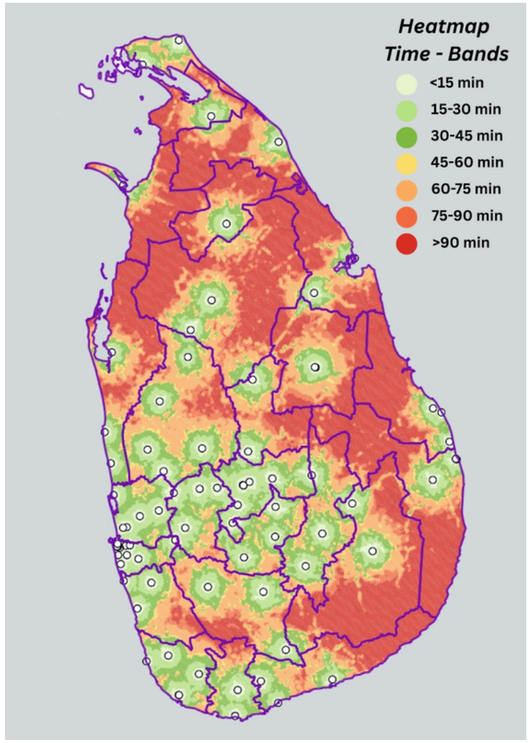
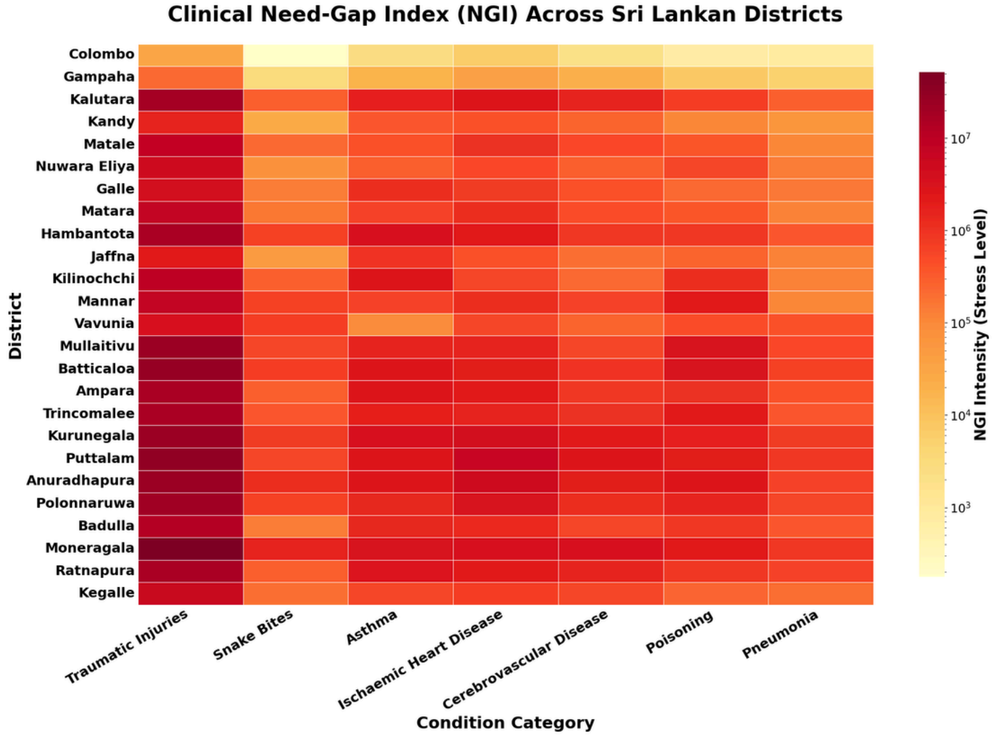
Golden Hour Divide: Trauma Care Accessbility and Resource Vulnerability in Sri Lanka





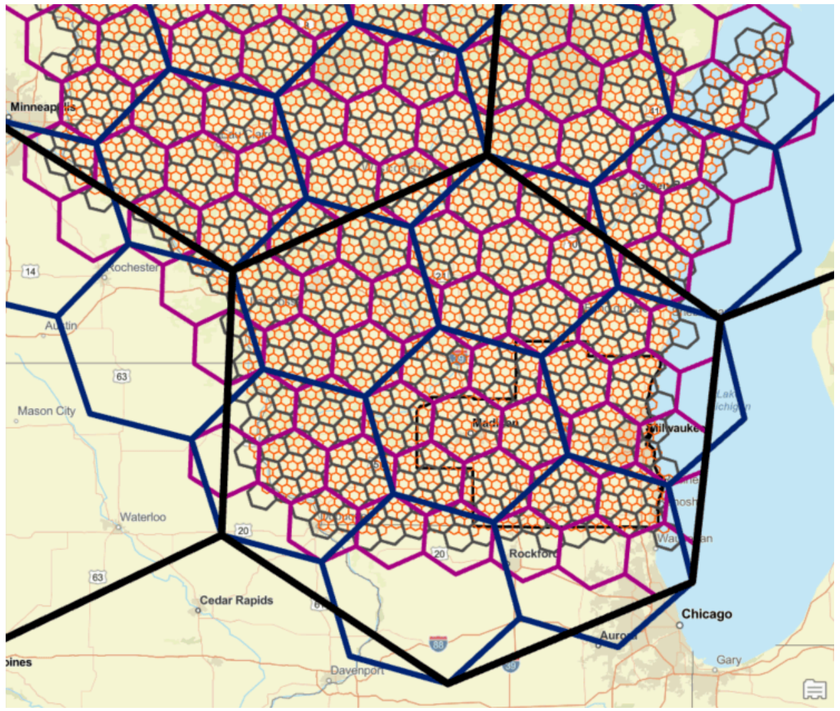
Sonath Kirindage, Vihanga Nimsara, Sakindu Rajapaksa, Kavyanga Hathurusinghe, Lahiru Dilshan, Subavarshana Arumugam, Nathali Athukorala, Nisansa de Silva, Sandareka Wickramanayake

Department of Computer Science & Engineering, University of Moratuwa, Sri Lanka

Golden Hour

Critical 60-minute window during which timely clinical intervention has the greatest impact on survival.



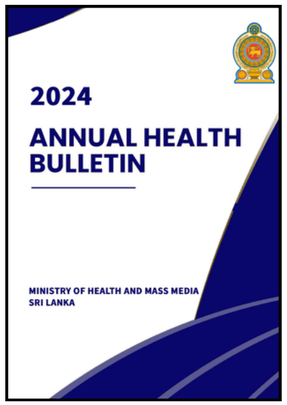


But, How quickly patients
can transition from initial stabilization to definitive care?

This study addresses these challenges through a data-driven framework that evaluates how effectively populations can reach life-saving medical services within the ***Golden Hour***.

Research Hypotheses & Data Pipeline

- **H1 (Spatial Fragmentation)**: Spatial Gap (Gd) is driven by terrain, not just ICU density.
- **H2 (Infrastructure Mirage)**: Definitive care (ICUs/OTs) correlates higher with survival outcomes (Lr) than primary ETU density.
- **H3 (Specialist Scarcity)**: Systemic pressure (NGI) is driven by specialist scarcity over physical bed capacity.
- **H4 (Pareto Optimization)**: Targeted intervention yields disproportionately higher national pressure reduction than uniform distribution.



Annual Health Bulletin (2024)



Medical Statistics Unit (MSU) of the Ministry of Health, Sri Lanka

Demographic and Administrative Baseline

Clinical Demand and Epidemiological Profile

Institutional Supply and Specialist Resource Mapping

Geospatial Repository

Methodology - Phase 1
Terrain-Aware Spatial Gap (Gd)

- **Spatial Discretization (Uber H3)**
  - Partitioned Sri Lanka into Uber H3 hexagons (Resolution 8, ~0.737 km² per cell) for fine-grained spatial modeling.
  - Road network geometries sourced from OpenStreetMap (OSM)

- **Terrain-Aware Speed Model**
  - Accounts for elevation changes by calculating road segment grade:

$$\text{Grade} = \frac{|\text{End Elevation} - \text{Start Elevation}|}{\text{Segment Length}}$$

  - Base speeds (Vbase) are penalized using a capped terrain factor to derive adjusted speed (Vadj)

$$V_{adj} = \max(V_{base} \times (1 - \min(0.5 \times \text{grade percentage}, 0.75)), 5)$$

- **Travel Time Estimation**
  - Distance computed from each hexagon centroid to the nearest of 83 ICU-equipped hospitals
  - Uses Haversine distance (D) with a 1.35 detour factor:

$$T = \frac{D \times 1.35}{V_{H3}}$$

- **Spatial Interpolation & Scale**
  - KNN Regressor & Open-Source Scalability

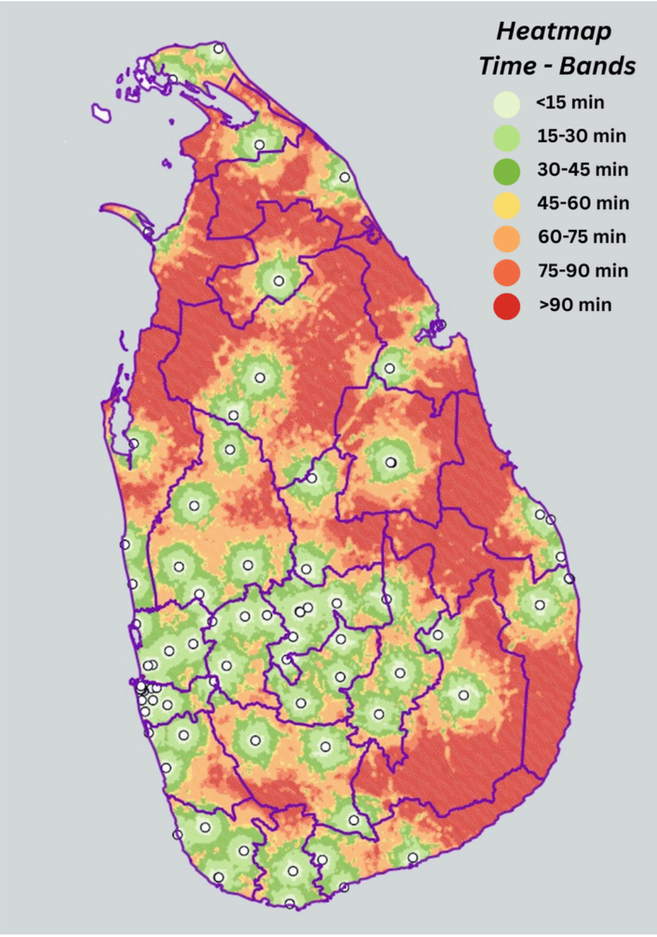
- **Spatial Gap (Gd) Metric**
  - Proportion of district land area exceeding the 60-minute Golden Hour threshold:

$$Gd = \frac{\text{Hexagons} > 60 \text{ min}}{\text{Total Hexagons in District}}$$

Phase 1 - Experiments & Results

District	0–15 min	15–30 min	30–45 min	45–60 min	>60 min	Total_hexagons	Covered_hexagons	spatial_gap_gd	Percentage
Ampara	124	339	338	402	4440	5643	1203	0.7868155237	78.68155237
Anuradhapura	158	403	724	981	6820	9086	2266	0.7506053269	75.06053269
Badulla	194	633	1011	724	1045	3607	2562	0.2897144441	28.97144441
Batticaloa	129	179	216	221	1926	2671	745	0.7210782478	72.10782478
Colombo	355	281	156	78	2	872	870	0.002293577982	0.2293577982
Galle	243	659	609	277	275	2063	1788	0.1333010179	13.33010179
Gampaha	331	715	503	193	13	1755	1742	0.007407407407	0.7407407407
Hambantota	145	349	523	439	1841	3297	1456	0.5583864119	55.83864119
Jaffna	109	210	276	282	225	1102	877	0.2041742287	20.41742287
Kalutara	165	418	408	370	735	2096	1361	0.3506679389	35.06679389
Kandy	404	1024	629	252	126	2435	2309	0.05174537988	5.174537988
Kegalle	326	787	532	280	188	2113	1925	0.08897302414	8.897302414
Kilinochchi	62	163	221	170	1067	1683	616	0.6339869281	63.39869281
Kurunegala	319	943	1428	1552	1982	6224	4242	0.3184447301	31.84447301
Mannar	29	72	136	169	2144	2550	406	0.8407843137	84.07843137
Matale	153	337	377	410	1327	2604	1277	0.5096006144	50.96006144
Matara	133	443	427	290	351	1644	1293	0.2135036496	21.35036496
Monaragala	187	397	587	716	5335	7222	1887	0.7387150374	73.87150374
Mullaitivu	65	137	238	370	2469	3279	810	0.7529734675	75.29734675
Nuwara Eliya	239	615	726	427	180	2187	2007	0.08230452675	8.230452675
Polonnaruwa	71	244	333	497	3165	4310	1145	0.7343387471	73.43387471
Puttalam	123	316	499	449	2635	4022	1387	0.6551466932	65.51466932
Ratnapura	215	671	831	947	1511	4175	2664	0.3619161677	36.19161677
Trincomalee	79	201	270	328	2493	3371	878	0.7395431623	73.95431623
Vavuniya	66	180	238	265	1792	2541	749	0.7052341598	70.52341598

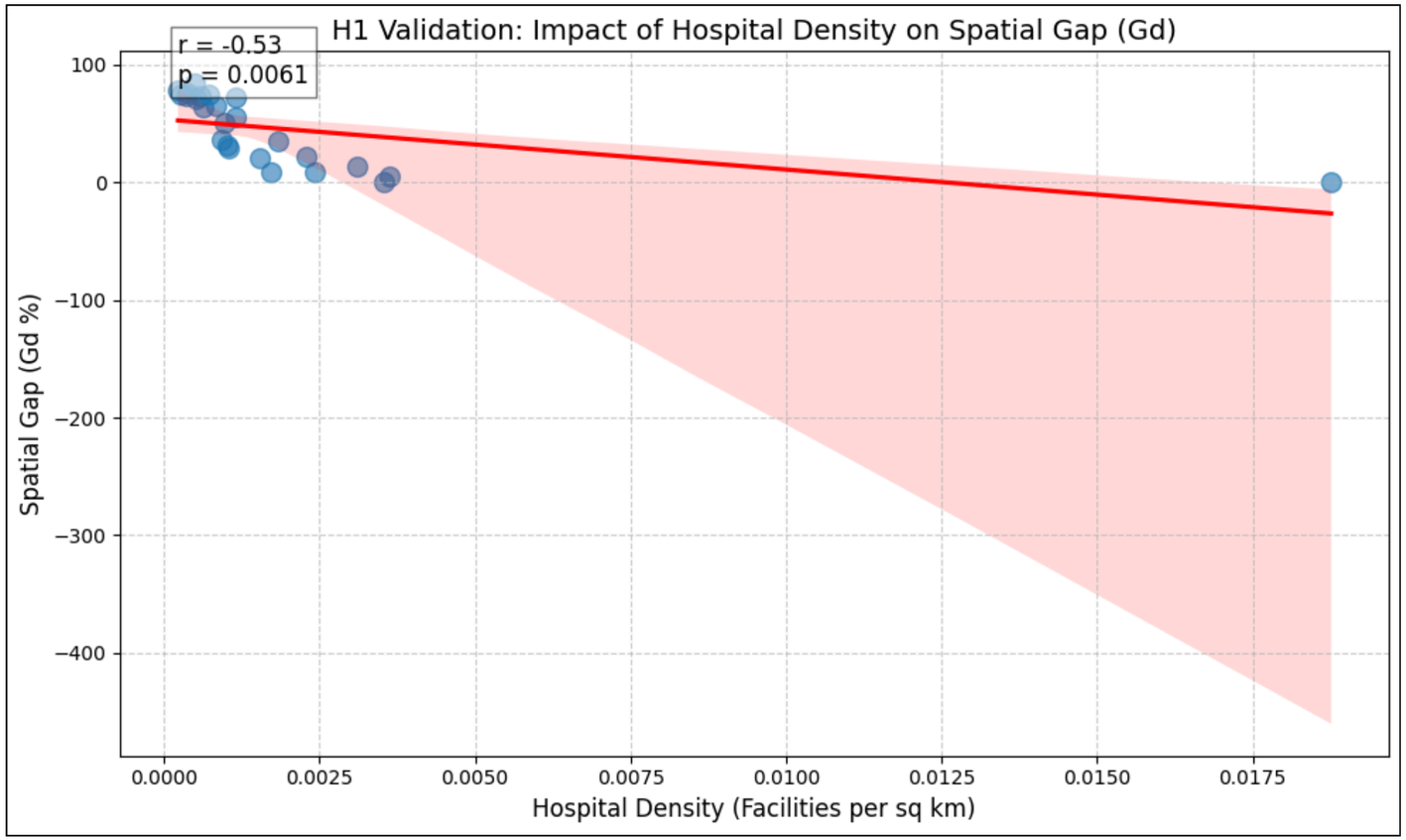
Distribution Across Covered Hexagons and Total Hexagons



Terrain-Aware Spatial Gap (Gd) distribution across districts

H1 Validation

RDHS Division	ICU Hospitals	Land Area (sq. km)	Hospital_Density
Colombo	13	693	0.01875901876
Gampaha	5	1418	0.003526093089
Kalutara	3	1647	0.001821493625
Kandy	7	1927	0.003632589517
Matale	2	2058	0.0009718172983
Nuwara Eliya	3	1745	0.001719197708
Galle	5	1617	0.003092145949
Matara	3	1317	0.002277904328
Hambantota	3	2627	0.001141987057
Jaffna	2	1298	0.001540832049
Kilinochchi	1	1565	0.0006389776358
Mannar	1	2047	0.0004885197851
Vavunia	1	1934	0.0005170630817
Mullaitivu	1	2681	0.0003729951511
Batticaloa	3	2623	0.001143728555
Ampara	1	4476	0.0002234137623
Trincomalee	2	2799	0.0007145409075
Kurunegala	5	4905	0.001019367992
Puttalam	3	3605	0.0008321775312
Anuradhapura	2	7215	0.0002772002772
Polonnaruwa	2	3472	0.0005760368664
Badulla	3	2871	0.001044932079
Moneragala	2	5757	0.0003474031614
Ratnapura	3	3286	0.0009129640901
Kegalle	4	1657	0.002414001207



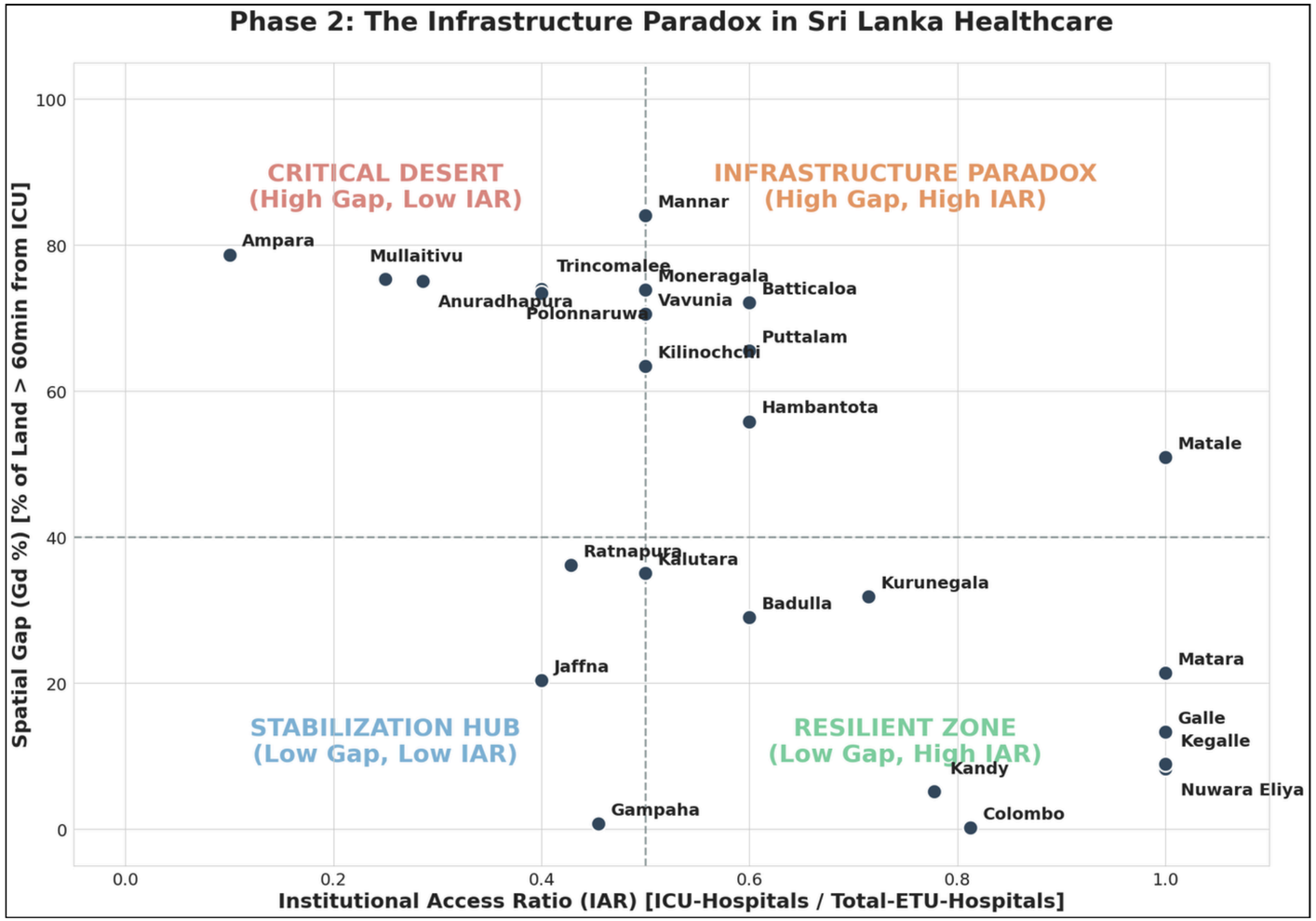
- Pearson correlation between hospital density and Gd yielded r = −0.53 (p = 0.006), **rejecting Hypothesis 1 (H0)**.
- The R2 of 0.284 shows that hospital density explains only 28% of the variance in Gd.

Methodology - Phase 2
The Infrastructure Paradox (Supply vs. Access)

Evaluates the systemic mismatch between primary stabilization capacity and definitive care infrastructure across Sri Lanka.

Institutional Access Ratio (IAR)

$$IAR = \frac{\text{ICU Equipped Hospitals}}{\text{ETU - Capable Hospitals}}$$



Methodology - Phase 3
Lethality Ratio(Lr) & General Need-Gap Index (NGI)

- **Lethality Ratio (Lr)**
    - Measures fatal outcomes to validate the clinical impact of accessibility gaps:

$$Lr = \frac{\text{Total Deaths}}{\text{Total Cases}}$$

- **Resource Intensity Weighting (Resource Score)**
    - Prioritizes specialized human capital over static bed counts:

Resource Score = (0.2 x ICU Beds) + (0.3 x OTs) + (0.5 x Specialists)

- **Territorial Coverage Ratio (TCR)**

$$TCR = \frac{\text{Covered Hexagon Area}}{\text{Total District Area}} \times 100$$

- **General NGI Formula**
    - Measures macro-level systemic pressure by relating demand, spatial gaps, and resources:

$$NGI = \frac{\text{(Total Cases/Population) x Gd}}{\text{(Resource Score/Population)}}$$

- **Macro-Level Indicator**
    - Annual Case Volumes: Hospital infrastructure and specialist counts are fixed yearly.
    - Systemic Pressure: Measures year-round resource deficits rather than daily operational noise.

Methodology - Phase 3
Disease-Specific NGI & Weighted Resource Intensity

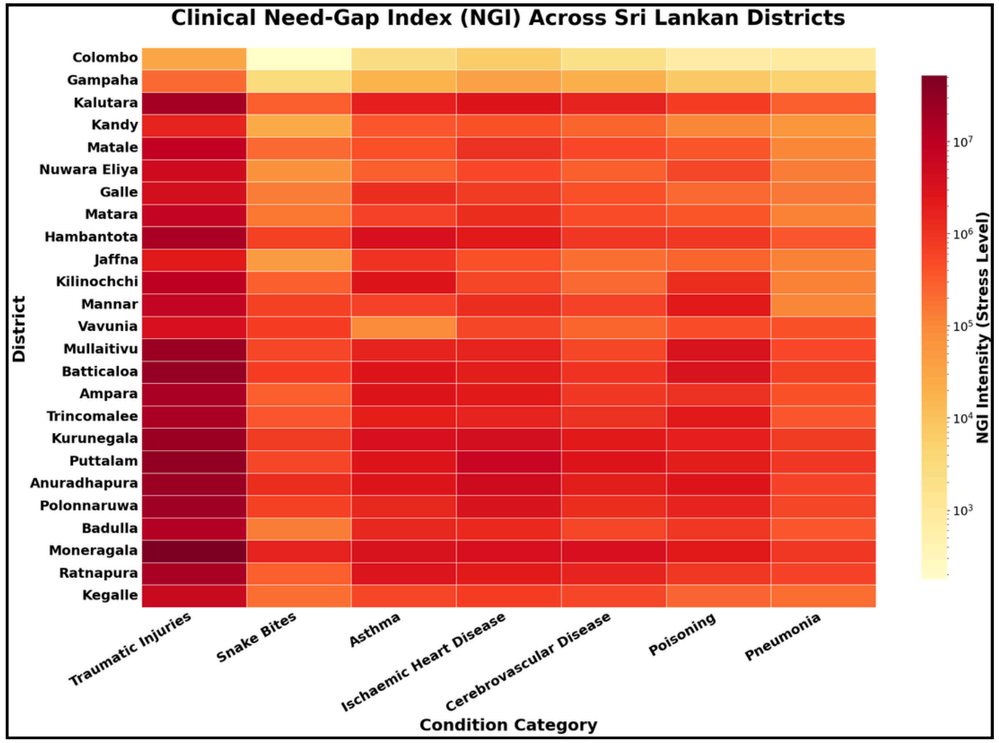
- **Disease-Specific Formulation**
    - Tailors resource requirements to clinical heterogeneity across 7 time-critical conditions:

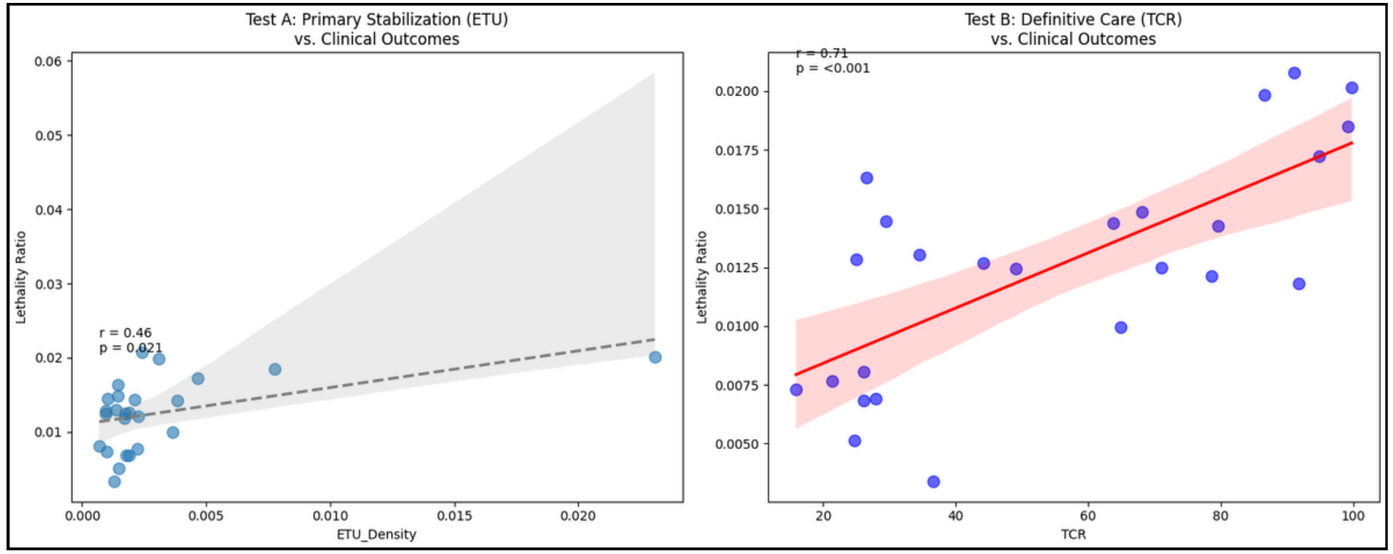
$$\text{NGI(disease)} = \frac{\text{(Condition Cases/Population) x Gd}}{\text{(Adjusted Resource Score/Population)}}$$

Condition Category	Resource Score Components
Ischaemic Heart Disease	Cardiologists (0.45) + Radiologists (0.15) + ETU (0.10) + ICU (0.20) + OT (0.10)
Cerebrovascular Disease	Neurologists/Neurosurgeons (0.35) + Radiologists (0.25) + ETU (0.10) + ICU (0.20) + OT (0.10)
Traumatic Injuries	Surgeons (Gen/Ortho/Neuro) (0.35) + Radiologists (0.15) + ETU (0.10) + ICU (0.20) + OT (0.20)
Snake Bites	General Physicians (0.50) + ETU (0.30) + ICU (0.20)
Poisoning	Anaesthesiologists/General Physicians (0.60) + ETU (0.20) + ICU (0.20)
Asthma	Chest Physicians (0.50) + Paediatricians (0.20) + ETU (0.20) + ICU (0.10)
Pneumonia	Physicians (Chest/General) (0.50) + Radiologists (0.20) + ETU (0.20) + ICU (0.10)

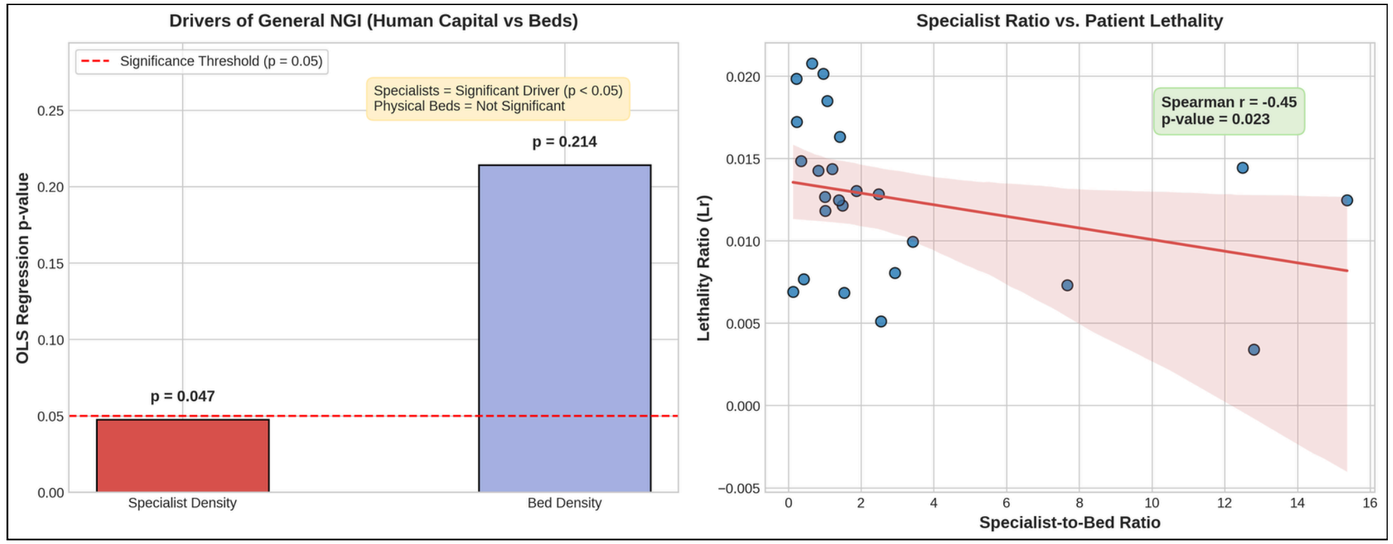
Condition Specific Resource Score Configuration

Clinical Pressure Mapping (NGI) & Hypotheses Testing (H2, H3)





H2 Validation



H3 Validation

Methodology - Phase 4
Policy Clustering & System Optimization

- **Clustering Input Vector:**

  [Spatial Gap (Gd), Need Gap Index (NGI),
  Lethality Ratio (Lr), TCR, Resource Score]

- **Optimal Cluster Selection (K = 4):**

  - Evaluated K=3 to K=6 given the 25-district dataset.
  - K=3 caused under-fitting; K >= 5 caused unstable singleton clusters.
  - K=4 provides optimal stability and domain interpretability.

- **Policy Actionable Archetypes**

  - 🔴 Cluster 1: Critical Structural Exclusion (Red) --> High Gd (>50\%), low TCR, high Lr.
  - 🟠 Cluster 2: Institutional Mirages (Orange) --> Low Gd, but high Lr and low specialist density.
  - 🟡 Cluster 3: Operational Capacity Strain (Yellow) --> Low Gd, but high NGI.
  - 🟢 Cluster 4: High-Resilience Benchmarks (Green) --> Low Gd, high TCR, low NGI.

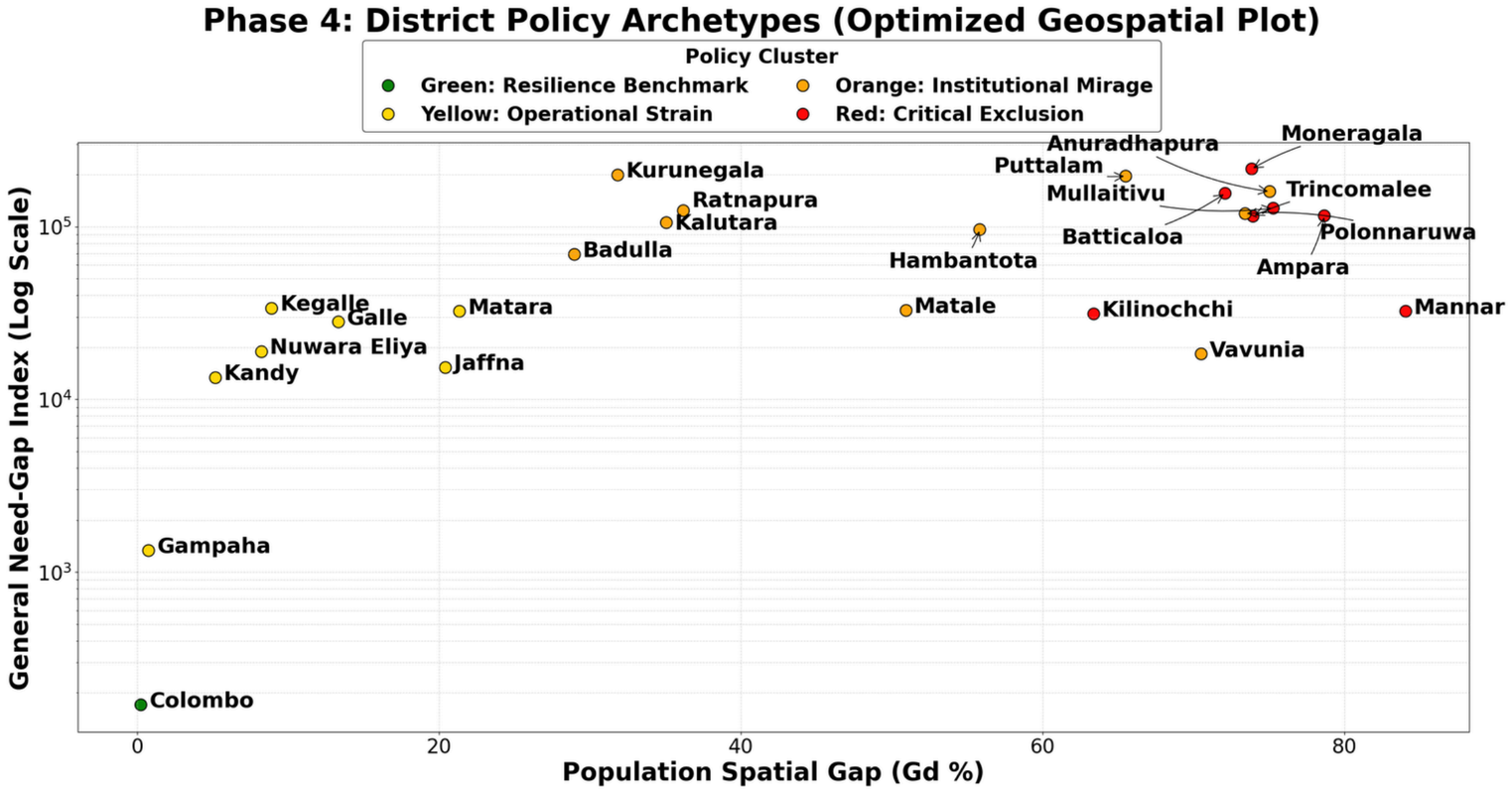
- **Simulation Design (Systemic ROI)**

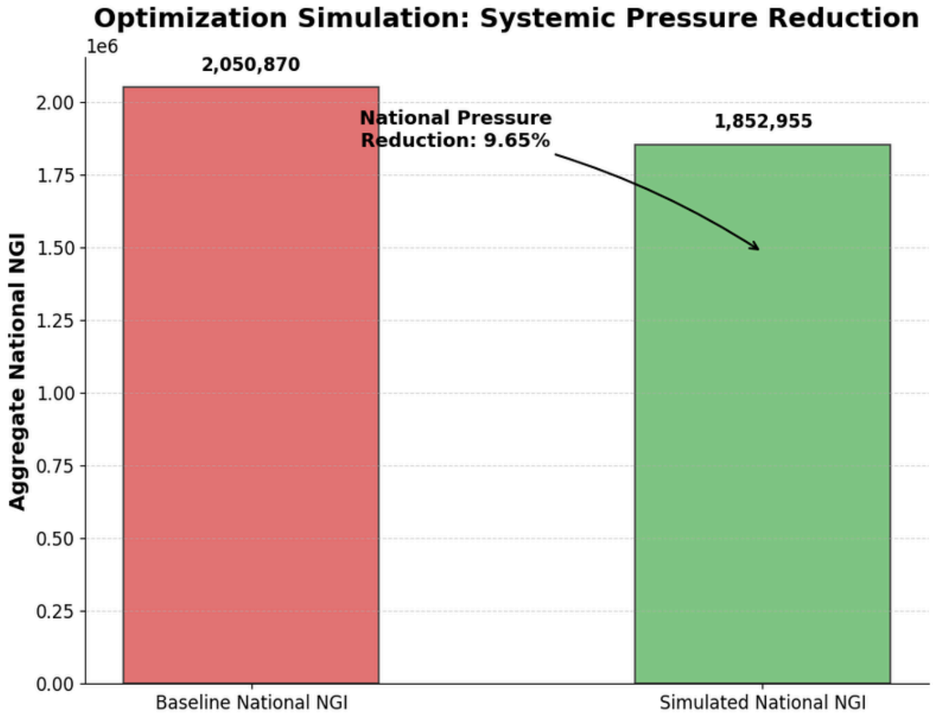
  - Tests the "Return on Investment" of targeted interventions vs. uniform resource distribution.
  - Mathematically reduces the Spatial Gap (Gd) in Red Clusters by 25%.

- **Targeted Policy Impact**

  - Evaluates how improving accessibility in the most excluded regions translates to aggregate national pressure reduction.
  - Demonstrates non-linear systemic gains: targeted expansion in isolated zones relieves pressure across the broader emergency network.

Phase 4 - Experiments & Results





Optimization Simulation Figure serves as prescriptive **proof for H4 (Targeted Investment)**. A 25% increase in definitive care within 7 “Red-Cluster” districts reduced the National NGI by 9.65%. This strongly suggests non-linear optimization: targeting the most excluded 20% of land area yields a 10% national efficiency gain.

Critical Discussion
The Referral Paradox & Spatial Friction

- **The Referral Paradox (Catchment Burden vs. Exclusion)**
    - Counter-Intuitive Finding: ETU density (r = +0.460) and Golden Hour Coverage (TCR, r = +0.714) correlate positively with Lethality (Lr).
    - Urban "Mortality Export": Urban hubs (Colombo, Kandy) absorb severe rural referrals as "final-mile" destinations.
    - Catchment vs. Exclusion: High urban Lr reflects regional catchment strain; low rural Lr masks non-access and unrecorded pre-hospital deaths.
- **Terrain Friction & Spatial Disparities**
    - Terrain-Blind Planning: 72% unexplained variance in Gd shows facility counts alone do not ensure access.
    - Extreme NGI Disparities: Mannar (NGI = 290,303.82) vs. Colombo (NGI = 170.23) highlights a "double burden" of high spatial gap (84.07%) and low resources (17.1).
- **Specialist Scarcity Drives Systemic Pressure**
    - Expertise-Weighted Pressure: Absence of key specialists (neurosurgeons, cardiologists, chest physicians) causes exponential condition-specific NGI spikes.
    - Severe Regional Deficits: Moneragala’s Trauma NGI reaches 52.0 x 10^6 due to total specialist collapse.
- **The "Institutional Mirage" Concept**
    - Underutilized Physical Assets: Districts like Puttalam (Heart Disease NGI = 6.6 x 10^6) and Kurunegala (Asthma NGI = 3.6 x 10^6) have beds but lack clinical capacity.
    - Severe Regional Deficits: Moneragala’s Trauma NGI reaches 52.0 x 10^6 due to total specialist collapse.

Methodological Limitations & Future Scope

- **Specialist Scarcity Drives Systemic Pressure**

    - Data Constraint: The Annual Health Bulletin aggregates total hospital admissions without categorizing cases by acute emergency triage versus elective care.
    - Impact: Baseline NGI demand inherently includes non-urgent presentations.
    - Systemic Need: Highlights a critical institutional need for the Ministry of Health to update national health reporting protocols to track acute emergency triage levels.

- **Travel-Time Surface Constraints**

    - Environmental & Urban Dynamics: Static travel-time modeling does not account for dynamic peak urban congestion (e.g., Colombo traffic) or monsoon-driven road washouts.

- **Hospital-Recorded Mortality Bias (Lr)**

    - Pre-Hospital Exclusion: Lr strictly tracks facility-recorded fatalities, missing out-of-hospital community deaths in isolated, high-Gd regions.
    - Systemic Impact: Systematically underestimates true mortality in the most vulnerable, remote rural populations.

Conclusion - Operationalizing Spatial Healthcare Equity

- **Aligning Spatial Access with Clinical Capability**
    - Core Paradigm Shift: Emergency resilience depends on pairing physical geographic access (Gd) with appropriate specialized human capital, not just building infrastructure.
- **Validation of Hypotheses (H1-H4)**
    - Empirical Confirmation: Confirms specialists are the primary drivers of survival.
    - The "Institutional Mirage" Reality: Without specialist coverage, facilities remain structurally present but functionally limited.
- **Decentralization Strategy (Targeting "Red Clusters")**
    - Strategic Deployment: Placing specialists within the most excluded 28% of regions (Red Clusters) enables localized stabilization and definitive care.
    - Mitigating the Referral Paradox: Alleviates extreme overflow into overburdened central hubs (Colombo, Kandy, Anuradhapura) by capturing emergencies closer t home.

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Thank You!