospatial data extraction, engineering cost functions, and cooperative game theory principles to evaluate the economic viability and stability of decentralized wastewater clusters.

Multi-Scale Geospatial Clustering Approach. We define the technical boundaries of potential infrastructure projects using a multi-scale heuristic approach based on housing density, which we operationalize as the spatial proximity between residential structures. The model groups processed household coordinates into potential clusters using the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm. To capture all possible cooperative groupings, we initialize the algorithm with a minimum cluster size of 2 households (min_samples = 2). The physical and economic limits of decentralized engineering dictate the spatial tolerance (ε), which ranges from 0.0005 to 0.020 decimal degrees. Our empirical tests define that the boundaries of spatial tolerance (ε) values below 0.0005 (≈182 feet) fail to capture sufficient density for collaborative grouping, while values above 0.020 (≈1.38 miles) yield clusters that exceed the economic feasibility threshold (i.e., OWTS installation cost) due to prohibitive piping costs. For each candidate cluster identified by DBSCAN, the optimal site for the shared treatment unit is determined by calculating the weighted centroid based on the spatial distribution of participating households. Once the treatment site is established, the model constructs an MST to determine the most efficient physical network connecting every household to this central source. To ensure baseline viability, a dual-stage filtering mechanism is applied: first, an economic feasibility filter retains only clusters where the average MST-derived piping costs plus fixed expenses remain below the defection threshold. Second, a hydraulic operational constraint limits the maximum cluster diameter based on system-level constraints, including pumping capacity, total dynamic head, and minimum flow requirements. For the case of the Black Belt, the Septic Tank Effluent Pump (STEP) technology is used; under these conditions, a maximum radius of 5 miles allows standard residential pumps to overcome friction losses in the force mains without requiring expensive intermediate lift stations.

Engineering Cost Function ($v(S)$). The engineering cost function is calibrated using empirical unit costs derived from recent infrastructure bids and engineering estimates from the Alabama Department of Environmental Management (ADEM), accurately reflecting the real-world financial burdens in the targeted counties. The model specifically focuses on initial capital thresholds, which represent the primary financial barrier to B&E deadlocks in limited-resource rural communities; detailed cost components are provided in the Data Collection section. Although long-term Operation and Maintenance (O&M) costs—such as electricity for STEP units and RME fees—are crucial for lifecycle sustainability, we exclude them from this game-theoretic analysis. This strategic focus targets the primary behavioral deadlock: the massive upfront investment required to transition from informal straight piping to formal infrastructure.

Network Optimization via Minimum Spanning Tree (MST). The framework defines the physical network of each cluster by constructing an MST. Using the spatial coordinates of households and the central treatment unit, the model identifies the shortest possible total network length that connects every participant without redundancy. Mathematically, the MST aims to find a subset of edges $E' \subseteq E$ that connects all vertices V while minimizing the total weight:

$$\min \sum_{(u,v)\in E'} w(u,v)$$

where $w(u,v)$ represents the Euclidean distance (and thus the associated piping cost) between nodes.

Fair Cost Allocation: From Shapley Value to Hierarchical MST. To ensure the economic stability of the coalition, this study moves beyond simple average cost-sharing by using a hierarchical cost-sharing rule based on an MST. While traditional cooperative game theory often suggests the Shapley Value to determine fair shares based on marginal contributions, its computational complexity—which grows exponentially with the number of connections (2^n)—renders it impractical for large-scale clusters (Qin et al., 2025). Instead, our model uses a graph-theoretic MST approach, serving as a computationally efficient proxy for the Shapley Value in networked infrastructure. This method, established as Bird's Rule (Bird, 1976), shows that every game generated by a minimum-cost spanning tree with an immovable source has a core—a set of stable allocations in which no group of users has an incentive to withdraw. The cost burden ϕ_i for each connection is calculated by identifying the shortest physical network required to connect all members to the shared treatment unit. This tree-based allocation distributes the capital cost C_e of each shared pipe segment e among the set of downstream beneficiaries n_e (the total number of households located further along the line that rely on that segment to reach the treatment unit). The total cost burden ϕ_i for an individual connection i is calculated by summing their shared portion of every pipe segment along their unique connection path (P_i):

$$\phi_i = \sum_{e\in P_i} \frac{C_e}{n_e}$$

This direct linkage between individual payments and the actual segments of the infrastructure a household utilizes effectively minimizes perceived cross-subsidization and strengthens internal coalition stability.

Stability Gap and Subsidy Analysis. The final step evaluates the individual participation constraint by comparing the allocated cost (ϕ_i) against the household's defection threshold (T_i) (see Table 1). Suppose $\phi_i > T_i$, then the household is incentivized to defect. Crucially, such defections are not isolated; they trigger a recursive cost redistribution (domino effect). As one household leaves, the shared infrastructure costs (C_e/n_e) are redistributed among fewer participants, potentially pushing previously stable neighbors above their own defection thresholds. To quantify the aggregate financial intervention required to stop this chain reaction, we calculate the total stability gap (G_{total}) for each cluster (S) as the sum of individual gaps for every participating connection (i):

$$G_{total} = \sum_{i\in S} \max(0, \phi_i - T_i)$$

We calculate the minimum strategic subsidy that the RME must administer. By neutralizing the defection incentive for red node households (those with $\phi_i > T_i$), the RME ensures the coalition remains in the core of the cooperative game, making the shared system the most rational choice for every participant from the outset.

Data Collection and Empirical Parameters. The data used in this study includes residential coordinates and engineering cost estimates that are processed through the socio-technical framework.

Geospatial Data Processing. The research utilizes a high-precision geospatial pipeline to identify residential locations within Wilcox and Lowndes counties, Alabama. To ensure a comprehensive inventory of all buildings, particularly in these low-density rural landscapes, the study employs the Microsoft U.S. Building Footprints dataset (Microsoft, 2023). This dataset provides a robust, high-resolution representation of residential structures, including scattered rural residences and isolated buildings, which are essential for accurate infrastructure modeling. To isolate the target population, structures within municipal boundaries—defined by the 2025 U.S. Census TIGER/Line Shapefiles (U.S. Census Bureau, 2025)—were removed. This exclusion is based on the fact that existing centralized sewer systems serve municipal buildings. The final dataset consists of precise coordinates for 11,465 decentralized rural households (5,470 in Wilcox County and 5,995 in Lowndes County) lacking access to municipal wastewater infrastructure.

Empirical Unit Costs and Parameter Values. Model parameters are specified using engineering cost estimates from ADEM. The Defection Threshold (T_i) is set at $25,000, representing the capital cost of a private advanced OWTS. While straight piping (direct discharge) remains a prevalent informal practice in the region due to extreme poverty, it represents a regulatory violation rather than a viable infrastructure alternative. Therefore T_i is defined as the cost of the minimum legal alternative for compliance. Fixed construction expenses include mobilization ($150,000), clearing and grubbing ($25,000), seeding and mulching ($35,000), and erosion control ($20,000). Variable infrastructure costs are dynamically calculated according to the coalition size (n) and network geometry, incorporating 2" Class 200 PVC force mains (9/LF) as determined by the MST algorithm, individual STEP assembly units ($9,500/unit), and septic tank abandonment ($800/unit).

Furthermore, capacity-based treatment costs are scaled by household demand, assuming an average of 2.75 persons per connection and a hydraulic loading of 100 GPCD, with a treatment capacity cost of $15 per gallon. To reflect the complex fiscal environment of infrastructure projects, a linear additive soft cost multiplier of 19.8% is applied to the construction subtotal, comprising 5% for construction contingency, 6.8% for engineering design, and 8% for construction engineering and inspection (CEI). Independent of this multiplier, fixed project overheads for equipment ($225,000), boundary and topographic surveying ($20,000), and stormwater permitting - monitoring and permit modification ($30,000) are integrated to capture the high upfront capital requirements that often characterize rural infrastructure projects.

Computational Implementation. We implemented the proposed optimization framework in Python 3.13.2 using the PyCharm Integrated Development Environment (IDE). Our workflow uses *pandas* and *NumPy* (Harris et al., 2020) for data manipulation, and *pyproj* for geospatial coordinate transformations. We implemented the multi-scale clustering approach using the DBSCAN algorithm from the scikit-learn library (Pedregosa et al., 2011). This density-based approach allows us to identify clusters of varying spatial tolerances without predefining the number of groups. To optimize the physical network and implement hierarchical cost routing, we used the sparse graph routines in SciPy (Virtanen et al., 2020) and the *NetworkX* package (Hagberg et al., 2008). We produced interactive geospatial maps using the *folium* Python library to validate and visualize the clustering results across diverse spatial topographies. These interactive layers allowed us to manually verify the spatial integrity of each coalition and the exact positioning of high-cost leaf nodes. Finally, we analyzed all statistical distributions and subsidy requirements using the *seaborn* and *matplotlib* libraries (Hunter, 2007) to ensure the mathematical and spatial coherence of the Optimal Coalition Zone.

RESULTS AND DISCUSSION

Optimal Coalition Identification. Multi-scale geospatial clustering analysis reveals how heterogeneous settlement patterns in Wilcox and Lowndes counties directly impact coalition formation. Fluctuations in cluster size relative to spatial tolerance (ε) demonstrate that housing density dictates initial economic viability; as shown in Table 2, tighter spatial clusters consistently yield lower per-household burdens. Within these defined stability parameters, the analysis identifies 11 distinct stable clusters in Wilcox County and 10 in Lowndes County.

The settlement morphology of each county dictates the specific conditions under which these stable groups emerge. In Wilcox County, high housing density enables immediate economic viability even under restrictive spatial constraints, forming a stable cluster of 93 households at a tight tolerance of $\varepsilon = 0.001$. In contrast, Lowndes County exhibits a more fragmented landscape where stable clusters fail to form at the same level. The model must expand the proximity threshold to $\varepsilon = 0.002$ to bridge the spatial gaps between isolated households and reach the critical mass (144 households) required to anchor the coalition. While our dual-stage filter ensures all clusters meet the 5-mile diameter and $25,000 threshold, the margin of stability differs significantly between the two regions. The geographic dispersion in Lowndes County increases piping overhead and creates a conditionally stable system that operates much closer to the breaking point. This fragmentation makes the coalition highly sensitive to individual defections, as the withdrawal of even a small number of households can destabilize the coalition. These dynamics highlight the need to move beyond aggregate averages and examine the distribution of infrastructure costs at the individual household level.

Table 2. Multi-Scale Clustering Results and Economic Feasibility

Cluster ID	County	Epsilon (ϵ)	Cluster Size (n)	Avg. Cost per Household ($)
W-001-93	Wilcox	0.001	93	24,862
W-001-218	Wilcox	0.001	218	20,424
W-002-108	Wilcox	0.002	108	24,246
W-002-136	Wilcox	0.002	136	23,549
W-002-329	Wilcox	0.002	329	20,269
W-005-129	Wilcox	0.005	129	24,825
W-005-194	Wilcox	0.005	194	23,430
W-005-243	Wilcox	0.005	243	22,934

W-005-368	Wilcox	0.005	368	20,214
W-010-146	Wilcox	0.010	146	23,987
W-010-169	Wilcox	0.010	169	24,163
L-002-144	Lowndes	0.002	144	23,412
L-002-145	Lowndes	0.002	145	23,690
L-005-121	Lowndes	0.005	121	24,273
L-005-122	Lowndes	0.005	122	24,087
L-005-177	Lowndes	0.005	177	23,623
L-005-274	Lowndes	0.005	274	22,010
L-010-121	Lowndes	0.010	121	24,273
L-010-150	Lowndes	0.010	150	24,426
L-010-213	Lowndes	0.010	213	24,181
L-015-131	Lowndes	0.015	131	24,914

Fair Cost Distribution Analysis. The cost-allocation results reveal substantial variation in individual financial burdens within clusters that is not captured under equal cost-sharing. Hierarchical allocation exposes uneven cost distributions that directly shape coalition stability. Our analysis of the Wilcox County cluster (n=93 households) reveals a 60.22% stability rate: while 56 households remain below the \$25,000 threshold, 37 households exceed it. As illustrated in Figure 1, the MST network visually distinguishes these groups, with green nodes representing stable connections and red nodes identifying non-stable households. Although red nodes are concentrated at the network periphery as terminal connections, stable green nodes occasionally appear between them. Strategic spatial positioning explains this disparity; households along the main pipeline route share the capital costs of shared segments with all downstream neighbors, significantly reducing their individual burden. In contrast, end-of-line connections lack additional participants to share infrastructure expenses, forcing those households to internalize the full marginal cost. Table 3 details the specific stability percentages across all remaining clusters in the study area. These results provide a direct basis for RME intervention. Targeted financial support to the 37 unstable households can bridge their stability gaps and prevent coalition collapse. Stabilizing these peripheral members limits cascading defections and preserves the viability of the entire cluster.

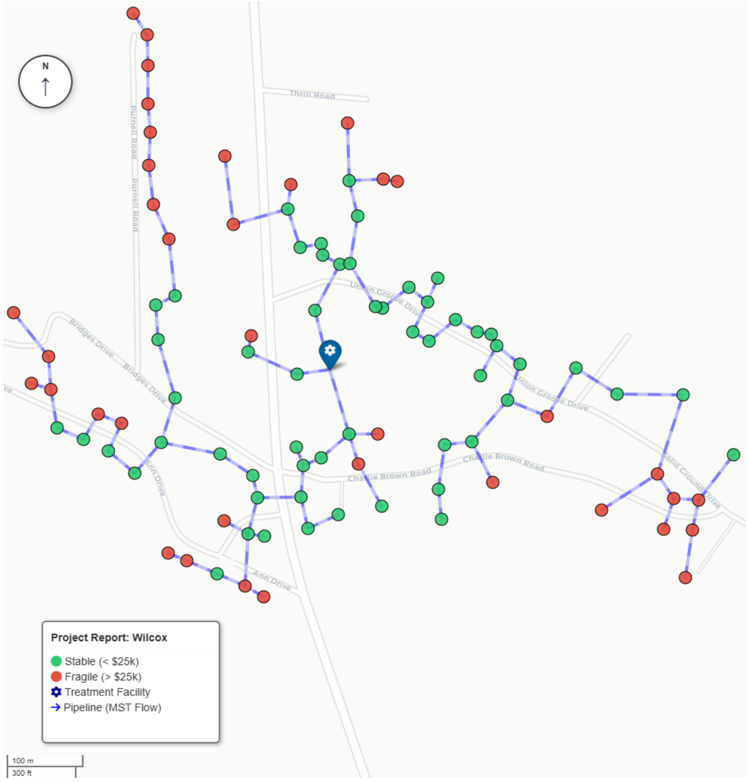

Figure 1. Fair Cost Allocation and MST Network for a Selected Cluster (n=93) in Wilcox County: Green nodes indicate stable connections, while red nodes signify participants requiring subsidies to prevent coalition defection.

Stability Gap and Subsidy. The results reveal substantial variation in the stability gap (G_{total}) across clusters, highlighting differences in coalition vulnerability that are not captured under equal cost-sharing. Clusters that appear viable on average often contain internal cost imbalances driven by network geometry, masking underlying cross-subsidization and creating localized instability. Household-level cost allocation identifies the specific participants whose costs exceed the OWTS threshold and therefore require external support to remain in the coalition. Our results in Table 3 reveal a fundamental principle: infrastructure efficiency is driven by network geometry, not just population size alone. For example, the Wilcox cluster (n=281) is well-coordinated that it requires only minimal state support ($897.12). In contrast, the smaller Wilcox cluster (n=169) requires $170,532.28—a massive escalation in cost despite having fewer participants. Physical layout—not just the number of users—determines whether a cluster functions as a high-performing asset or a significant financial burden. Consequently, larger clusters do not automatically guarantee superior economic outcomes; instead, the spatial alignment of households determines the final fiscal requirement.

A critical implication is that reliance on average costs introduces hidden feasibility risks. A cluster might appear economically viable under aggregate metrics, like Lowndes (n=213), but actually require over $281,000 in subsidies to prevent the coalition from collapsing. Without targeted intervention, such clusters remain vulnerable to household withdrawals. The RME could address this risk by acting as a fiscal stabilizer, leveraging these findings to direct financial support precisely where they are needed (the identified red nodes), stopping a domino effect of withdrawals before it begins. Ultimately, these findings demonstrate that a one-size-fits-all approach to cluster size is ineffective for decentralized wastewater planning. Spatial heterogeneity across counties requires an adaptive clustering approach. Instead of mandating fixed cluster sizes, the RME should identify optimal coalition zones—the specific sweet spots where minimal public investment creates the most stable, permanent, and manageable infrastructure solution.

Table 3. Economic Requirements for Coalition Preservation and Stability

Cluster ID	Avg. cost (equal allocation)	Total subsidy Gap G_{total}	Stable Connections (%)
W-001-93	\$24,862.37	\$45,155.48	60.22
W-001-218	\$20,424.49	\$897.12	99.64
W-002-108	\$24,246.94	\$45,559.20	75.93
W-002-136	\$23,549.13	\$57,681.67	81.62
W-002-329	\$20,269.06	\$10,112.44	98.48
W-005-129	\$24,825.96	\$149,554.78	81.44
W-005-194	\$23,430.61	\$148,861.32	83.13
W-005-243	\$22,934.95	\$22,421.64	97.83
W-005-368	\$20,214.20	\$134,278.18	67.44
W-010-146	\$23,987.11	\$78,984.72	74.66
W-010-169	\$24,163.54	\$170,532.28	75.15
L-002-144	\$23,690.58	\$73,400.46	77.24
L-002-145	\$23,412.40	\$46,964.15	79.17
L-005-121	\$24,273.42	\$175,611.16	78.53
L-005-122	\$24,087.39	\$67,430.50	78.69
L-005-177	\$23,623.58	\$64,080.22	90.15
L-005-274	\$22,010.83	\$76,169.76	73.55
L-010-121	\$24,273.42	\$215,547.49	77.33
L-010-150	\$24,426.19	\$76,169.76	73.55
L-010-213	\$24,181.97	\$281,482.37	70.89
L-015-131	\$24,914.17	\$201,061.72	75.57

Bridging the Stability-Affordability Gap. While the estimated subsidies close the stability gap by neutralizing defection incentives, the region's socioeconomic profile introduces a secondary, more profound affordability gap. The \$25,000 threshold serves as a strategic benchmark to prevent households from opting for individual OWTS; however, this figure remains high relative to local economic capacity. In Wilcox and Lowndes counties, where poverty rates reach 40%, even technically stable cost allocations—where no household has an incentive to defect to an individual OWTS—remains financially inaccessible for the majority of residents. The RME functions as the strategic administrator that bridges these two distinct financial realities. While the subsidies in Table 3 represent the theoretical equilibrium needed to maintain the structural integrity of the cluster, the RME's operational role is to channel additional capital assistance to close the affordability gap. By precisely targeting these funds, the RME ensures that the infrastructure is not only technically stable (preventing defection) but also socially inclusive (enabling participation). Without this targeted distribution of external funds, households face a forced regression into the hazardous status quo of straight piping. This outcome is driven not by choice but by a system that remains financially unattainable. Consequently, findings of this study provide the RME with a definitive operational guideline to establish the minimum financial support needed to sustain long-term, managed, and affordable wastewater solutions in the Black Belt.

STUDY CONTRIBUTIONS

This study contributes to the limited literature on decentralized wastewater system clustering by introducing a novel coalition-based perspective on feasibility. We extend existing typological and cost-focused work by formalizing coalition stability through the stability gap, which links engineering cost structures to behavioral feasibility via the OWTS-based defection threshold. The study further conceptualizes the RME as a strategic coordinating agent and demonstrates how institutional leadership utilizes fair-cost allocation to manage the strategic tensions inherent in rural infrastructure provision. Our integration of perceived fairness and cooperative game-theoretic cost allocation expands the understanding of how socio-technical dynamics shape the viability of clustered systems, thereby addressing a key gap in both theory and implementation.

For practice, this study provides a robust decision-support framework for decentralized wastewater planning in limited-resource rural contexts, such as Alabama's Black Belt. Our proposed framework empowers RMEs and policy-makers with a structured, data-driven approach to identify optimal coalition zones, while simultaneously enabling them to distinguish between coalition instability and engineering constraints, as well as to estimate the precise external subsidy required to sustain participation. More broadly, this work demonstrates the practical value of integrating spatial, engineering, and cooperative game-theoretic insights to support collective infrastructure provision under extreme operating conditions, including entrenched poverty, challenging geology, and institutional constraints.

CONCLUSION

Establishing stable decentralized wastewater clusters in limited-resource rural regions remains a complex challenge due to spatial fragmentation, high infrastructure costs, and the strategic tension between individual incentives and collective benefits. This study developed an optimization framework to evaluate cluster feasibility by integrating multi-scale spatial clustering, MST network design, and cooperative game-theoretic cost allocation. An application to rural Alabama's Black Belt demonstrates that aggregate cost metrics obscure critical internal imbalances; stability depends on how costs are distributed across households, particularly in peripheral connections, where costs frequently exceed the OWTS-based defection threshold. These findings highlight that, while larger clusters benefit from economies of scale, coalition viability is ultimately determined by spatial configuration and the specific cost-allocation structure. The framework provides RMEs and policymakers with a practical tool to identify unstable participants, quantify the stability gap, and direct targeted financial support to prevent coalition collapse. In doing so, it enables a shift from uniform planning assumptions toward adaptive, coalition-based infrastructure strategies that sustain participation and improve long-term service delivery.

Although this study focuses on the technical and fiscal dimensions of coalition stabilization, the long-term effectiveness of the proposed framework also depends on adequate institutional capacity and governance support. In limited-resource rural regions such as Alabama's Black Belt, RMEs often operate under conditions of weak local governance, limited administrative capacity, and constrained financial resources (Bakchan & White, 2024). Accordingly, the proposed framework should be viewed as a foundational decision-support mechanism whose effectiveness depends on broader institutional and governance capacity.

This study establishes a critical strategic baseline by evaluating coalition stability at the point of the initial formation stage—where capital funding represents the primary barrier to system implementation. It is important to recognize that stability in practice is inherently dynamic. Factors such as household turnover, demographic change, and infrastructure deterioration introduce temporal challenges that extend beyond initial formation and long-term operation and maintenance (O&M). To address these complexities, future research could expand the framework through longitudinal models and life-cycle cost analysis (LCCA) to capture evolving O&M burdens, such as electricity for STEP units, administrative fees, bill-payment support mechanisms, and long-term affordability considerations. Subsequent work could also integrate high-resolution digital elevation models to optimize pipe routing and the placement of treatment facilities. This study establishes a strategic economic baseline using Euclidean-based MST; however, incorporating terrain data would enable greater reliance on gravity-fed flow. This optimization reduces the need for costly lift stations and lowers long-term energy requirements, both of which are critical factors in the stability gap. Furthermore, future research should examine how institutional capacity, governance structures, and inter-organizational coordination influence the long-term implementation and operational effectiveness of RMEs in decentralized wastewater management. Additionally, these estimated stability gaps could be correlated with granular socioeconomic surveys to align fair cost allocations with Black Belt residents' actual willingness-to-pay. These integrated advancements will empower RMEs to manage subsidies that sustain both initial coalition stability and long-term service affordability for low-income communities.

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AI STATEMENT

Generative AI tools were not used to develop the structure, methodology, analysis, interpretation, or arguments of this manuscript. AI assistance was limited to language editing for grammar, clarity, and readability.

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