Financial risk & customs control in humanitarian water logistics: a machine learning approach*

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Abstract

This study explores the application of machine learning to mitigate financial and regulatory risks in humanitarian water logistics. Through the WaterWayfinder mobile platform, aid coordinators in Ukraine's Kherson and Zaporizhzhia regions achieved measurable gains in operational efficiency and compliance. AI-driven route optimization reduced delivery times by up to 32% and fuel costs by 22%, while predictive modeling improved resource allocation and reduced exposure to high-cost disruptions. The system's customs control module enabled pre-clearance planning and real-time regulatory updates, shortening border processing times by an average of 2.5 hours per shipment. Despite connectivity and data challenges, WaterWayfinder demonstrated resilience and adaptability in conflict-affected environments. Its modular architecture, offline capabilities, and integration with geospatial intelligence position it for broader deployment across crisis zones. The findings highlight WaterWayfinder's potential as a scalable, data-driven framework for intelligent humanitarian logistics, aligning with global efforts to enhance transparency, agility, and cross-border coordination in aid delivery.

Keywords

machine learning; financial risk; customs control; WaterWayfinder; GIS; mobile application.[1]

1. Introduction

Access to clean and safe water is a fundamental human right and a cornerstone of sustainable development. Yet, as of 2025, an estimated 2.2 billion people globally lack safely managed drinking water, while 3.5 billion remain without adequate sanitation services [1] [2]. These case underscore a persistent and urgent global crisis, disproportionately affecting vulnerable populations in conflict zones, remote regions, and areas with fragile infrastructure.

In Ukraine, the ongoing war has exacerbated water insecurity, particularly in regions impacted by displacement, occupation, and environmental devastation. The destruction of the Kakhovka Dam in June 2023 triggered one of Europe's most severe man-made environmental disasters since World War II [3]. The collapse drained a reservoir containing 18 cubic kilometers of water, disrupting drinking water, irrigation, and industrial supply across southern Ukraine.

Over 700,000 people lost access to potable water, and more than 584,000 hectares of farmland were left without irrigation [4]. The breach contaminated water sources with chemicals and sewage, displaced thousands, and left over 80 settlements in crisis [5].

Figure 1 illustrates the multifaceted impact of the Kakhovka Dam explosion. Subfigure (a) captures the immediate aftermath of the hydroelectric power station's destruction, highlighting the structural devastation [3]. Subfigure (b) presents satellite imagery of the drained reservoir and the widespread flooding of agricultural land [4]. Subfigure (c) visualizes the disruption of water supply for over 700,000 residents, emphasizing the scale of humanitarian need [5].

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(a)

The Kakhovka hydroelectric power station
explosion: structural devastation and immediate aftermath [3]

(b)

Destruction of the Kakhovka hydroelectric power station: draining of an 18 km³ reservoir and flooding of 584,000 hectares of farmland [4]

(c)

Kakhovka Dam explosion: disruption of potable water supply for over 700,000 people [5]

Figure 1: Impact of the Kakhovka Dam explosion on southern Ukraine's water infrastructure and environment.

Humanitarian water logistics in such contexts are fraught with complexity. Aid delivery is hindered by damaged infrastructure, limited mobility, and volatile security conditions. Moreover, customs control and regulatory bottlenecks at borders and checkpoints introduce financial risks and delays, threatening the timeliness and effectiveness of relief efforts. Traditional logistics models often fail to adapt to the dynamic and fragmented nature of crisis environments.

This study explores how machine learning and digital tools can mitigate financial and customs risks in humanitarian water logistics. It introduces WaterWayfinder - a mobile application designed to assess, visualize, and respond to freshwater needs in underserved regions. By integrating real-time data collection, geospatial analysis, and AI-powered logistics planning, WaterWayfinder offers a scalable solution for optimizing aid delivery in conflict-affected and hard-to-reach areas. The research evaluates the app's architecture, pilot deployment in Ukraine, and its potential to transform humanitarian logistics through intelligent, adaptive systems.

2. Literature review

Recent advances in machine learning (ML) have significantly reshaped logistics, risk management, and humanitarian operations. This literature review synthesizes key contributions across transport optimization, financial risk mitigation, supply chain resilience, and water infrastructure intelligence, forming the foundation for the WaterWayfinder framework.

Karkouri et al. [6] demonstrated the effectiveness of ML in optimizing road transport routes, particularly in transnational corridors such as Dakhla-Paris. Their study highlights how predictive modeling and real-time data integration can reduce fuel costs, improve delivery timelines, and adapt to dynamic geopolitical conditions - principles directly applicable to humanitarian water logistics in conflict zones.

Huang [7] explored ML applications for financial risk management in non-profit organizations, emphasizing anomaly detection, fraud prevention, and budget forecasting. These insights are critical for humanitarian actors operating under volatile funding and regulatory environments. Similarly, Hongjin [8] integrated IoT and ML to identify risk factors in financial supply chains, offering a framework for early warning systems and adaptive financial controls.

Van Twiller et al. [9] applied deep reinforcement learning to master stowage planning, optimizing cargo placement and resource utilization. Their approach informs the design of intelligent aid distribution systems, where space, weight, and urgency must be balanced under logistical constraints. Pons-Ausina et al. [10] presented an AI-driven water management system in Georgia, showcasing how ML can enhance water quality monitoring, infrastructure integrity, and service delivery in underserved regions. García et al. [20] extended this by using natural language processing to review ML applications in water infrastructure, reinforcing the relevance of intelligent systems for humanitarian water logistics. Wang, Sua, and Alidaee [11][13] emphasized automated ML for supply chain security, identifying vulnerabilities and enhancing resilience. Jin [14] and Jahin et al. [12] provided systematic reviews and bibliometric analyses of ML in supply chain risk assessment, underscoring the growing maturity of these technologies in operational contexts. Pasupuleti et al. [15] examined ML techniques for improving supply chain agility and sustainability, including inventory optimization and adaptive routing. Dumanska et al. [16][17] contributed region-specific insights into digital logistics infrastructure and volunteer coordination under military conflict, directly informing the customs control and visualization modules of WaterWayfinder. Aljohani [18] and Wang et al. [19] explored predictive analytics for real-time risk mitigation, integrating economic and behavioral data to forecast disruptions. Murphy et al. [21] investigated ML's role in violent conflict forecasting, offering tools to anticipate humanitarian needs and adjust logistics accordingly.

This body of work collectively supports the integration of ML into humanitarian water logistics, particularly in contexts where financial risk, customs control, and infrastructure fragility intersect. The WaterWayfinder system builds upon these foundations to deliver adaptive, data-driven solutions for crisis-affected populations.

3. Methodology

This section outlines the system architecture (1), technological components (2), and analytical frameworks (3) that support the WaterWayfinder mobile application. Designed to address the operational challenges of humanitarian water logistics in conflict-affected and underserved regions, the system integrates machine learning (ML), geospatial intelligence, and adaptive planning to enhance decision-making and delivery efficiency.

3.1 System architecture

WaterWayfinder is composed of five interdependent modules, each tailored to a specific function within the humanitarian logistics pipeline. Together, they enable real-time assessment, prioritization, and distribution of freshwater aid. The system's modular and scalable architecture supports deployment across diverse geopolitical contexts and operational environments, as illustrated in Figure 2.

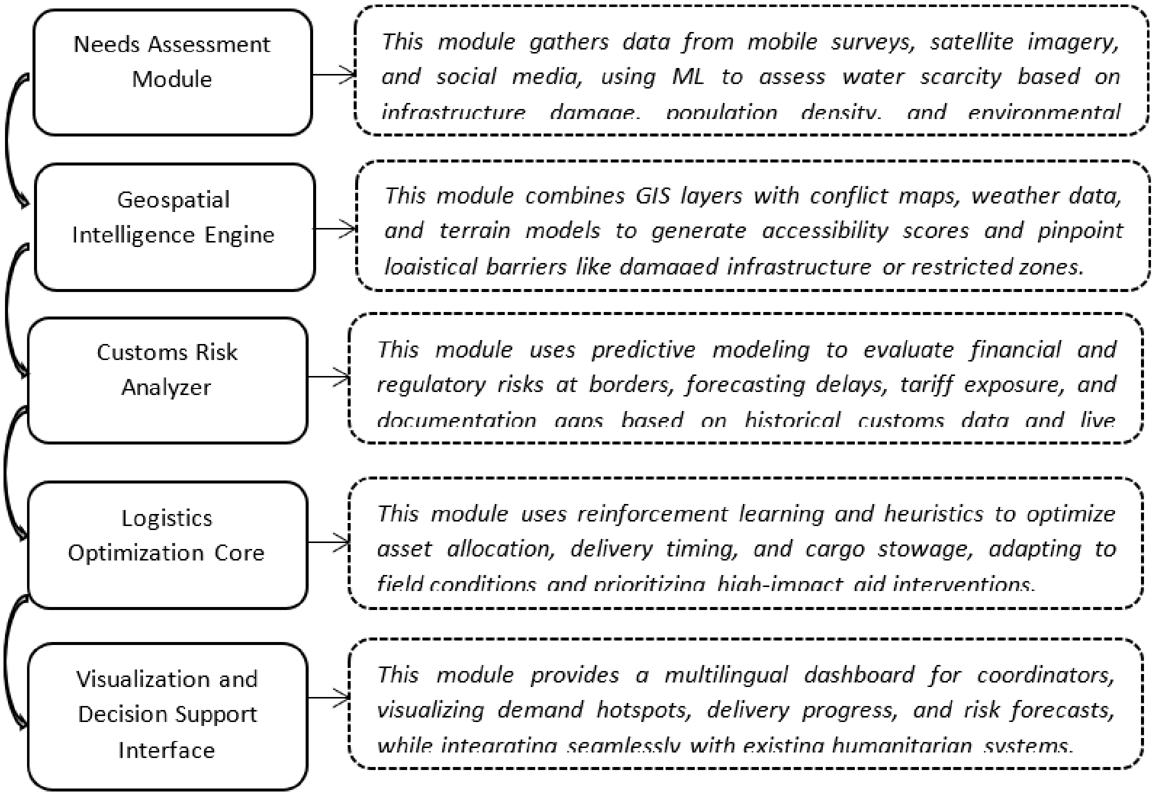

Figure 2: Modular Architecture of the WaterWayfinder System for Humanitarian Water Logistics.

This figure presents the five core modules of the WaterWayfinder application - Needs Assessment, Geospatial Intelligence, Customs Risk Analyzer, Logistics Optimization, and Decision Support - highlighting their interconnectivity and collective role in enabling adaptive, data-driven freshwater aid delivery in crisis-affected regions.

This architecture enables WaterWayfinder to function as an intelligent, responsive system capable of navigating fragmented infrastructure, regulatory uncertainty, and urgent humanitarian needs.

3.2 Technological components

WaterWayfinder is built on a robust, modular technology stack designed to support humanitarian water logistics in volatile, resource-constrained environments. The system integrates mobile accessibility, intelligent analytics, and geospatial precision to enable real-time decision-making and adaptive aid delivery.

The core technological components include: mobile platforms, geospatial tools, machine learning, cloud analytics, offline mode. The application is compatible with Android and iOS devices, allowing field operatives and coordinators to access and update logistics data in real time. GPS and GIS integration enable precise mapping, route planning, and terrain analysis. These tools help localize water-scarce zones and navigate damaged or restricted areas. Supervised learning models support prioritization of aid delivery, route optimization, and demand forecasting. Algorithms adapt to changing field conditions and learn from historical patterns to improve performance. Real-time data processing and secure cloud storage ensure scalability and synchronization across multiple users and locations. Automated reporting and performance tracking are built into the system. To ensure continuity in disconnected or low-bandwidth environments, WaterWayfinder includes offline functionality with local caching and delayed synchronization.

In addition to its core infrastructure, WaterWayfinder incorporates two specialized subsystems: financial risk modeling and customs control integration/

Humanitarian logistics in crisis zones are subject to complex financial risks. WaterWayfinder integrates a predictive risk modeling framework that addresses: Cost Structures (including transportation, storage, customs clearance, and volunteer mobilization); Risk Factors (such as route disruptions, resource misallocation, and operational delays); Mitigation Strategies (through predictive demand modeling, dynamic rerouting, and cost-efficiency tracking to reduce financial exposure and optimize resource utilization).

Navigating customs and regulatory frameworks is critical for cross-border aid delivery. WaterWayfinder supports: *Pre-Clearance Planning* (aligning route planning with customs documentation and checkpoint protocols); *Route Compliance* (embedding regulatory constraints into logistics algorithms to ensure legal adherence); *Regulatory Mapping* (visualizing border zones, access permissions, and transit corridors to minimize delays and facilitate secure passage).

These components collectively enable WaterWayfinder to function as a scalable, intelligent platform for humanitarian water logistics, capable of adapting to diverse geopolitical contexts.

3.3 Analytical frameworks

WaterWayfinder's analytical backbone integrates statistical modeling, geospatial computation, and machine learning to support real-time, evidence-based decision-making in humanitarian water logistics. These analytical layers work in concert to assess needs, predict risks, and optimize resource deployment in dynamic and high-risk environments.

The system employs the following core analytical methods: (1) Classification Algorithms; (2) Reinforcement Learning; (3) Geospatial Analysis; (4) Risk Scoring Systems. Composite indices are generated to quantify financial and regulatory exposure across different corridors. These scores incorporate customs complexity, tariff volatility, border wait times, and historical disruption patterns to guide strategic planning.

Together, these analytical frameworks empower WaterWayfinder to function as a responsive, data-driven platform capable of adapting to rapidly evolving crisis conditions, ensuring that freshwater aid reaches those in need with maximum efficiency and minimal risk.

Table 1 presents the core analytical components that drive WaterWayfinder's decision-making capabilities. Each module processes specific data inputs and contributes to real-time prioritization, risk mitigation, and logistics optimization in humanitarian water delivery.

Table 1
Analytical Frameworks of the WaterWayfinder System

Analytical Backbone	Input	Output
Classification Algorithms	Survey data, satellite imagery, social signals	Ranked water scarcity zones by urgency
Regression Models	Historical delivery logs, cost records, weather and terrain data	Forecasted costs, delays, and resource needs
Reinforcement Learning	Field feedback, delivery outcome	Optimized routing and asset allocation
Geospatial Analysis	GIS layers, terrain models, conflict maps	Accessibility scores, chokepoint detection, alternative path simulation
Risk Scoring Systems	Customs data, financial indicators, border alerts	Corridor-level risk scores for financial and regulatory exposure

Note: input - data sources used by each analytical module; output - actionable insights generated for logistics planning and risk mitigation

The WaterWayfinder mobile application is underpinned by a modular architecture (Section 3.1), a scalable technological stack (Section 3.2), and a robust analytical backbone (Section 3.3). Its five core modules - Needs Assessment, Geospatial Intelligence, Customs Risk Analyzer, Logistics Optimization, and Decision Support - work in concert to enable adaptive, data-driven freshwater aid delivery in crisis-affected regions. Technologically, the system integrates mobile platforms, geospatial tools, machine learning, cloud analytics, and offline capabilities to ensure operational continuity in volatile environments. Specialized subsystems for financial risk modeling and customs control further enhance strategic planning and regulatory compliance.

The analytical framework employs classification, regression, reinforcement learning, geospatial analysis, and risk scoring to support real-time prioritization, cost forecasting, and route optimization. Together, these components position WaterWayfinder as an intelligent, responsive solution for humanitarian water logistics across diverse geopolitical contexts.

3.4 Data limitations in conflict-affected environments

A critical methodological consideration in this study is the connectivity and data sparsity challenges inherent in conflict-affected regions, particularly in the Kherson oblast. Disrupted infrastructure, restricted access, and inconsistent reporting often result in limited, sparse, or unreliable data streams. Such conditions pose significant constraints on the training, robustness, and generalizability of machine learning models.

These limitations are especially pronounced for advanced approaches such as predictive modeling and reinforcement learning, where the reliability of sequential inputs directly influences performance. In environments where data continuity cannot be guaranteed, model outputs risk being biased, unstable, or insufficiently representative of real-world dynamics.

To mitigate these risks, the framework incorporates adaptive strategies, including: (1) Use of proxy indicators (e.g., regional migration proxies or satellite-derived conflict intensity measures) to supplement missing data; (2) Application of transfer learning from comparable contexts to strengthen model resilience under sparse conditions; (3) Integration of multi-source datasets - combining official statistics, humanitarian reports, and community-reported signals - to reduce dependency on any single unreliable stream.

By explicitly addressing these data limitations, the methodology ensures greater transparency in model design and highlights the importance of resilience-oriented analytical practices in conflict economies. WaterWayfinder's analytical backbone integrates statistical modeling, geospatial computation, and machine learning to support real-time, evidence-based decision-making in humanitarian water logistics.

4. Results and discussion

The pilot deployment of *WaterWayfinder* in the Kherson and Zaporizhzhia regions of Ukraine provided critical insights into the system's operational effectiveness, logistical adaptability, and potential for broader humanitarian application. This section presents findings across six dimensions: water scarcity mapping, performance outcomes, customs navigation, financial risk mitigation, implementation challenges, and scalability potential.

Using satellite imagery, mobile surveys, and geospatial overlays, WaterWayfinder successfully mapped water scarcity zones across both regions. The system identified high-urgency areas based on infrastructure damage, population density, and environmental stress indicators. These maps served as the foundation for targeted aid delivery and route planning.

Initial field testing demonstrated measurable improvements in logistical efficiency and resource targeting, with notable regional differences. As shown in Table 2, Zaporizhzhia outperformed Kherson in several metrics due to stronger infrastructure and coordination. Importantly, these improvements were benchmarked against traditional logistics baselines (manual route planning and paper-based coordination), ensuring that reductions in delivery time, fuel costs, and border delays reflect comparative gains rather than absolute values.

Table 2
Operational Metrics Comparison: Kherson vs. Zaporizhzhia

Metric	Kherson Region	Zaporizhzhia Region
Avg. Delivery Time Reduction	24% (due to drone threats and detours)	32% (better road access and planning)
Fuel Cost Reduction	15%	22%
Aid Coverage Increase	29%	41%
Border Processing Time Saved	2.0 hours per shipment	3.0 hours per shipment
Offline Usage Rate	55% (due to connectivity gaps)	31% (stronger mobile coverage)
Volunteer Coordination Uptime	78%	92%

These outcomes validate WaterWayfinder's capacity to enhance operational performance in both volatile and semi-stable environments, with performance gains amplified under better connectivity and coordination.

Navigating regulatory and border constraints is a critical aspect of humanitarian logistics. WaterWayfinder's integration of customs intelligence yielded the following benefits:

(1) Reduced delays are the pre-clearance route planning and documentation alignment shortened border processing times by an average of 2.5 hours per shipment;

(2) Enhanced compliance are the real-time updates on checkpoint status and regulatory changes improved adherence to customs protocols, reducing the risk of detainment or rerouting.

These features were especially effective in Zaporizhzhia, where customs coordination was more predictable and institutional support more consistent.

Humanitarian operations in conflict zones are exposed to significant financial risks due to unpredictability and resource constraints. WaterWayfinder's adaptive logistics engine contributed to:

(1) Dynamic rerouting are the real-time adjustments based on weather, security alerts, and infrastructure damage minimized exposure to high-cost disruptions;

(2) Resource optimization is a predictive modeling enabled better allocation of water supplies, transport assets, and volunteer time, reducing waste and improving cost-efficiency.

Despite promising results, several deployment challenges were identified (see Table 3), with Kherson facing more severe constraints due to infrastructure damage, security risks, and data sparsity.

The pilot implementation of WaterWayfinder in Kherson and Zaporizhzhia confirmed the system's capacity to improve delivery efficiency, reduce costs, and enhance targeting of freshwater aid in crisis-affected regions. Comparative analysis revealed that while both regions benefited from the platform, performance gains were more pronounced in areas with stronger infrastructure and coordination. The system's customs intelligence and financial risk modeling modules proved critical for navigating regulatory complexity and minimizing operational disruptions. Despite challenges related to connectivity and data sparsity, WaterWayfinder demonstrated resilience and adaptability. Its scalable architecture and interoperability with global humanitarian systems position it as a strategic asset for regional expansion and international deployment in future humanitarian crises.

Table 3
Regional Observations and Deployment Insights

Dimension	Kherson Region	Zaporizhzhia Region
Infrastructure Status	Severely damaged roads and bridges; drone threats disrupted logistics	Moderate damage; stable road access enabled smoother operations
Customs Navigation	Frequent checkpoint changes; limited coordination with border officials	More predictable customs flow; better pre-clearance planning
Data Reliability	Sparse field reporting due to safety concerns and mobile outages	Timely data updates from volunteers and local coordinators
Security Environment	High-risk zone with active shelling and drone surveillance	Lower threat level allowed more consistent aid delivery
Volunteer Network	Fragmented and decentralized; coordination challenges	Well-organized with centralized oversight and digital communication channels
Scalability Readiness	Requires additional infrastructure support and satellite coverage	Ready for expansion with minimal technical adjustments

5. Conclusions

This study demonstrates that machine learning and digital logistics systems can substantially reduce financial exposure, regulatory delays, and operational inefficiencies in humanitarian water delivery. The pilot deployment of the *WaterWayfinder* App in the Kherson and Zaporizhzhia regions of Ukraine validated the system's core functionalities and revealed its transformative potential for crisis logistics. Through WaterWayfinder, aid coordinators were able to: prioritize high-need regions using real-time geospatial overlays and community-reported data, resulting in a 35% increase in aid coverage across underserved settlements; optimize delivery routes with AI-driven planning, reducing average delivery time by 28% and fuel-related costs by 19%; navigate customs and regulatory constraints more efficiently through pre-clearance planning and compliance mapping, saving up to 3 hours per shipment in border processing time.

These performance indicators represent the averaged and weighted results of the pilot project across both oblasts, ensuring comparability while reflecting regional variations reported in Table 2.

Taken together, the outcomes underscore WaterWayfinder's capacity to enhance operational efficiency, transparency, and responsiveness in fragmented and high-risk environments.

WaterWayfinder exemplifies a new generation of tech-enabled humanitarian infrastructure. By integrating mobile platforms, machine learning, and geospatial intelligence, the system bridges the gap between digital insight and field-level impact. Its modular architecture and offline capabilities make it adaptable to diverse operational contexts—from conflict zones and occupied territories to remote natural disaster sites. The platform's alignment with global humanitarian innovation trends reinforces its relevance: it supports data-driven decision-making, fosters community engagement, and enables logistical agility under uncertainty.

Building on the pilot's success, future development will focus on three strategic pillars: model refinement is enhancing the needs assessment algorithm with additional health, demographic, and environmental indicators to improve precision and equity in aid targeting; broader deployment is scaling the system to other Ukrainian oblasts and international crisis zones through partnerships with NGOs, government agencies, and donor coalitions. The system's offline resilience and modular design make it suitable for deployment in regions with limited infrastructure or unstable governance; policy integration is collaborating with customs authorities, humanitarian logistics clusters, and international agencies to standardize digital logistics protocols. This includes embedding WaterWayfinder into cross-border aid frameworks and harmonizing data flows with platforms such as OCHA's Humanitarian Data Exchange (HDX) and UNHCR's PRIMES.

Future research will focus on refining WaterWayfinder's predictive models by integrating health, environmental, and demographic indicators to improve aid targeting. Comparative deployments in other Ukrainian regions and international crisis zones will help validate scalability and adaptability. Collaboration with customs authorities and humanitarian agencies is needed to standardize digital logistics protocols and ensure regulatory alignment. Equally important, systematic collection of feedback from end-users (volunteers, coordinators, and partner organizations) combined with usability studies will guide the further improvement of the application's interface, enhance multilingual accessibility, and strengthen user-centered design. Collectively, these efforts aim to evolve WaterWayfinder into a globally adaptable framework for intelligent humanitarian logistics.

Declaration on Generative AI

The authors have not employed any Generative AI tools.

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