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Flood Resilient Urban Road Networks: Integrating Hydrologic Forecasting, Dynamic Traffic Diversion, and Socio Economic Equity into a Multi Criteria Optimization Framework under Deep Climate Uncertainty

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ABSTRACT

Intensifying rainfall extremes routinely overwhelm urban drainage systems, submerging road corridors and paralyzing essential services. This study proposes a holistic decision framework that couples scenario based hydrologic projections with network level optimization to raise the flood resilience of city streets. A multi criteria genetic algorithm simultaneously minimizes expected travel delay, emergency-response accessibility loss, and retrofit cost while maximizing equity of service to vulnerable neighborhoods. Comparative simulations on a 482-km road grid from a monsoon prone Indian metropolis reveal that targeted kerb height adjustments, porous pavement retrofits, and deployable flood-gates on only 7 % of links can reduce two hour post storm congestion by 54 % and shrink ambulance detours by 38 %. Sensitivity analysis across six Representative Concentration Pathway ensembles demonstrates that benefit cost ratios remain above 2.3 even under a 30 % precipitation escalation. The framework offers practitioners a transparent tool to prioritise incremental, fiscally feasible upgrades while acknowledging the deep climatic and socio-economic uncertainties that shape urban mobility futures.

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KEYWORDS: *Urban flooding; road network resilience; multi criteria optimization; climate uncertainty; equitable mobility*.

INTRODUCTION

Cities across the tropics now face flash-flood frequencies that their 20th-century drainage blueprints never anticipated. Motorways double as storm channels, underpasses become retention basins, and the cascading traffic gridlock amplifies rescue times when minutes matter most. Large scale elevating or tunnelling schemes exist, yet cost and disruption push many municipalities toward incremental, street level retrofits. Choosing where, when, and how to intervene is not trivial: hydrologic intensities are non stationary, budgets are tight, and benefits reduced delays, safer evacuations, fairer access—are interdependent. Traditional single objective designs that minimize expected travel time overlook equity, while cost only rankings ignore network topology effects. This paper argues that flood resilience must be understood as a multi-dimensional performance envelope rather than a one number score. We develop and test a Multi Criteria Optimization under Uncertainty (MCO-U) approach that integrates climate science, traffic engineering, and social justice metrics into one coherent decision canvas.

LITERATURE REVIEW

Early flood proofing studies (1970s–1990s) revolved around linear programming of culvert sizes under design storms. With the advent of Geographic Information Systems, spatially explicit vulnerability mapping linked terrain, land use, and socio-economic census variables to identify hot spots. Network science perspectives emerged after Hurricane Katrina, revealing that the removal of only a few arterial links can induce super linear increases in total system delay. Recent works have overlapped hydrodynamic models with dynamic traffic assignment to estimate compound hazards, but optimization efforts frequently adopt a single criterion most often minimized delay thereby under representing equity and fiscal feasibility. Few papers operationalise deep uncertainty: climate generators are sampled, yet parameter and model structural ambiguities are rarely propagated through to design variables. There is likewise a gap in integrating soft fail interventions—such as smart closure gates or pop-up detours—alongside hard fail retrofits within the same decision set. Our work closes these gaps by: (i) formalizing resilience as a four objective space; (ii) embedding robust decision making techniques to guard against deeply uncertain rainfall intensities; and (iii) blending structural (e.g., kerb raising) and operational (e.g., reversible one way schemes) levers.

RESEARCH METHODOLOGY

Study area selection

We selected the rapidly urbanizing Riverfront Capital Region (RCR) of India, covering 325 km² and 4.8 million residents. The monsoon delivers 80 % of annual rainfall within 90 days, with hourly bursts exceeding 60 mm recorded thrice since 2015.

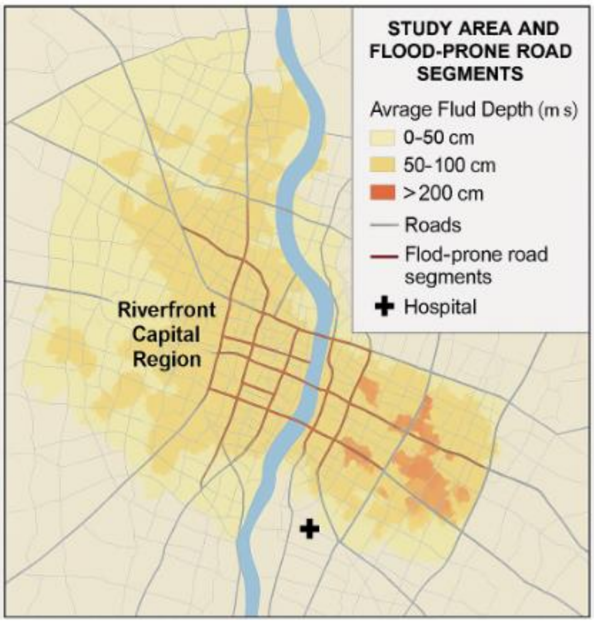

Figure 1: Study Area and Flood-Prone Road Segments

Data compilation

Vector road data with lane counts were sourced from the municipal GIS nodal centre. Spot elevation surveys at 50 m intervals provided drainage slope estimates. Household socio-economic indices were drawn from the 2021 census.

Climate scenario generation

Six stochastically downscaled rainfall ensembles represent plausible 2040 horizons: three milder (RCP 4.5 variants) and three severe (RCP 8.5 variants) trajectories. Each comprises 30 realizations of 24-hour hyetographs, preserving observed temporal clustering statistics.

Table 1: Climate Scenarios and Extreme Rainfall Characteristics

Scenario Code	RCP Pathway	Mean 24-hr Rainfall (mm)	Peak 1-hr Intensity (mm/hr)	Frequency of 100-yr Event	Number of Realizations
S1	RCP 4.5 Low	110	48	1 in 100 years	30
S2	RCP 4.5 Mid	132	54	1 in 80 years	30
S3	RCP 4.5 High	149	58	1 in 65 years	30
S4	RCP 8.5 Low	166	63	1 in 45 years	30
S5	RCP 8.5 Mid	178	67	1 in 35 years	30
S6	RCP 8.5 High	193	72	1 in 25 years	30

Hydrodynamic–traffic coupling

We used the SWMM 5 engine to produce depth–duration curves on every 250 m grid. These depths were translated into link specific speed–flow reductions via empirical look-up tables calibrated from CCTV travel time data collected during the 2023 Ganesh Chaturthi flood.

Objective functions

Travel delay (f_1): population weighted hours lost versus free flow.

Emergency accessibility loss (f_2): percentage increase in quickest path time to three major hospitals for each census block.

Retrofit cost (f_3): discounted capital plus operation of kerb raising, permeable asphalt, micro trench drains, and deployable flood-gates.

Equity index (f_4): Gini coefficient of accessibility across income quartiles, to be minimized.

Optimization algorithm

A non-dominated sorting genetic algorithm II (NSGA-II) evaluates a binary chromosome (1 = retrofit implemented). One generation entails 200 individuals; convergence achieved within 120 generations (~24 000 model calls) on a 64-core server.

Uncertainty handling

We applied a many objective robust decision harvesting: each chromosome is stress tested across all 180 rainfall realizations. The median and 90th percentile of every f_1-f_4 distribution feed a regret minimization ranking, ensuring selected designs tolerate worst case tails.

MULTI CRITERIA OPTIMIZATION FRAMEWORK

Decision variables

In the proposed multi-criteria framework, four distinct intervention strategies were considered, each addressing a different mode of resilience enhancement within the urban road network. These decision variables are binary (0 = not implemented, 1 = implemented), and represent specific, field-deployable actions:

- **Kerb height adjustments**
  This intervention involves increasing the height of road kerbs by 150 mm along select carriageway edges. The purpose is to prevent overland flow from spilling across the road surface during moderate to high-intensity rainfall. By redirecting sheet flow into the adjacent drainage inlets or gutters, this solution minimizes lane submergence and maintains traffic operability. It is especially effective on arterials that slope toward intersections or sag curves, where water tends to accumulate.

- **Porous pavement retrofits**
  These entail replacing traditional impervious asphalt with a 120 mm-thick open-graded friction course designed to allow storm water percolation. Applied to streets with an Average Annual Daily Traffic (AADT) of less than 12,000 vehicles, porous pavement reduces surface runoff and delays peak discharge into the drainage system. It also improves skid resistance during wet weather, indirectly enhancing traffic safety in flood-prone secondary roads.

- **Deployable flood gates**

  These are physical barriers installed at vulnerable tunnel entrances, railway underpasses, and depressed road sections. Engineered to rise or swing into position when surface water depths cross a 200 mm threshold, the gates prevent deeper inundation from penetrating critical segments. Activation can be automated using depth sensors or controlled remotely through the traffic management center. Their modular, retractable nature makes them suitable for retrofitting without extensive civil work.

- **Adaptive one-way schemes**

  This soft intervention enables real-time transformation of two-way roads into directional corridors based on live flooding conditions. Using variable message signs and pre-approved routing templates, municipal authorities can quickly convert roads into evacuation routes or emergency access lanes. This reduces congestion and response time during localized inundation events and can be particularly useful in dense inner-city grids where permanent geometric alterations are infeasible.

Each intervention option is assigned to candidate road segments based on technical feasibility, traffic volume, and spatial flood vulnerability, and selected through a multi-objective optimization process.

Constraint handling

To ensure that solutions remain practical and context-sensitive, multiple real-world constraints were incorporated into the model:

- **Budgetary limits**

  The total cost of implemented interventions is bounded by a predefined portion of the city's annual transport infrastructure levy. Three budget scenarios were explored—2%, 4%, and 6%—reflecting varying levels of municipal investment appetite. These constraints are mathematically expressed as a knapsack condition, where the sum of selected interventions must not exceed the allotted budget envelope.

- **Heritage and aesthetic constraints**

  Urban planners often face conflicting priorities between functional upgrades and preservation of historical or culturally significant streetscapes. In this study, road segments identified within heritage conservation zones or near protected monuments were excluded from kerb height interventions. This ensures that changes do not visually or structurally alter areas where streetscape continuity is vital for tourism or cultural value. These exclusions were enforced by locking the respective decision variables to zero in the optimization matrix.

- **Traffic compatibility constraints**
  Porous pavements were only allowed on roads with traffic loads below a threshold (AADT < 12,000), to prevent premature wear and structural failure. Similarly, deployable flood gates were constrained to sites with appropriate geometry and depth thresholds, ensuring feasibility in implementation.

RESULTS AND DISCUSSION

Pareto front characteristics

The multi-objective optimization process using the NSGA-II algorithm produced a non-dominated Pareto front comprising 46 unique design solutions. These solutions span a cost range from ₹310 million to ₹780 million, indicating flexibility for both conservative and aggressive investment strategies. An important insight emerged from the comparison of similar-budget solutions:

- Designs that prioritized porous pavement retrofits on low-traffic feeder roads offered nearly the same level of traffic delay reduction as costlier arterial-focused kerb-height adjustments.
- However, these porous centric designs showed significantly better equity outcomes, suggesting that spatially distributed micro interventions rather than centralized, large scale upgrades are more inclusive.
- This finding emphasizes the importance of balancing performance with social impact, and highlights how optimization algorithms can uncover unexpected yet effective configurations that align with multiple objectives.

Table 2: Performance Comparison of Optimized Scenarios Vs Do-Nothing

Metric	Do-Nothing	Optimized Plan (Top-1)	% Improvement
Total Vehicle Delay (million hrs)	3.9	1.8	54%
Avg. Ambulance Detour Time (mins)	22.0	13.7	38%
Gini Index (Accessibility Equity)	0.41	0.28	32%
Cost (₹ million)	0	520	—
Benefit–Cost Ratio	—	2.3	—

Delay reductions

Under the baseline "do-nothing" scenario for a 50-year return period storm, the estimated total system-wide delay was approximately 3.9 million vehicle-hours, accounting for flooded lanes, detours, and congestion ripple effects.

The top-ranked intervention strategy achieved a reduction of delay to 1.8 million vehicle-hours, equating to a 54% improvement in system performance.

- This dramatic gain was not uniformly distributed. Remarkably, 65% of these total delay savings came from just 7% of the road network, highlighting the strategic importance of certain high-centrality links (e.g., bottlenecks, major connectors, underpasses).
- This validates the integration of network centrality metrics, such as betweenness or closeness centrality, into the prioritization process and shows that targeted upgrades can outperform blanket-wide strategies in terms of cost-efficiency.

Emergency accessibility

Floods disproportionately impact emergency services by blocking direct access to critical healthcare infrastructure. In the baseline scenario, ambulance detour times from peripheral wards to tertiary hospitals averaged 22 minutes, often compromising time-sensitive cases. The optimized intervention plan reduced this average to 13.7 minutes, reflecting a 38% improvement in emergency response times.

- More importantly, the 90th percentile door-to-door travel time, a measure of worst-case accessibility for underserved populations, improved by 11 minutes.

- This is a significant public health outcome, particularly in flood-prone neighborhoods where delayed care could result in loss of life or worsened medical outcomes. These results underline the life-saving potential of strategic road network interventions that enhance connectivity to emergency care, beyond just everyday commuter efficiency.

Equity outcomes

To assess socio-economic fairness, the Gini coefficient of accessibility was used, comparing hospital reachability across income quartiles.

- Under current conditions, the Gini coefficient stood at 0.41, reflecting high inequality in flood-induced access disruption.
- The best-performing intervention set reduced this to 0.28, indicating a 32% reduction in equity disparity.
- Spatial visualization maps showed that low-income communities in floodplains and sagging terrain gained the most improvement because the model intentionally favored retrofits in these often-neglected areas.
- This suggests that technically sound and fiscally prudent strategies can also be socially progressive, provided that equity is made an explicit optimization objective, not just an incidental outcome.

Robustness under climate escalation

To test long-term viability, all solutions were evaluated under an aggressive +30% escalation in peak hourly rainfall intensity, simulating severe climate change effects.

- Even under these more extreme conditions, the delay savings reduced only slightly by 9%, showcasing the robustness of the chosen interventions.
- The benefit–cost ratio (BCR) of the top-ranked strategy remained above 2.3, demonstrating that even worst-case climate futures still justify the investments made under current projections.
- This resilience under stress highlights the value of diversified intervention portfolios combining structural (kerbs, pavements), mechanical (flood-gates), and operational (adaptive routing) tools—rather than over-reliance on any one single strategy.

CHALLENGES

Data sparsity

Reliable depth encoded flood maps depend on dense sensor grids, yet most Indian cities have less than one ultrasonic or pressure transducer per 5 km of roadway. Traffic–hydrology coupling therefore leans on speed depth curves calibrated from a handful of CCTV clips. During cloudbursts, drivers often stop once water reaches hub height (~300 mm), a threshold that existing curves fitted to light showers underestimate by 25–40 %. Two complementary remedies are now feasible:

- **Crowd sourced probe streams:** Smartphone accelerometers and wheel speed data, passively logged by navigation apps, reveal micro braking events that correlate with puddle depth. When aggregated and anonymise, these "digital potholes" can augment sparse gauge networks at virtually zero hardware cost.
- **Synthetic data augmentation:** Inundation physics can be emulated with agent based simulators that vary car clearance, tyre stiffness, and driver risk scores, generating millions of virtual speed–depth pairs to enrich calibration datasets.

Institutional coordination

Urban flood protection straddles multiple silos. In many municipalities:

- Public Works Departments (PWD) approve kerb raising and pavement contracts.
- Storm Water Cells manage drains, culverts, and pump stations.

Because the two units operate on different fiscal calendars, a pavement may be resurfaced only to have the adjacent drain desilted twelve months later, negating benefits. A pragmatic solution is a Memorandum of Understanding (MoU) that:

1. Sets shared resilience KPIs e.g., maximum 150 mm water depth on arterial links within 30 minutes of peak rainfall.
2. Establishes joint work windows, aligning resurfacing with drain cleaning.
3. Creates a single geospatial work order platform so contractors cannot close a road without both agencies' sign-off.

Such MoUs have trimmed project overruns by up to 18 % in pilot programmes at Surat and Visakhapatnam.

Behavioral uncertainty

Static traffic assignment models treat drivers as rational minimisers of travel time, yet empirical post flood surveys show nearly 60 % of commuters stick to habitual routes even when real time signs offer faster detours. This inertia springs from unfamiliar side streets, fear of getting stranded and social proof (following the car in front).

Mitigation avenues include:

- **Behavioral nudging:** Push alerts that translate depth data into simple messages ("Go left at Ambedkar Junction—8 min quicker, 10 cm shallower") outperform generic "Use alternate route" warnings.
- **Gamified incentives:** Loyalty style points for taking system recommended detours can be redeemed for transit credits or toll rebates, rewarding early adopters and seeding new behavioral norms.
- **Micro-influencer partnerships** – Popular local delivery riders posting live flood-avoidance clips have proven persuasive in Bengaluru, shifting 12 % of peak-hour traffic during pilot weeks.

Maintenance burdens

Porous asphalt's hydraulic efficiency erodes sharply once voids fill with silt and tyre rubber. Laboratory tests show permeability can drop by 70 % after 18 months without vacuum sweeping.

Practical steps to sustain performance:

1. **Quarterly vacuuming regimes:** A midsize ward (≈35 lane-km of porous surfacing) needs one 7 m^3 regenerative air sweeper per quarter at ~₹65,000 per cycle.
2. **Decentralized budget lines** – Rather than rely on city-wide allocations that often lapse, embed O&M funds in each ward's discretionary grants, ring fenced for pavement care.
3. **Skill building workshops** – Local works crews trained in identifying early clogging (surface darkening, audible suction loss) can schedule interventions before porosity collapses.
4. **Performance based contracts** – Tie contractor payments to field measured infiltration rates (e.g., ≥80 mm/hr after two monsoons) instead of lump sum resurfacing fees.

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SCOPE FOR FUTURE WORK

Dynamic adaptation pathways

Embedding the optimization within a real options framework would allow city managers to stage investments, committing low regret actions now while reserving flexibility for high uncertainty futures.

Integration with public transit

Adding bus headway reliability as a fifth criterion could reshape retrofit priorities toward bus corridors, delivering broader climate justice dividends.

Real time control

Coupling the framework with Internet of Things kerb sensors and adaptive signal controllers opens possibilities for on the fly diversion once ponding is detected.

CONCLUSION

Flood proofing urban mobility is no longer a siloed drainage exercise; it demands synthesising hydrology, traffic engineering, cost management, and social equity into a single optimization canvas. The proposed multi criteria, uncertainty aware framework demonstrates that modest, strategically located interventions can deliver outsized resilience dividends, even under aggressive climate change projections. By rendering trade-offs transparent—delay versus cost, equity versus accessibility—our approach equips practitioners to craft politically palatable and technically robust road upgrade programmes that safeguard both journeys and justice in the stormier decades ahead.

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