Real-Time Decision Support for Flood Evacuation: Integrating Network Optimisation and LLM-Based Agents



Research overview

When a flood forces a town to evacuate, the plan prepared in advance begins to age as soon as it is put into action: roads flood, accidents block routes, and drivers do not always go where they are told. Emergency authorities must then revise decisions within minutes, using information that arrives from sensors, flood forecasts and responders in the field. This research brings together operational research and large language models (LLMs) to support these decisions in real time. It develops a decision-support system for flood evacuation in England that combines a network optimisation model, which accounts for road capacity and queues under uncertain flood development, with an LLM-based agent that turns incoming information into structured updates and data-driven strategic recommendations for a human operator to approve. The project aims to contribute to evacuation modelling under uncertainty, to updating evacuation plans quickly while they are being carried out, and to the design of human-in-the-loop AI for emergency management. The methods will be tested in an open simulation environment built on real road, elevation and flood-history data from an English town.

Statement of motivation

My MSc in Business Analytics at the University of Kent (Distinction) and my work building LLM-based agents with human oversight prepare me to pursue this project.

Word count (excluding references): 1,915

Positioning of the research

Flooding poses a substantial risk to communities and transport infrastructure in England. The Environment Agency's 2024 national assessment estimates that about 6.3 million properties are in areas at risk of flooding from rivers, the sea or surface water, and that around 38% of England's road network, by length, is also at risk (Environment Agency, 2024). A flood can therefore threaten both the people who may need to leave and the roads they depend on to do so.

The time available to act can be short. During Storm Desmond in December 2015, the time Cockermouth residents had to take action after a flood warning ranged from about 34 minutes to five hours, depending on their warning area (Environment Agency and Cumbria County Council, 2016). The investigation that followed recommended reviewing "traffic arrangements at pinch points within Cockermouth to ensure residents are able to evacuate safely during a flood event" (ibid., p. 38).

Evacuation plans therefore need to adapt as conditions change. Once an evacuation is under way, a road may become impassable, an alternative route may approach capacity, queues may spread back through junctions, and many vehicles may already be on their way. In England, flood responses use multi-agency strategic and tactical coordination alongside each agency's own command structures, often termed Gold (strategic), Silver (tactical) and Bronze (operational); the police and local authorities manage traffic and the Environment Agency provides flood warnings and information (Cabinet Office, 2013). These bodies must reassess the available road capacity and adjust traffic measures within minutes.

The information behind these decisions arrives in different forms: sensor counts, river levels, flood forecasts and radio reports from officers in the field. ArcGIS Network Analyst supports routing, fleet allocation and analyses using live or historical traffic (Esri, n.d.). This project investigates the additional integration of evolving flood scenarios, queue-aware optimisation, field reports and tested interventions for human review. A recent review of 479 studies on human behaviour in large-scale evacuations calls for models that use real-time data, support human-in-the-loop decision-making and move "beyond prescribing shortest paths" (Moslemi et al., 2027, pp. 43–44).

LLM-based agents can now interpret field reports, call external tools and use several data sources to make recommendations. Open simulation tools make it possible to test those recommendations reproducibly before any operational use.

Research gap and questions

Operational research provides powerful tools for planning emergency evacuations. Bayram and Yaman (2018) develop models for shelter location and evacuation route assignment under uncertainty, while Bayram and Yaman (2024) consider evacuation timing, shelter-in-place decisions and the allocation of traffic-control resources. However, plans developed before an emergency may need substantial revision once conditions begin to change.

During a flood, roads may become impassable, accidents may block junctions, and traffic queues may develop in unexpected locations. Lim, Baharnemati and Kim (2016) investigate real-time evacuation rerouting, while Darvishan and Lim (2021) extend this to multiple road disruptions. Their work demonstrates the importance of updating evacuation decisions quickly, but treats disruptions as known inputs. In reality, the next disruption may still be uncertain. Pre-computed flood scenarios offer a way to anticipate potential road closures before they occur (Environment Agency, 2019). The challenge is to use these forecasts alongside changing traffic conditions without assuming that future flood development is known.

Traffic behaviour adds another difficulty. Drivers may not follow recommended routes, and their collective choices can create bottlenecks even on roads that remain open. Moslemi et al. (2027) highlight the importance of modelling human behaviour and moving beyond shortest-path recommendations. Effective evacuation management therefore requires a network-wide approach that accounts for road capacity, growing queues, uncertain flood conditions and the operational decisions available to emergency authorities.

Making such decisions within minutes also presents a computational challenge. Evacuation studies have investigated dynamic routing and re-optimisation (Shahabi and Wilson, 2018; Darvishan and Lim, 2021). In freight transport, Taherkhani, Hosseini and Hassanzadeh (2025) use a two-stage stochastic model for tactical network design under uncertain shipment demand. Their Benders decomposition algorithm reuses solutions and cuts across replications with different demand samples. This motivates testing whether warm starts and re-optimisation focused on affected parts of the network can deliver timely, high-quality updates to a queue-aware evacuation plan as flood forecasts and traffic conditions change.

A further challenge is turning information into decisions. Flood forecasts and sensor readings arrive in different forms and may be incomplete or conflicting, while trained officers provide field reports following established reporting protocols. Karanjit et al. (2026) investigate integrating human intelligence and AI for flood evacuation decisions, while recent research explores LLM-based agents and optimisation tools (Cercola et al., 2025; Ye et al., 2026). These developments suggest an opportunity to investigate whether an agent can coordinate information gathering, optimisation and simulation to support evacuation decisions. Rather than relying on an LLM to calculate routes or make final decisions, the proposed research examines an agent that identifies emerging problems, constructs and tests alternative interventions in a controlled simulation environment, and presents evidence-based strategic recommendations for human approval.

Central research question:

> How can flood forecasts, dynamic network optimisation and LLM-based agents be integrated to support timely, reliable and human-supervised evacuation decisions as road and traffic conditions change?

RQ1 — Simulation and methodological foundations:

> How can a reproducible flood evacuation testbed be developed to represent changing road conditions and unpredictable traffic behaviour, and which existing optimisation and acceleration methods offer the most promising foundations for rapid network re-optimisation?

RQ2 — Network optimisation and computational efficiency:

> How can a queue-aware network optimisation model be developed and efficiently re-optimised as flood risks, road availability and traffic conditions change, particularly by focusing computation on affected parts of the network?

RQ3 — Agentic decision support and feasibility:

> Can an LLM-based agent, operating with incomplete information and controlled access to optimisation and simulation tools, autonomously investigate emerging network problems, test alternative interventions and provide reliable, timely strategic recommendations for human approval?

Research design and methodology

Chapter 1 develops a reproducible simulation testbed and critically reviews existing methods for fast network re-optimisation (Darvishan and Lim, 2021; Moslemi et al., 2027). The testbed combines an OpenStreetMap-derived road network of Cockermouth with SUMO traffic simulation and pre-computed flood scenarios from an existing LISFLOOD-FP hydraulic model (Alvarez Lopez et al., 2018; Sharifian et al., 2023). The testbed will represent heterogeneous and partially compliant driver behaviour through explicit scenario assumptions and reproducible random seeds, without treating simulated behaviour as a validated account of a real evacuation. Alongside developing the testbed, the chapter reviews heuristic and fast re-optimisation approaches, assessing their reported solution times, solution quality and applicability to the proposed network optimisation problem (Shahabi and Wilson, 2018; Darvishan and Lim, 2021). It also examines the potential of GPU acceleration for solving linear subproblems (Lu and Yang, 2025). The output is a critical review paper identifying promising algorithmic and hardware techniques for development and experimental evaluation in Chapter 2.

Chapter 2 develops a queue-aware, CTM-based network optimisation model and a practical re-optimisation method, building on the findings of Chapter 1 (Ziliaskopoulos, 2000; Darvishan and Lim, 2021). The model is designed to be fast and draws on approaches such as Dynamic CASPER (Shahabi and Wilson, 2018). The chapter investigates whether re-optimisation can be restricted to affected parts of the network, drawing inspiration from dynamic evacuation routing approaches (Shahabi and Wilson, 2018). It evaluates solution time and solution quality. The output is a computational paper.

Chapter 3 designs and evaluates an LLM-based agent for flood evacuation decision support (Cercola et al., 2025). The agent operates within a controlled harness, with access to flood forecasts, traffic data, field reports, the optimisation tools developed in Chapter 2, and a SUMO simulation sandbox. It works with incomplete information, without access to the true flood conditions hidden within the Chapter 1 testbed. When a network problem is detected or an operator reports an incident, the agent identifies the affected areas, generates alternative intervention scenarios, and tests them using optimisation and simulation. It then presents the most promising options, supported by their estimated outcomes, for the human operator to review and approve. The chapter evaluates the feasibility, reliability and response time of this integrated approach under simulated evacuation conditions. The output is a systems/application paper.

Ethical considerations and use of findings

Emergency authorities and Local Resilience Forums in flood-prone regions could use the approach to evaluate evacuation strategies as roads flood, close or become congested. By incorporating local road networks, flood forecasts and traffic data, the approach could be adapted to different regions, subject to local validation.

Environmental agencies and transport planners can use the testbed to investigate how flood conditions, traffic behaviour and operational decisions interact during evacuations.

The research community will benefit from three planned journal papers and openly released simulation tools, code and evaluation methods, where licensing permits.

The testbed uses reproducible random seeds to simulate driver behaviour and synthetic data for field reports. The planned evaluation uses no identifiable data from real participants. Recommendations remain subject to human approval in the testbed, and operational use would require local validation. Findings will be shared through conferences and a policy brief.

Proposed timetable of study

The project will run over three years, with each chapter contributing to the next and producing one planned journal paper.

Period	Planned activities	Milestones
Year 1, Months 1–6	Review fast optimisation methods, heuristics and hardware acceleration techniques. Develop the Cockermouth testbed using OpenStreetMap, SUMO and pre-computed flood scenarios.	Initial testbed and structured literature review
Year 1, Months 7–12	Complete the testbed, critically assess the applicability of existing solution methods and identify promising approaches for Chapter 2.	Review paper submitted (Paper 1)
Year 2, Months 13–18	Develop the queue-aware, CTM-based optimisation model. Implement selected solution methods, including approaches for rapid re-optimisation.	Working optimisation model
Year 2, Months 19–24	Experimentally evaluate solution time, solution quality and scalability. Investigate local re-optimisation and suitable CPU/GPU approaches.	Computational paper submitted (Paper 2)
Year 3, Months 25–30	Develop the LLM-based agent and its controlled harness. Integrate flood and traffic information, optimisation tools and a SUMO sandbox for testing alternative interventions.	Integrated agentic decision-support prototype
Year 3, Months 31–36	Evaluate feasibility, reliability and response time under simulated evacuation conditions. Complete the final paper and dissertation.	Systems/application paper submitted (Paper 3); dissertation submitted

References

Alvarez Lopez, P., Behrisch, M., Bieker-Walz, L., Erdmann, J., Flötteröd, Y.-P., Hilbrich, R., Lücken, L., Rummel, J., Wagner, P. and Wießner, E. (2018) 'Microscopic traffic simulation using SUMO', in 2018 21st International Conference on Intelligent Transportation Systems (ITSC). Maui, HI: IEEE, pp. 2575–2582. https://doi.org/10.1109/ITSC.2018.8569938

Bayram, V. and Yaman, H. (2018) 'Shelter location and evacuation route assignment under uncertainty: A Benders decomposition approach', Transportation Science, 52(2), pp. 416–436. https://doi.org/10.1287/trsc.2017.0762

Bayram, V. and Yaman, H. (2024) 'A joint demand and supply management approach to large scale urban evacuation planning: Evacuate or shelter-in-place, staging and dynamic resource allocation', European Journal of Operational Research, 313(1), pp. 171–191. https://doi.org/10.1016/j.ejor.2023.07.033

Cabinet Office (2013) Emergency Response and Recovery: Non statutory guidance accompanying the Civil Contingencies Act 2004. Version 5, October 2013. London: Cabinet Office. Available at: https://www.gov.uk/government/publications/emergency-response-and-recovery

Cercola, M., Gatti, N., Huertas Leyva, P., Carambia, B. and Formentin, S. (2025) 'Automating the loop in traffic incident management on highway', in Proceedings of the 7th Annual Learning for Dynamics & Control Conference (L4DC). Proceedings of Machine Learning Research, 283, pp. 272–284. Available at: https://proceedings.mlr.press/v283/cercola25a.html

Darvishan, A. and Lim, G.J. (2021) 'Dynamic network flow optimization for real-time evacuation reroute planning under multiple road disruptions', Reliability Engineering & System Safety, 214, 107644. https://doi.org/10.1016/j.ress.2021.107644

Environment Agency (2019) Real-time flood impacts mapping: Technical report SC120023/R1. Authors: Cox, T., Hampson, R., Hooper, R., Hunter, N., Porter, I.-H., Revilla-Romero, B., Stroud, R. and Wylde, R. (JBA Consulting). Bristol: Environment Agency. ISBN 978-1-84911-441-7. Available at: https://www.gov.uk/government/publications/real-time-flood-impacts-mapping

Environment Agency (2024) National assessment of flood and coastal erosion risk in England 2024. Published 17 December 2024 (updated 5 August 2026). Available at: https://www.gov.uk/government/publications/national-assessment-of-flood-and-coastal-erosion-risk-in-england-2024

Environment Agency and Cumbria County Council (2016) Cockermouth Flood Investigation Report: Flood Event 5–6th December 2015. Final version. Section 19 report under the Flood and Water Management Act 2010. Cumbria County Council. Available at: https://www.cumbria.gov.uk/eLibrary/Content/Internet/536/6181/42774103411.pdf

Esri (n.d.) Introduction to the ArcGIS Network Analyst extension. ArcGIS Pro documentation. Redlands, CA: Esri. Available at: https://doc.esri.com/en/arcgis-pro/latest/help/analysis/networks/what-is-network-analyst-.html (Accessed: 28 October 2026).

Karanjit, R., Samadi, V., Hughes, A.L., Murray-Tuite, P. and Stephens, K.K. (2026) 'Converging human intelligence with AI systems to advance flood evacuation decision', Environmental Modelling & Software, 201, 106958. https://doi.org/10.1016/j.envsoft.2026.106958

Lim, G.J., Baharnemati, M.R. and Kim, S.J. (2016) 'An optimization approach for real time evacuation reroute planning', Annals of Operations Research, 238(1–2), pp. 375–388. https://doi.org/10.1007/s10479-015-2072-5

Lu, H. and Yang, J. (2025) 'cuPDLP.jl: A GPU implementation of restarted primal-dual hybrid gradient for linear programming in Julia', Operations Research, 73(6), pp. 3440–3452. https://doi.org/10.1287/opre.2024.1069

Moslemi, S., Arıkanoğlu, A., Bayram, V. and Yıldız, B. (2027) 'Modeling and simulating human behavior in large-scale emergency evacuations: A comprehensive review', Transportation Research Part B: Methodological, 215, 103611. https://doi.org/10.1016/j.trb.2026.103611

Shahabi, K. and Wilson, J.P. (2018) 'Scalable evacuation routing in a dynamic environment', Computers, Environment and Urban Systems, 67, pp. 29–40. https://doi.org/10.1016/j.compenvurbsys.2017.08.011

Sharifian, M.K., Kesserwani, G., Chowdhury, A.A., Neal, J. and Bates, P. (2023) 'LISFLOOD-FP 8.1: New GPU-accelerated solvers for faster fluvial/pluvial flood simulations', Geoscientific Model Development, 16(9), pp. 2391–2413. https://doi.org/10.5194/gmd-16-2391-2023

Taherkhani, G., Hosseini, M. and Hassanzadeh, A. (2025) 'Exact solution method for multi-stakeholder freight transportation systems under uncertainty', Transportation Research Part B: Methodological, 200, 103288. https://doi.org/10.1016/j.trb.2025.103288

Ye, T., Deza, A., Mohan, V., Er Raqabi, E.M. and Van Hentenryck, P. (2026) 'Democratizing large-scale re-optimization with LLM-guided model patches', arXiv preprint, arXiv:2605.18692. https://doi.org/10.48550/arXiv.2605.18692

Ziliaskopoulos, A.K. (2000) 'A linear programming model for the single destination system optimum dynamic traffic assignment problem', Transportation Science, 34(1), pp. 37–49. https://doi.org/10.1287/trsc.34.1.37.12281