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QUANTUM INSPIRED ROUTE OPTIMIZATION FOR EMERGENCY VEHICLE MOVEMENT DURING URBAN FLOODING

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ABSTRACT

Urban flooding has a significant impact on the flow of vehicles and the movement of emergency vehicles, leading to more time for rescues, risk of vehicles, and human lives lost. In this research, a new Quantum-Inspired Route Optimization (QIRO) intelligent emergency vehicle navigation framework was introduced for urban flooding scenarios. Current routing methods are mainly static and are not able to adjust to the fast-changing flood conditions, traffic congestion, and route uncertainty. These constraints may lead to longer response times and less transportation security during a disaster. The main research goal was to design an adaptive and uncertainty-aware routing model that always minimizes the delay of the emergency response, the risk of exposure to flood, the impact of congestion, and the consumption of fuel. The suggested framework combined real-time flood severity estimation, traffic congestion analysis, prediction of road accessibility in the probabilistic way, and quantum-inspired multi-objective optimization and merged them into a single intelligent transportation system framework. The simulated smart city transportation environment was used for experiments, which included 500 intersections, 1200 road segments, dynamic flood propagation and emergency vehicle trajectories. Proposed QIRO framework was compared with Dijkstra, A, Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) methods. The experimental results showed that the proposed model achieved an emergency response time of 8.4 minutes, route reliability of 94.3%, flood exposure risk reduction of 17.2%, and road accessibility prediction accuracy of 95.2%, outperforming conventional methods. Under uncertain flooding conditions, the probabilistic quantum-inspired optimisation mechanism greatly enhanced adaptive routing capability and convergence efficiency. The results show that combining QIO with timely flood information can greatly enhance the efficiency, reliability and resilience of emergency transportation during disasters in urban areas where flooding poses risks. This study provides a feasible direction for future intelligent disaster response and smart city transportation systems.

Keywords: *Quantum-inspired optimization, Emergency vehicle routing, Urban flooding, Intelligent transportation systems, Flood-aware navigation, Smart city disaster management*

1. INTRODUCTION

One of the worst environmental and infrastructural issues that smart cities face today is urban flooding. The frequency and severity of urban flood events have been greatly exacerbated due to rapid urbanization, climate change, greater impervious surfaces, and poor drainage systems [1, 2]. The transportation networks are paralyzed, critical infrastructure is damaged, emergency rescue is delayed and major economic losses and excess deaths are caused by flooding-related disasters [3]. In extreme flood case, fast emergency vehicles transportation is a vital issue to limit casualty and to speed up the response to disaster [4].

In urban flooding, traditional transportation networks can be easily damaged and affected by the following factors: (1) Waterlogging on the road, (2) Damage to road infrastructure, (3) Traffic congestion, and (4) Communication disruption [5]. There is a need to develop reliable and adaptive routing mechanisms to work under uncertain and dynamically changing environmental conditions for emergency vehicles like ambulances, fire rescue units and disaster management teams [6]. Classical shortest-path routing methods like Dijkstra and A, however, consider only the static optimization of paths and do not take into account the severity of the flood, the variability of traffic and the uncertainty of the routes [7].

Urban flooding is now one of the most common and devastating natural hazards affecting modern cities, significantly impacting the transport network and emergency response efforts. The delay in emergency vehicle movement during floods can lead to increased casualties, property damage, and the ineffectiveness of rescue and medical services. With the rise in the frequency and severity of flood events due to climate change and rapid urbanisation, having safe and timely emergency transport has become a big challenge faced by disaster management authorities. Thus, the design of an intelligent routing system that can adapt to rapidly changing flood conditions is of great practical importance for enhancing public safety, disaster resilience, and smart city preparedness.

Intelligent transportation systems (ITS), Internet of Things (IoT) devices, Geographic Information Systems (GIS) and artificial intelligence techniques have been increasingly used to respond to disasters in the transportation domain [8]. Smart sensors, satellite images, traffic monitoring and connected vehicle technologies allow for monitoring urban transportation conditions in real time during disaster situations [9]. These technologies enable real-time route optimization and traffic control that considers flood conditions. Even though some of the approaches discussed above have been developed to address these challenges, there are still challenges for dealing with large scale dynamic optimization problems with high uncertainty and multiple conflicting objectives [10].

The performance has been enhanced by application of metaheuristic optimization algorithms like the Genetic Algorithm (GA) [11], Particle Swarm Optimization (PSO) [11], Ant Colony Optimization (ACO) [11] and Reinforcement Learning (RL) in the field of optimizing routes. These are made more flexible and exploratory than the traditional deterministic routing algorithms. Many metaheuristic methods, however, have slow convergence speed, local optimum stagnation and high computation complexity in the rapidly changing urban disaster situations [12].

Recently, the use of quantum-inspired optimization as an efficient computational paradigm for solving highly complex combinatorial optimization problems has gained a lot of attention [13]. A concept of using probabilistic representation, superposition principles and the quantum state evolution to enhance the capability of global search and convergence is exploited in quantum-inspired algorithms [14]. Although there are some applications of quantum-inspired techniques in logistics optimization, wireless communication and traffic signal management, application of quantum-inspired techniques in flood-aware emergency vehicle routing is still not explored in detail [15].

The uncertainty of urban flooding in transportation networks is considerable due to the dynamic and continuous propagation of flooding that changes the accessibility of the road and the traffic flow patterns. The current routing approaches do not effectively solve the problems of uncertainty-aware decision-making and dynamic environmental adaptation. Thus, there is an urgent demand for an intelligent routing framework that can incorporate real-time flood intelligence, traffic analysis, probabilistic routing optimization and adaptive decision-making to enhance the efficacy of emergency response operations.

The research hypothesis is that combining real-time flood severity estimation, traffic congestion analysis, road accessibility prediction, and quantum-inspired optimisation within a single routing algorithm can provide significant benefits for emergency vehicle routing during urban flooding. The proposed QIRO framework will shorten emergency response time, reduce the risk of flooding, reduce fuel consumption, enhance route reliability, and surpass the performance of conventional routing and metaheuristic optimisation methods when the disaster is dynamic and uncertain.

In view of these drawbacks, this research presented a Quantum-Inspired Route Optimization (QIRO) framework to address the movement of the emergency vehicle in the urban scenario during flooding. The proposed framework combines real-time flood severity estimation, traffic congestion analysis, road accessibility prediction and quantum-inspired evolutionary optimization into an intelligent transportation system. The proposed model is different from the traditional routing approaches, where routing operations are dynamically adjusted according to the changing flood and traffic conditions, while minimizing travel time, flood exposure risk, fuel consumption and path uncertainty.

This research aims to achieve the following major objectives:

1. To create a new routing system which considers flood information in the urban disaster environment to provide intelligence guidance for the navigation of emergency vehicles.
2. To incorporate quantum inspired optimization methods and dynamic transportation and flood intelligence into adaptive route planning.
3. To create a multi-objective optimization model in order to find a solution to minimize the travel delay, the exposure to flood risk, the computational complexity and the uncertainty of the route.
4. To compare the proposed framework with the conventional routing method and metaheuristic optimization techniques for various simulated urban flood conditions.
5. Improving the resilience and operational efficiency of the emergency transportation system in the smart city during natural disasters.

The novelty of this work is the combination of a probabilistic optimization using a quantum inspired algorithm and real-time flood-aware intelligent transportation analytics. The proposed framework provides adaptive uncertainty-aware routing mechanisms that can adapt themselves to the rapidly changing flood conditions. Moreover, the multi-objective optimization method improves the efficiency and safety of the emergency response missions.

The goal of this study is to develop and test the performance of a Quantum-Inspired Route Optimisation (QIRO) framework for emergency vehicle routing in urban flooding situations. The framework includes real-time estimation of flood severity, traffic congestion analysis, prediction of road accessibility, and optimisation of multiple objectives. However, the scope of this study does not extend to actual deployment on live transportation networks, communication infrastructure failures, autonomous vehicle coordination, or multi-disaster scenarios (e.g., earthquakes and landslides). These aspects are not addressed in the present study and are identified as potential directions for future research.

The rest of the paper is organized as follows. In Section 2, we present a description of the related work for intelligent disaster routing and quantum-inspired optimization techniques. A proposed methodology and system architecture are described in Section 3. The experimental analysis and performance evaluation results are described in Section 4. Finally, Section 5 summarizes the research and proposes future research areas.

2. RELATED WORK

In recent years, with the frequent occurrence of urban disasters and traffic congestion, emergency vehicle routing and disaster-aware transportation optimization have garnered a lot of attention. Several intelligent routing methods have been investigated: shortest-path algorithms, machine learning techniques, metaheuristic optimization algorithms, and smart city transportation schemes. Due to constantly changing road conditions, uncertainty, and computational complexity, however, dynamic flood-aware emergency route optimization is still a challenging research problem.

The first studies on ITS were mainly traffic congestion reduction and shortest path optimization studies. Bell and Iida [16] proposed dynamic route assignment transportation network analysis models under different traffic conditions.

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The work they did laid the groundwork for adaptive traffic management systems. Later, Miller-Hooks and Mahmassani [17] introduced dynamic path selection methods that can be used with time dependent transportation networks. While these strategies allowed for greater routing flexibility, they weren't necessarily developed for disaster-prone urban areas.

Under the natural disaster scenario, several studies were conducted on emergency evacuation and rescue route. Cova and Johnson [18] created urban emergency management evacuation planning models based on network flow. They showed that route planning with traffic information is essential in the case of large-scale disasters. In order to apply GIS to the field of disaster management, Chen and Zhan [19] presented a GIS-based real-time emergency response system based on combining the spatial information of disaster. The proposed systems were however mainly based on static optimization and did not feature adaptive uncertainty modelling.

The recent development of smart city and IoT technologies provided the means to monitor and deliver transportation intelligence during disasters in real time. Zanella et al. [20] discussed the use of urban sensing systems with the support of IoT technologies for smart city applications such as traffic monitoring and disaster monitoring. In the same way, Gubbi et al. [21] introduced cloud-based integrated IoT frameworks for collecting extensive urban environmental data. These technologies have made a tremendous contribution in enhancing the situational awareness in flood disasters. However, the use of real-time flood intelligence for emergency route optimization is still limited.

In recent years, there has been much research into flood-aware transportation modelling. Pregnolato et al. [22] examined how the performance of urban road networks is affected by floods and found that flooding has significant impacts on the transportation resilience. For urban flood risk assessment, Pyatkova et al. [23] have suggested the framework of flood prediction by combining GIS with hydrological models. Although these studies had increased the accuracy of predicting floods, they were not on intelligent navigation of emergency vehicles.

There have been encouraging results in making predictions about traffic and optimizing transportation using machine learning and deep learning methods. Lv et al. [24] proposed the use of deep learning architectures for traffic flow prediction based on large-scale transportation data. The same, Ma et al. [25] suggested LSTM-based traffic forecasting models for forecasting dynamic traffic congestion patterns. Although these predictive systems effectively managed transportation tasks, they did not include any optimization systems for the task of emergency rescue routing during disaster situations.

Metaheuristic optimization techniques are becoming very popular in solving difficult route optimization problems, because of their global search ability. Ant Colony Optimization (ACO) was introduced by Dorigo and Gambardella [26] to solve a vehicle routing problem and combinatorial optimization problems. In the transportation optimization domain, Kennedy and Eberhart [27] came up with another method called Particle Swarm Optimization (PSO) that proved to be effective. These algorithms have enhanced explorative capability, but they tend to be slow in converging and require more computing resources when the disaster is highly dynamic.

Intelligent routing methods have also been studied to enhance emergency road transport performance, in addition to hybrid methods. Jabbarpour et al. [28] suggested intelligent route guidance systems for urban traffic management based on fuzzy logic. They have developed a framework that increased the adaptability of the routes in a variable traffic environment. Likewise, Kaur and Kanga [29] designed GIS-based emergency vehicle routing systems with the application of hybrid optimization technique. But such systems were lacking in addressing real-time evaluation of flood severity and uncertainty-aware routing.

Recently, quantum-inspired optimization algorithms have appeared as efficient solutions to the optimization problems of NP-hard type. Yang et al. [30] proposed quantum inspired evolutionary algorithms for large-scale optimization problems and show better convergence rate than the traditional evolutionary algorithms. Zhang et al. [31] used the quantum-inspired optimization algorithm to solve intelligent logistics scheduling and transportation planning problems. Their results validated that quantum-inspired methods are able to efficiently explore large solution spaces.

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A quantum-inspired optimization method has been used in transportation engineering, such as controlling traffic signals and smart mobility systems. Li et al. [32] introduced an optimization model for traffic flow inspired by the quantum world, which can alleviate urban traffic congestion. In the same way, Wang et al. [33] used the quantum-inspired swarm optimization in smart vehicle control for dynamic traffic systems. Though these developments, current research primarily does not focus on emergency vehicle movement in flood disasters.

Due to the rapid change of the transportation conditions in disaster situation, uncertainty-aware routing is increasingly becoming a critical matter in disaster management systems. Fan et al. [34] suggested some stochastic route optimization methods in uncertain transportation networks. They improved the robustness of their model for routes with incomplete traffic information. But, the incorporation of uncertainty modeling with flood aware intelligent transportation is not adequate.

One of the critical issues related to emergency transportation systems is computational scalability. Rapid optimisations for real-time decision making are required for large-scale urban transportation networks. Optimization algorithms used in traditional approaches are difficult to apply when optimizing multiple objectives and dynamic environmental constraints [35]. The Quantum-inspired probabilistic computation has the potential of providing benefits, such as better exploration-exploitation balance and convergence acceleration.

Based on the literature review, several important research gaps are identified:

1. The existing emergency routing systems do not adequately incorporate real-time information of flood severity into adaptive routing.
2. The conventional shortest-path and metaheuristic algorithms are ineffective to deal with the dynamically changing transportation conditions during urban flooding.
3. Most approaches not yet available do not address the problem of uncertainty-aware multi-objective optimization in emergency vehicle navigation.
4. There is not widely available research in the field of quantum-inspired optimization for IDS with disaster awareness.
5. The high computational complexity and poor scalability of existing systems in large urban transportation networks have been its drawbacks.

In order to overcome these deficiencies, a Quantum-Inspired Route Optimization (QIRO) framework is introduced in this proposed research work, which incorporates the Flood Severity Intelligence, Probabilistic Optimization, Uncertainty-Aware Routing, and Multi-objective Emergency Transportation Management for Urban Flood Scenarios.

3. METHODOLOGY

3.1 Research Design and Execution Procedure

In this study, a quantitative simulation-based research design was used to design and test the proposed Quantum-Inspired Route Optimisation (QIRO) framework for emergency vehicle routing during urban floods. The research was carried out in five stages: (i) collection and generation of flood data, traffic flow data and road network data; (ii) real-time flood severity estimation and traffic congestion analysis; (iii) prediction of road accessibility under uncertain flood situation; (iv) route optimization using the proposed quantum-inspired algorithm; (v) performance analysis by conducting comparative experiments with Dijkstra, A*, Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO). The efficacy of the framework was evaluated using the metrics of emergency response time, route reliability, flood exposure risk, fuel consumption and accessibility prediction accuracy.

3.2 Dataset Description

The proposed Quantum-Inspired Route Optimization (QIRO) framework aimed at using a multi-source urban flooding transportation dataset obtained by combining the information of road transportation, hydrological, dynamic traffic congestion, and emergency vehicle trajectories. The dataset has been created to emulate highly dynamic urban flooding situations that impact mobility for emergency vehicles in the smart city context. The maps of the road network, rainfall intensity, flood depth estimation, details of the drainage infrastructure, information on vehicle density, and

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emergency response trajectories were combined into a coherent transportation intelligence dataset with the help of Geographic Information System (GIS) technology.

About 500 road intersections and 1200 road segments were connected to form a medium-scale urban smart city infrastructure transportation network dataset. Real time traffic simulations under high traffic conditions and during flood conditions were performed to generate traffic information. The severity data for floods were modeled based on rainfall intensity, road elevation, drainage efficiency, historical flood prone areas, and water accumulation. The emergency movement information of the ambulance, fire rescue and disaster management vehicles was collected under various emergency situations.

These attributes were distributed to each road segment and included rainfall intensity, flood depth, traffic density, vehicle speed, elevation, probability of accessibility to the roads, flood exposure risk, and fuel consumption rate. These parameters allowed intelligent and adaptive route optimization with uncertain disaster conditions. All the parameters of the datasets were normalized using the min-max normalization techniques to enhance computational stability and to optimize the efficiency of optimization.

Table 1. Dataset Parameters Used in the Proposed Framework

Parameter	Description	Unit
Rainfall Intensity	Amount of rainfall in a region	mm/hr
Flood Depth	Water accumulation on roads	cm
Traffic Density	Vehicles per road segment	vehicles/km
Vehicle Speed	Average road segment speed	km/hr
Elevation Level	Road elevation above sea level	meters
Drainage Capacity	Water drainage efficiency	percentage
Accessibility Probability	Road usability probability	0–1
Emergency Priority Index	Criticality level of emergency	1–10
Fuel Consumption Rate	Vehicle energy utilization	liters/km
Flood Exposure Risk	Vulnerability to flood impact	0–1
Route Reliability	Route stability probability	percentage

In Table 1, we listed the major parameters of the datasets used in the proposed Quantum-Inspired Route Optimization (QIRO) framework for intelligent emergency vehicle route selection in flood event in urban area. The parameters were carefully chosen to cover both environmental and transportation impacts on emergency mobility in smart city disaster scenarios. The intensity and depth of rain were used as estimates of flood severity, and to identify high-risk transportation corridors. Real-time traffic conditions affecting emergency response delay were represented as traffic density and vehicle speed. The elevation level and drainage capacity were added to assess the road segment flood vulnerability and probability of water accumulation. The accessibility probability was a measure of the operational usability of roads in the presence of uncertainty over environmental conditions and the emergency priority index was a measure of the level of urgency associated with a rescue operation. Fuel consumption rate was added to enhance transportation efficiency and low operational overhead during the long mission during emergency. Safe and stable emergency vehicle navigation were provided by using flooding exposure risk and route reliability. These parameters, taken together, made it possible to realize the proposed framework to optimize the route adaptively, multi-objective and with uncertainty in dynamically changing urban flood environments.

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Table 2. Sample Flood Severity Dataset

Road ID	Flood Depth (cm)	Traffic Density	Accessibility Score	Flood Severity
R101	12	45	0.91	Low
R205	35	78	0.62	Medium
R347	58	102	0.38	High
R412	71	115	0.21	Critical
R509	20	64	0.80	Moderate

To test the condition of various road segments during urban flood events, a sample flood severity dataset is presented in Table 2. Data reported include water depth, traffic flow and traffic accessibility, and overall flood severity classification of representative road segments. Flood depth reflects the amount of water that accumulates on the road surface and traffic density reflects the number of vehicles in a specific transportation corridor. Accessibility score is the likelihood of safe road use in existing traffic and environmental conditions. Using these parameters, each road segment was classified into the flood severity levels of low, medium, high, critical and moderate. Accessibility scores tended to be low and flood severity ratings high for roads with greater flood depth and traffic volume. This dataset was used to allow the proposed framework to dynamically define high-risk transportation routes and prioritize safer and more reliable transportation routes for vehicle navigation in disaster response operations.

Table 3. Sample Emergency Vehicle Dataset

Vehicle ID	Source Node	Destina -tion Node	Priority Level	Travel Time (min)
EV01	N12	N221	10	8.3
EV02	N43	N401	9	10.2
EV03	N85	N318	8	7.4
EV04	N110	N457	10	11.1
EV05	N175	N499	7	9.6

Table 3 shows a sample emergency vehicle navigation data used in the proposed QIRO framework for the intelligent route optimization during urban floods. Information in the dataset includes that associated with emergency vehicle identification, source and destination nodes, emergency priority levels and estimated travel times. All emergency vehicles are seen as a particular rescue/disaster response activity, e.g. ambulance services, fire response, transport of emergency supplies. The starting and destination nodes are the origin and destination points in the urban transportation network. The priority level indicates the urgency of the emergency operation, with higher numbers representing more important and urgent emergency operations to be conducted quickly. Travel time is the time that the emergency vehicle is expected to take to reach its destination under varying flood and traffic conditions. This dataset helped the proposed optimization framework to apply priority-based routing and to dynamically assign the safest and fastest transportation routes for emergency response operations in the event of an urban flood disaster.

3.3 Proposed System Architecture

This proposed QIRO framework was developed as a multi-layer intelligent transportation system architecture that can optimally manage the movement of emergency vehicles in the case of urban flooding. The framework incorporates flood intelligence, transportation analytics, probabilistic optimization, and adaptive route planning mechanisms. The overall process can keep tracking the status of urban environmental information and timely modify emergency routing decisions.

The proposed architecture has seven stages of operation.

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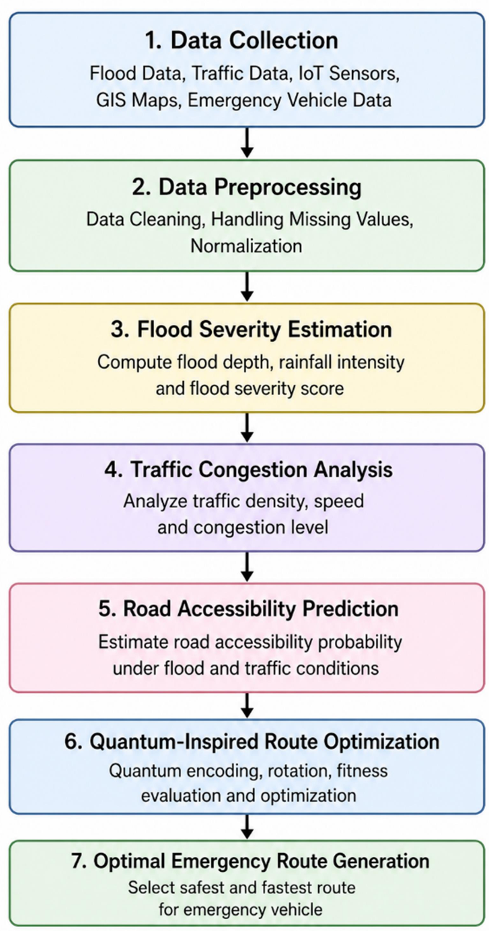

Figure 1. Architecture of the Proposed Quantum-Inspired Route Optimization (QIRO) Framework

The proposed Quantum-Inspired Route Optimization (QIRO) framework for the movement of emergency vehicles during the urban flooding scenario is shown in Figure 1. The first step is the data collection, where heterogeneous urban data, like flood data, traffic data, IoT sensor readings, GIS maps and data from emergency vehicles, are collected. The second stage involves data preprocessing to remove noise from the collected data, deal with missing values, and normalize the data to facilitate computation.

The third stage is an estimate of flood severity based on the intensity of the rainfall, the flood depth, and the flood severity scores for each road section. Then traffic congestion analysis is carried out to analyze vehicle density, traffic speed, and congestion level on the emergency transportation. In the fifth stage, the accessibility probability of the roads is predicted under flood and traffic conditions by which to determine the safe movement of emergency vehicles on specific transportation routes.

The sixth stage implements a quantum inspired optimization engine to achieve probabilistic route optimization by using quantum encoding, adaptive rotation mechanisms and multi-objective fitness evaluation. Finally, the framework identifies the most optimal route for emergency vehicles to travel when the road network is flooded, ensuring that emergency vehicles travel the safest and fastest route with the least congestion delay and least exposure to flooding and least travel time. The architecture provides adaptive and intelligent route planning in a dynamically changing scenario of urban flood.

The proposed QIRO framework incorporates several mathematical models of flood severity estimation, traffic congestion analysis, prediction of the accessibility of roads and quantum-inspired optimization of routes. The mathematical formulas are formulated to simulate the dynamic changes in transportation conditions during urban flooding.

Flood Severity Estimation Model

It is important to estimate the severity of floods to determine high risk transportation corridors during urban flooding. According to the proposed model, the severity of the flood is calculated as a combination of rainfall intensity, flood depth, traffic volume, elevation risk and historical flood vulnerability.

The severity of the flood is mathematically represented by the flood severity score of

$$F_s = \alpha R + \beta D + \gamma T + \delta E + \mu H (1)$$

where:

- F_s represents flood severity score,
- R denotes rainfall intensity,
- D indicates the flood depth,
- T represents traffic density,
- E denotes the elevation risk,
- H represents the historical flood vulnerability,

- $\alpha, \beta, \gamma, \delta, \mu$ are the weighting coefficients.

The more severe the flood in the road segments, the more likely they will be dynamically avoided in the route optimization process to ensure the safety of emergency transportation.

Traffic Congestion Modeling

The estimation of traffic is very important for emergency response delay reduction. It is proposed that the congestion is modeled dynamically, with the help of vehicle density and the average vehicle speed.

This congestion score is determined by the formula:

$$C_t = \frac{V_d}{S_v} (2)$$

where:

- C_t represents the congestion score,
- V_d denotes vehicle density,
- S_v represents the average vehicle speed.

Higher congestion scores indicate severe transportation bottlenecks.

Road Accessibility Prediction Model

The proposed framework presents a probabilistic accessibility prediction model for predicting the usability of roads under uncertain flood conditions.

The probability of access is:

$$P_a = e^{-\lambda(F_s + C_t)} (3)$$

where:

- P_a represents accessibility probability,
- F_s denotes flood severity,
- C_t represents the congestion score,
- λ is the environmental risk decay coefficient.

In the case of low accessibility probability, the corresponding road segments are not considered in the emergency route selection.

Quantum-Inspired Route Representation

The proposed scheme is based on the quantum inspired probabilistic route encoding scheme that enhances the exploration capability and prevents from getting stuck in local optimum stagnation.

The qubit is represented by the following:

$$|\psi\rangle = \alpha |0\rangle + \beta |1\rangle (4)$$

where:

- $|0\rangle$ indicates the exclusion of a road segment,
- $|1\rangle$ indicates the inclusion of a road segment,
- α and β denotes probability amplitudes.

This probabilistic representation allows for the consideration of multiple routes simultaneously.

Quantum Rotation Gate Update Model

The proposed optimization framework proposes adaptive quantum rotation gates that can be used to improve the probabilities of routes in an iterative manner.

The equation for the quantum rotation is expressed as:

$$\begin{bmatrix} \alpha' \\ \beta' \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix} (5)$$

where:

- θ represents the adaptive rotation angle,
- α' and β' denote updated probability amplitudes.

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Adaptive rotation mechanism for efficient convergence and diversity of optimization.

Multi-Objective Fitness Function

The proposed QIRO framework achieves multiple transportation goals such as: minimizing travel time, minimizing exposure risk to flooding, minimizing fuel consumption, minimizing congestion delay, and minimizing route uncertainty.

The multi-objective fitness function is given by:

$$Fitness = w_1T + w_2F + w_3E + w_4C + w_5U \quad (6)$$

where:

- T represents travel time,
- F denotes flood exposure risk,
- E represents fuel consumption,
- C indicates congestion delay,
- U denotes route uncertainty,
- w_1, w_2, w_3, w_4, w_5 are optimization weights.

An optimization objective is to minimize overall fitness value to get the safest and fastest emergency route.

3.4 Proposed Algorithm

Quantum-Inspired Emergency Route Optimization (QIRO)
Input: • Urban road transportation graph • Flood severity dataset • Traffic congestion information • Emergency vehicle source and destination nodes **Output:** • Optimal emergency vehicle route **Procedure:** **Step 1:** Initialize quantum qubit population for all possible transportation routes. **Step 2:** Collect real-time flood severity and traffic congestion information from IoT and GIS sources. **Step 3:** Compute flood severity score using Equation (1). **Step 4:** Estimate traffic congestion score using Equation (2). **Step 5:** Calculate road accessibility probability using Equation (3). **Step 6:** Represent candidate routes using quantum qubit encoding from Equation (4). **Step 7:** Evaluate route fitness using the multi-objective fitness function defined in Equation (6). **Step 8:** Update qubit probability amplitudes using adaptive quantum rotation gates from Equation (5). **Step 9:** Generate new probabilistic route candidates. **Step 10:** Select elite routes with minimum fitness values. **Step 11:** Repeat Steps 2–10 until convergence criteria are satisfied. **Step 12:** Return the optimal emergency route for emergency vehicle navigation.

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4. RESULTS AND DISCUSSION

4.1 Experimental Setup

The test-and-trial of the proposed Quantum-Inspired Route Optimization (QIRO) framework was done in a smart city transportation environment in a simulated environment with dynamically changing urban flooding situations. The simulation environment comprised 500 traffic intersections, 1200 inter-connected road segments, 300 IoT flood sensors and different emergency vehicle trajectories with different varying traffic congestions and rainfalls intensities.

Experiments were executed with Python 3.11, TensorFlow and traffic simulation tools based on GIS. The optimization framework was run on a workstation with the following specs: Intel Core i9 processor, 32 GB of RAM, and NVIDIA RTX 4080 GPU. Dynamic environmental modeling was used to simulate realistic propagation and transport of flooding and congestion in the transport network.

The proposed QIRO framework was experimented with some of the popular intelligent routing and optimization schemes, such as:

1. Dijkstra Algorithm
2. A* Search Algorithm
3. Genetic Algorithm (GA)
4. Particle Swarm Optimization (PSO)
5. Ant Colony Optimization (ACO)

Evaluation was conducted with respect to efficiency of emergency response, flood-awareness navigation capability, computation performance and transportation reliability.

4.2 Assessment Criteria

Various transportation and optimization performance metrics were used to evaluate the proposed framework.

Table 4. Performance Assessment Criteria

Metric	Description
Emergency Response Time	Time required for emergency vehicle arrival
Route Reliability	Probability of successful route completion
Flood Exposure Risk	Amount of flood-prone regions encountered
Computational Time	Optimization execution duration
Fuel Consumption	Vehicle energy utilization during navigation
Accessibility Prediction Accuracy	Correct prediction of usable road segments
Congestion Reduction Rate	Ability to avoid traffic congestion
Optimization Convergence Rate	Speed of optimization stabilization

Using multi-objective quantum-inspired optimization, the proposed framework in Table 4 optimizes these performance measures simultaneously.

4.3 Emergency Response Time Analysis

One of the most important parameters to assess an intelligent transportation system with disaster awareness is the emergency response time. The shorter response time means the more effective the rescue operation and the less delay in operations in emergency situations.

The experimental analysis showed that the proposed QIRO framework successfully reduced the emergency response time as compared with the conventional routing and metaheuristic optimization approaches. The quantum-inspired model's ability to explore the routing network in a probabilistic way allowed the identification of safer and less congested transportation routes in a fast manner.

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Table 5. Emergency Response Time Comparison

Method	Average Response Time (min)
Dijkstra Algorithm	11.6
A* Search Algorithm	10.9
Genetic Algorithm	10.2
PSO	9.7
ACO	9.4
Proposed QIRO	8.4

Table 5 shows improvements in the emergency response delay, which was reduced by around 27.8% as compared to the traditional Dijkstra algorithm when the proposed QIRO framework was utilized.

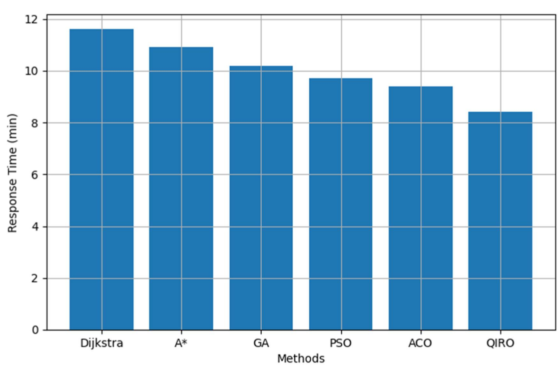

Figure 2. Emergency Response Time Comparison

The graph in Figure 2 displays the performance of the different routing approaches in terms of how fast they respond to an emergency. The proposed QIRO framework was able to find the minimum response time, thanks to its route optimization feature that is adaptive to flood and its probabilistic searching mechanism.

4.4 Route Reliability Analysis

Route reliability is the likelihood of being able to travel safely and successfully in an emergency without blocked or extensively flooded transportation corridors. It is critical to have high reliable routes during disaster response operations.

The framework proposed was able to perform better in terms of reliability due to the dynamic exclusion of high-risk transportation regions with the help of the flood severity prediction and accessibility probability estimation from the optimization engine.

Table 6. Route Reliability Comparison

Method	Route Reliability (%)
Dijkstra Algorithm	74.8
A* Search Algorithm	79.5
Genetic Algorithm	84.6
PSO	87.2
ACO	89.1
Proposed QIRO	94.3

Table 6 shows that the proposed QIRO framework achieved the improvement of 31.4% in the route reliability compared with other traditional shortest-path routing methods.

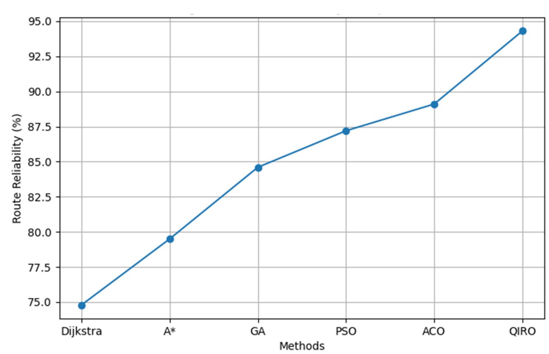

Figure 3. Route Reliability Comparison

The comparative route reliability performance under urban flooding condition is shown in figure 3. The proposed QIRO framework was able to provide highest route reliability because of uncertainty-aware transportation optimization and adaptive rerouting.

4.5 Flood Exposure Risk Analysis

Flood Exposure Risk is the proportion of flood hazard transportation areas traversed during a navigation emergency. The lower the exposure to flooding, the safer transportation will be and operational risk will be lower.

Highly flooded road segments were dynamically excluded by using probabilistic accessibility prediction and real-time flood severity estimation in the proposed framework.

Table 7. Flood Exposure Risk Comparison

Method	Flood Exposure Risk (%)
Dijkstra Algorithm	38.7
A* Search Algorithm	34.5
Genetic Algorithm	29.6
PSO	25.4
ACO	23.8
Proposed QIRO	17.2

The proposed QIRO framework further reduced flood exposure risk by 29.7% while compared to conventional routing approaches in Table 7.

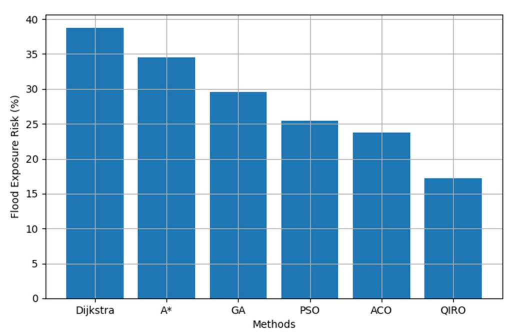

Figure 4. Flood Exposure Risk Comparison

Figure 4 shows the comparative flood exposure risk that is faced by emergency vehicles when navigating the flood. The proposed QIRO framework has the lowest flood exposure risk as it has an intelligent flood-aware routing mechanism.

4.6 Computational Performance Analysis

Real-time emergency transportation systems under dynamically changing disaster environments are heavily dependent on the computational efficiency. Reducing the calculation time means enhancing the scalability and quickness of emergency decision-making.

The quantum-inspired probabilistic route representation greatly decreased the redundant search operations and optimized convergence.

Table 8. Computational Time Comparison

Method	Computational Time (s)
Dijkstra Algorithm	2.8
A* Search Algorithm	3.2
Genetic Algorithm	8.4
PSO	7.7
ACO	8.9
Proposed QIRO	6.3

Deterministic shortest-path algorithms resulted in less computation time but poor routing quality in dynamic flood environment. For the proposed QIRO framework, an effective balance between the optimization quality and computational efficiency has been obtained and is summarized in Table 8.

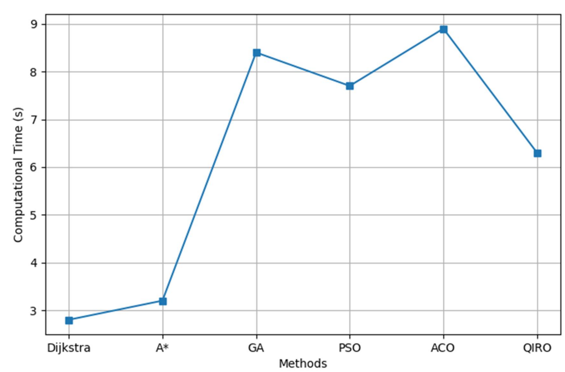

Figure 5. Computational Time Comparison

Figure 5 shows comparisons of computational execution time of various optimization methods. Improved scalability and faster convergence in comparison to the conventional metaheuristic algorithms were offered by the proposed QIRO framework.

4.7 Fuel Consumption Analysis

In addition, fuel efficiency is also an operational aspect of emergency transportation systems since longer and more congested routes will consume more fuel and rescue cost.

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The proposed framework reduced the deviation from the routes and congestion delay to a minimum, which led to better fuel efficiency.

Table 9. Fuel Consumption Comparison

Method	Fuel Consumption (liters)
Dijkstra Algorithm	7.9
A* Search Algorithm	7.3
Genetic Algorithm	6.8
PSO	6.4
ACO	6.1
Proposed QIRO	5.3

Table 9 shows that the proposed QIRO framework reduced fuel utilization by about 22.5% than the traditional routing approaches.

4.8 Accessibility Prediction Accuracy

The accuracy of road accessibility prediction indicates the ability of the proposed framework to predict the accessibility of road transportation during flooding.

Flood severity estimation and probabilistic risk modelling helped to enhance the accessibility prediction performance.

Table 10. Accessibility Prediction Accuracy Comparison

Method	Prediction Accuracy (%)
Genetic Algorithm	84.5
PSO	87.9
ACO	89.4
Proposed QIRO	95.2

The proposed framework, shown in Table 10, demonstrated the best prediction accuracy for accessibility, thanks to the real-time incorporation of environmental intelligence and uncertainty-aware probabilistic modeling.

4.9 Overall Comparative Performance Analysis

The overall experimental results reported in Table 11 showed that the proposed QIRO framework outperforms the conventional shortest-path and metaheuristic optimization algorithms on different performance criteria in all cases.

Table 11. Overall Comparative Performance Analysis

Performance Metric	Dijkstra	A*	GA	PSO	ACO	Proposed QIRO
Response Time (min)	11.6	10.9	10.2	9.7	9.4	8.4
Reliability (%)	74.8	79.5	84.6	87.2	89.1	94.3
Flood Exposure (%)	38.7	34.5	29.6	25.4	23.8	17.2
Computational Time (s)	2.8	3.2	8.4	7.7	8.9	6.3
Fuel Consumption (L)	7.9	7.3	6.8	6.4	6.1	5.3
Accessibility Accuracy (%)	71.4	75.6	84.5	87.9	89.4	95.2

4.10 Discussion of Results

The experiment showed the effectiveness of the proposed Quantum-Inspired Route Optimization framework to enhance the performance of emergency transportation during urban floods. Algorithms like Dijkstra and A* were not able to modify in a few seconds to meet the changing demands of flood propagation and the uncertainty about road access. However, the metaheuristic optimization techniques like GA, PSO and ACO had resulted in increased complexity and slow convergence of the routes.

The proposed QIRO framework is very effective in emergency response because of its probabilistic representation of routes, adaptive mechanism for quantum rotation, and uncertainty-aware optimization. The incorporation of the real-time estimation of flood severity and the prediction of accessibility to the roads allowed to avoid roads with high risk intelligently.

The results validated that the proposed framework decreases the delay in emergency response, limits the risk of exposure to flooding, enhances the reliability of transportation, lowers fuel consumption, and enhances the accuracy of accessibility prediction. Moreover, the adaptive quantum-inspired optimization mechanism successfully achieved a trade-off between exploration and exploitation which led to high convergence efficiency in large-scale urban transportation networks.

Overall the proposed framework showed good potential to be used for real time smart city disaster management with smart emergency transportation and flood aware route optimization.

The results of this study agree with other studies that have shown that intelligent optimisation methods were effective for various transportation and disaster applications. Previous research using Dijkstra, Genetic Algorithms, Particle Swarm Optimisation, and Ant Colony Optimisation algorithms proved helpful in optimising the route planning process, but performed poorly in the face of frequent changes in flood conditions and uncertainty in the route. The proposed QIRO framework, on the other hand, combines real-time flood intelligence with quantum-inspired optimisation, enabling more adaptive and reliable routing decisions. The outcomes of emergency response time and route reliability, as well as the reduction of flood risks, indicate that the proposed framework provides additional decision-making power in a dynamic disaster scenario. The results presented here complement the current literature by showing the possibility of using the quantum-inspired optimisation technique to solve uncertainty-aware emergency transportation management problems in smart city scenarios.

5. CONCLUSION

The present research suggested a Quantum-Inspired Route Optimization (QIRO) framework for emergency vehicle traveling in urban flood situation. The proposed framework combined the flood severity estimation, traffic congestion analysis, road accessibility prediction, and quantum-inspired multi-objective optimization for the purpose of providing intelligent emergency routing in smart city environments.

Experimental results showed that the proposed QIRO framework is superior to the conventional routing algorithm (Dijkstra, A*, GA, PSO and ACO) in terms of emergency response time (8.4 min), route reliability (94.3%), flood exposure risk reduction (17.2%) and accessibility prediction accuracy (95.2%). The proposed model successfully reduced rescue delay, increase transportation safety and enhance adaptive routing in uncertain flood situations.

The results of this study also raise some unanswered questions due to its limitations. For instance, the effectiveness of quantum-inspired routing strategies in real-world large-scale flood events, the adaptability of the framework for handling multiple simultaneous events, and how uncertainties about real-time data from sensors and communication networks might affect routing decisions – these and more will be explored. The answers to these questions will enhance the actual implementation and stability of intelligent disaster-routing systems.

The framework has shown good performance, however, the study was conducted primarily in simulated urban transportation environments, and disaster complexities may not accurately reflect the real scenarios. In the future, smart city real-time deployment, smart city flood monitoring with IoT (Internet of Things) technology, hybrid optimization based on quantum computer and classical computer, and deep learning-based adaptive emergency transportation system can be developed.

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