Data-Driven Optimization of Civil Defense Response Time Using Spatial Clustering and Queueing Models

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Analysis of 1,000 real emergency interventions in Qalqilya, Palestine, revealed substantial response-time delays, with only 9.5% of incidents meeting international NFPA standards. By combining spatial clustering (K-Means and DBSCAN) with queueing-based simulation, we identified five optimal civil defense center locations. The proposed configuration reduced average waiting times by 31%, lowered congestion, improved response reliability, and significantly decreased the occurrence of extreme delays.

I. Motivation & Problem

- Only 9.5% of incidents meet NFPA standards (4 min Response time).
- 26.6% of incidents exceed 20 minutes response time.
- Existing station locations create coverage gaps.

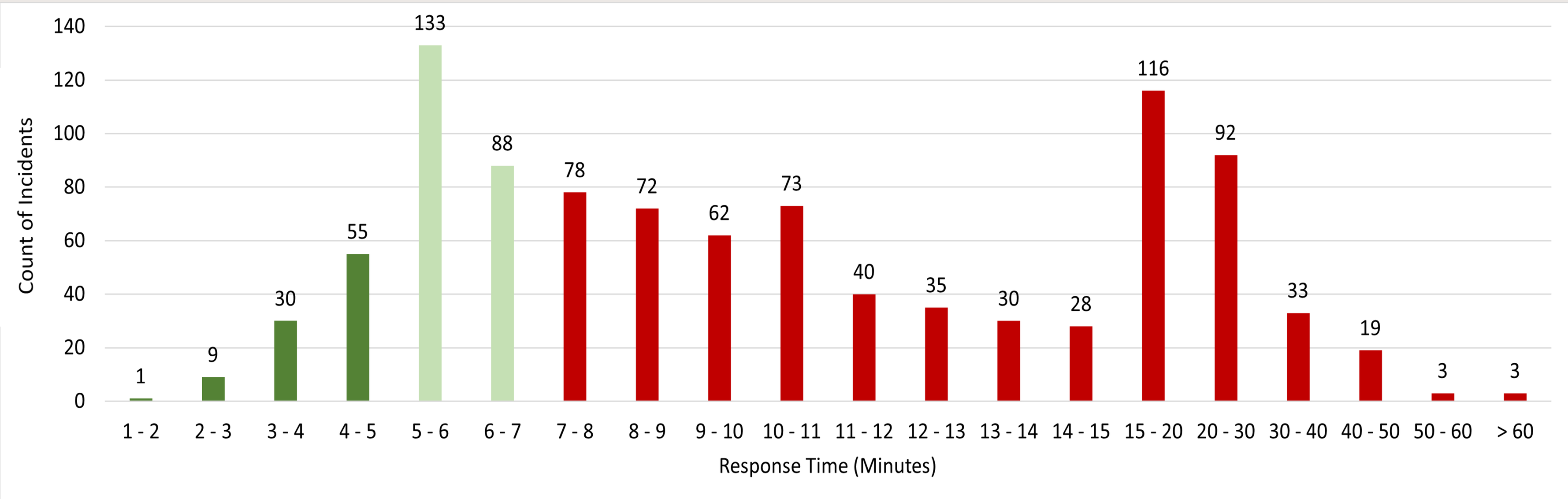
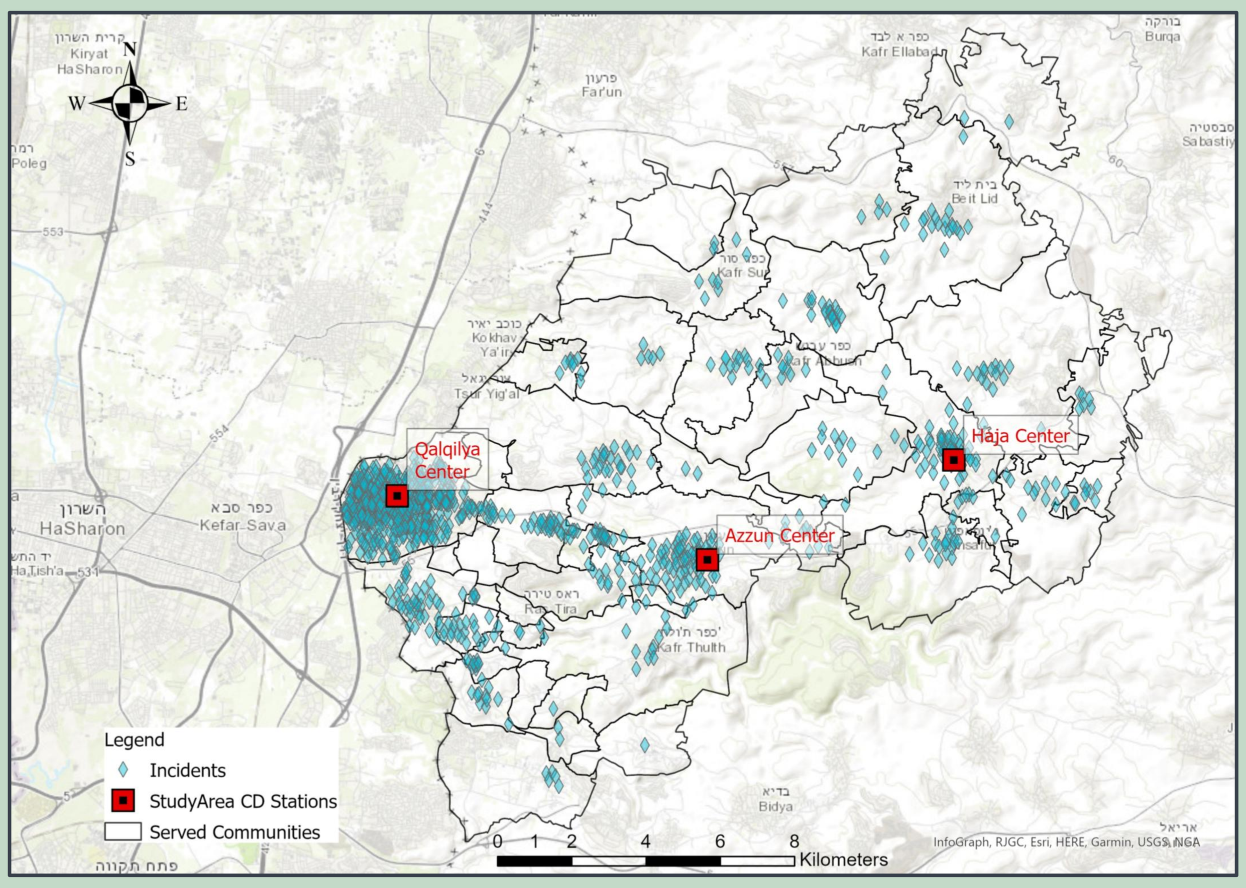


Figure: Qalqilya Civil Defense Response Time [minutes] from September 2024 to December 2025.

II. Study Area & Dataset

Qalqilya Governorate
West Bank , Palestine
Sep. 2024 – Dec. 2025

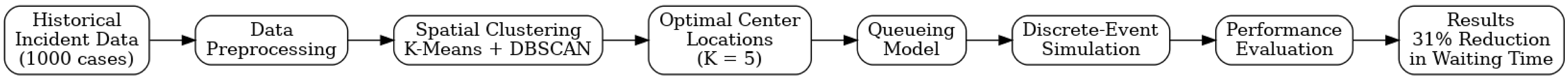
Metric	Value
Incidents	1,000
Period	15 months
CD Centers	3
Vehicles	7
Population	140,000
Area	240 km²



III. Methodology

Dispatch Dely: $W_i = T^{(i)}_{dispatch} - t_i$

Response Time: $R_i = W_i + \max_{c \in S_i} d_{c,i}$



IV. Spatial Optimization

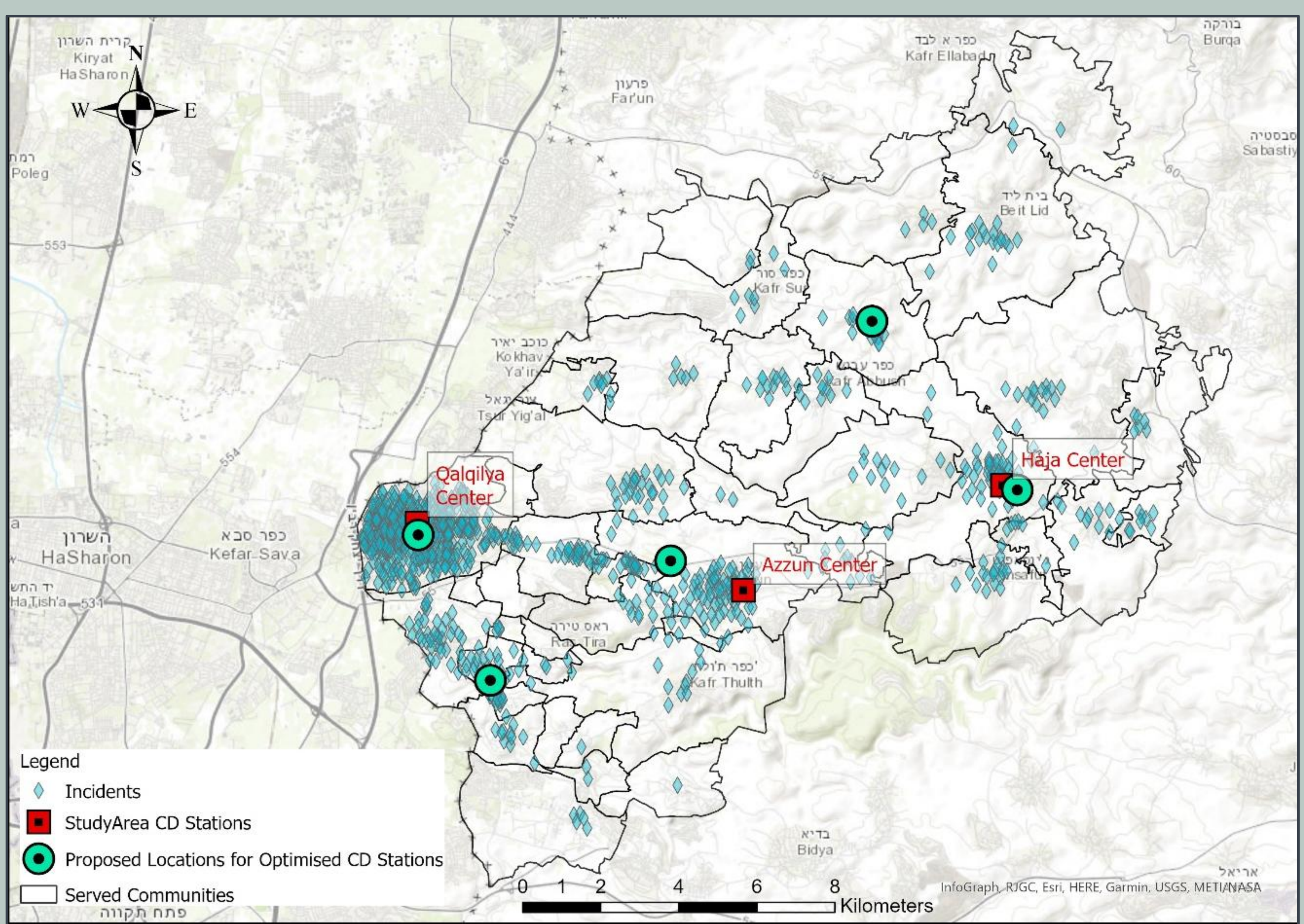


Figure: Existing Distribution (K=3) and Proposed Locations (K=5) of the Civil Defense Centers.

K	WCSS	BSS	Dunn	Xie-Beni	Interpretation
3	4.1847	0.0120	0.0051	35.5341	Actual Situation, clusters are very spread out, not compact
4	0.474	3.723	0.324	0.310	Some hotspots grouped together, less granularity; clusters less distinct.
5	0.326	**3.871**	**0.375**	**0.215**	Optimal balance, clusters compact, separated
6	**0.314**	3.863	0.161	1.053	Over-segmentation, uneven, overlapping, less operationally useful.

Table: Comparison of clustering metrics for K = 4, 5, and 6 clusters.

V. Results

- Response & Waiting Times: The 5-center configuration produces smoother performance with fewer congestion peaks.

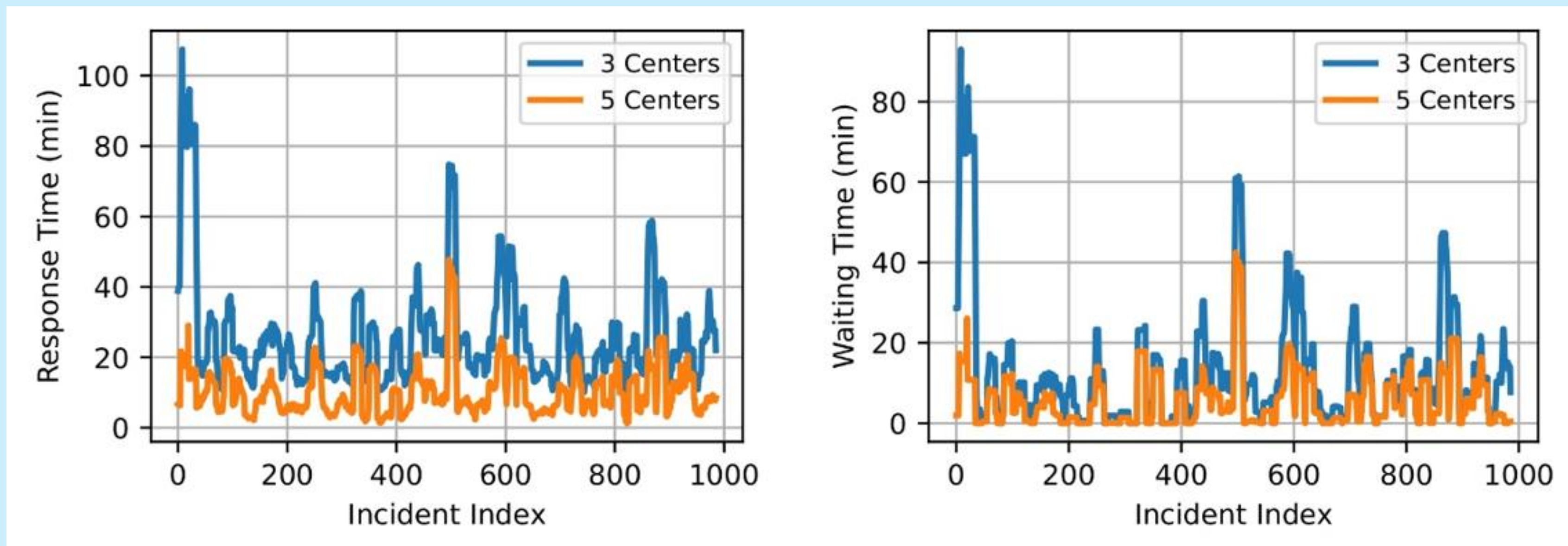


Figure: Waiting Time and Response Time per Incident.

- CDF Curves: The 5-center system stochastically dominates the 3-center system across all response-time thresholds.

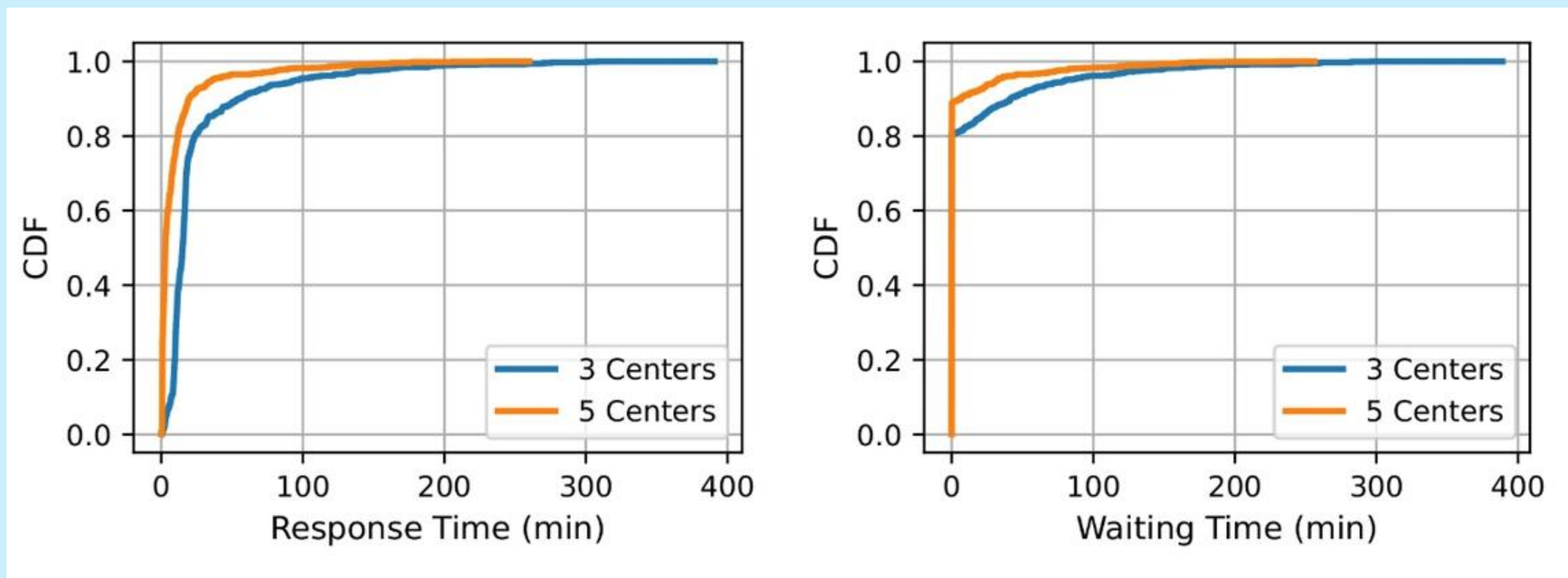


Figure: Cumulative Distribution Function (CDF) of Response Time and Waiting Time..

VI. Conclusion

✓ Spatial clustering identified optimal station locations.
✓ Five centers provided the best balance between coverage & practicality.
✓ Average waiting time reduced by approximately 31%.
✓ Extreme delays were reduced.
✓ The framework supports data-driven emergency planning.

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