FloodOps Twin: A Role-Based Spatial Intelligence Digital Twin for Reducing Cognitive Overload in Urban Flood Emergency Operations

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Abstract

Rapid-onset urban flooding generates significant operational challenges for Emergency Operation Centers (EOCs), where decision-makers must interpret large volumes of heterogeneous hydrological, infrastructural, and transportation data under severe time constraints. Existing flood dashboards frequently rely on centralized visualization paradigms that expose all users to the same high-density information environment regardless of operational role, potentially increasing cognitive burden and decision latency. This study presents *FloodOps Twin*, a web-based urban flood digital twin framework designed to support adaptive operational intelligence through a Role-Based Spatial Intelligence (RBSI) architecture. The framework integrates real-time hydrological telemetry, National Weather Service flood thresholds, transportation network conditions, and parcel-level exposure datasets within a synchronized spatial decision-support environment. Iowa City, Iowa and conditions associated with the 2008 Iowa River flood were used as the operational case study to evaluate system behavior during escalating flood scenarios. The framework dynamically transformed shared telemetry into differentiated operational products for emergency managers, transportation teams, public works personnel, planners, and public users. Results demonstrated the capability of the system to support contextual situational awareness, roadway passability analysis, automated detour generation, infrastructure-oriented operational filtering, and dynamic economic exposure estimation within a unified operational environment. The study highlights the potential of cognitively adaptive digital twin architectures to improve urban flood coordination, operational scalability, and role-specific emergency intelligence. Future work should incorporate formal usability evaluation, predictive flood modeling, and AI-assisted operational analytics to further strengthen adaptive flood response capabilities.

Keywords: Urban flood digital twin; Role-Based Spatial Intelligence (RBSI); Disaster informatics; Flood decision-support systems; Cognitive load reduction.

1. Introduction

Flooding is one of the most cost-intensive and difficult natural hazards to control in communities across the world. Increasingly frequent and widespread urban flooding in many regions of the world in recent years is associated with more intense rainfall from climate change, fast urban growth and impervious surface expansion, and outdated drainage infrastructure (IPCC, 2021; UNDRR, 2022). Unlike river floods, which generally creep across wider rural regions, urban floods tend to be fast-onset and fast-moving. They can concurrently impair transportation, emergency services, utilities, communication systems and other key infrastructures (Hammond et al., 2015; Jha et al., 2012; Alabbad et al., 2024). The confluence of these phenomena makes flood response extremely difficult in that emergency managers are called upon to evaluate information from numerous sources (hydrological, meteorological, infrastructural, and social), often in real time, to support critical judgments (Sajja et al., 2025; Pursnani et al., 2025).

With the increasing complexity of urban flood response, there is a rising demand for enhanced decision support systems (DSS) that assist experts to retain real-time situational awareness and coordinate activities efficiently (Kadiyala et al., 2025). Tools like Geographic Information Systems (GIS), interactive dashboards, and flood visualization platforms are now commonly utilized in Emergency Operation Centers (EOCs) and are progressively integrated into smart city resilience initiatives (Goodchild and Glennon, 2010; Yesilkoy et al., 2024; Kilsedar et al., 2023). At the same time, advances in the Internet of Things (IoT), cloud computing and cyber-physical systems have facilitated the rise of urban digital twins, virtual representations that continually replicate the state of real-world infrastructure (Batty, 2018; Sermet et al., 2020; Fuller et al., 2020). In disaster management, digital twins are being increasingly recognized as powerful tools to integrate different real-time streams of data into a single platform to assist with flood forecasting, infrastructure monitoring, evacuation planning, and coordinated emergency response (Deren et al., 2021; Lu et al., 2020; Demir et al., 2018).

However recent technical breakthroughs, several operational flood management platforms still demonstrate considerable deficiencies from the standpoint of human-computer interface (HCI) and cognitive systems engineering. Current emergency management dashboards often utilize monolithic information architectures that present identical telemetry streams, spatial layers, and warning products uniformly to all users, regardless of their operational responsibilities or domain expertise (Endsley, 1995; Comfort, 2007). As a result, transportation engineers, emergency managers, public works teams, urban planners, and field responders frequently need to independently analyze complex and diverse geographical information to get operationally pertinent knowledge. In high-tempo flood crises, information saturation can immediately lead to cognitive overload, decision fatigue, delayed response coordination, and diminished situational awareness (Chen et al., 2008; Seppänen & Virrantaus, 2015).

Cognitive overload in Emergency Operations Center systems has emerged as a significant study issue in disaster informatics and emergency management literature. Emergency operations naturally entail expedited decision-making processes, insufficient information, need for interagency collaboration, and swiftly changing danger circumstances (Mendonça et al., 2007). In these circumstances, operators must consistently analyze many simultaneous data streams, including stream gauge telemetry, weather radar outputs, flood predictions, road closure notifications, evacuation alerts, and infrastructure condition reports (Yildirim et al., 2023). Studies in cognitive engineering have shown that high information density and inadequately filtered interfaces may significantly hinder operator performance, especially in high-stress and time-critical situations (Wickens, 2008; Cummings, 2004). Although contemporary GIS systems have greatly enhanced geographic visualization, relatively less focus has been placed on adaptive role-based intelligence aimed at alleviating operational cognitive load (Sit et al., 2021) during disaster response.

At the same time, the development of digital twin technologies has mostly focused on physical infrastructure representation, simulation quality, and the integration of real-time sensor data, rather than on operational cognition and decision priority. Urban digital twins have been widely studied for transportation optimization, utility monitoring, environmental sensing, and smart infrastructure management (Bolton et al., 2018; Qi et al., 2021). However, many systems are still essentially visualization-centric, preferring exhaustive data representation over selected intelligence abstraction (Xu et al., 2019). In actual emergency operations the problem is not only information availability, but how to turn diverse data sources into operationally usable intelligence tailored for specific organizational roles and tactical duties.

This constraint is particularly apparent in the case of urban flood situations, because various operating teams require fundamentally different types of situational awareness. Emergency managers place value on macro-scale operational posture, interagency collaboration and critical infrastructure vulnerability. Public works teams need infrastructure-specific field deployment duties and priorities for drainage intervention. Transportation coordinators emphasize corridor travers ability, evacuation routing, and mobility continuity. Exposure calculation, repetitive-loss assessment, and long-term recovery implications are needed by urban planners and resilience experts. In traditional dashboards these analytical needs are seldom differentiated, thereby imposing the same high density information environment on all users in any operational scenario.

To overcome these challenges, this study proposes FloodOps Twin, a web-based urban flood digital twin based on a Role-Based Spatial Intelligence (RBSI) framework. The proposed system is built on role-based access paradigm, extending beyond permission management to operational intelligence transformation. The system goes beyond providing access to datasets; it dynamically translates similar hydrological telemetry and geographical information into differentiated, role-specific actionable outputs for the decision requirements of diverse operational stakeholders. The framework incorporates real-time hydrological telemetry from United States Geological Survey (USGS) stream gauges, the National Weather Service (NWS) flood warnings, dynamic analysis of transportation passability, parcel-level economic exposure estimation through the use of ArcGIS REST services, and automated tactical field-order generation in a common spatial decision support environment.

The conceptual basis of the proposed framework is derived from many multidisciplinary disciplines such as disaster informatics, cyber-physical systems, spatial decision support systems, GIScience, cognitive systems engineering and human-centered computing. From a disaster informatics viewpoint, the work contributes to the nascent attempts to improve the operational intelligence synthesis during the emergency response (Palen et al., 2010). The research contributes to GIScience by advancing spatial decision support frameworks that can dynamically integrate heterogeneous real-time geospatial information into adaptive operational processes (MacEachren et al., 2005). From an HCI standpoint, the work tackles long-standing problems with information filtering, interface complexity, and role-adaptive visualization in high-consequence operating situations.

The main novelty of the system is the direct integration of dynamic economic exposure modeling into actual operational operations. Flood exposure evaluations are often relied on static precomputed flood plain overlays, or census-based damage predictions that are unrelated to dynamic real-time hydrological states (Merz et al., 2010). In contrast, FloodOps Twin asynchronously retrieves live parcel-level value information from the Johnson County Assessor ArcGIS REST API to dynamically assess stage-dependent economic exposure as river conditions develop. This technique provides emergency managers and planners with the ability to continually assess expected monetary exposure under various flood scenarios, rather than depending only on static hazard products.

Furthermore, the framework includes automatic tactical intelligence creation using threshold-trigger logic algorithms. These algorithms translate raw hydrological conditions into operational work orders (e.g., roadway closure suggestions, HESCO barrier deployment alerts, drainage inspection duties, and pump station monitoring instructions). The transportation subsystem also analyzes road corridor passability by comparing river stage conditions to road elevation thresholds and calculates evacuation diversions dynamically using OpenRouteService routing APIs bound by inundation polygons. With these techniques, the system can move operational processes from passive monitoring to semi-automated intelligence support.

The setting of the retrospective operational simulation is Iowa City, Iowa, and the catastrophic 2008 Iowa River flood. The 2008 flood event was one of the most catastrophic hydrological catastrophes in Iowa history, causing widespread urban inundation, disruption of transportation, infrastructure damage, and economic loss throughout the Iowa River corridor (Mutel, 2010). The disaster therefore offers a useful example background to examine how adaptive spatial intelligence systems might help to coordinate urban flood response under extreme hydrological circumstances.

Therefore, the major aims of this study are three folds. The work aims, first, to develop a real-time urban flood digital twin that can integrate heterogeneous hydrological, meteorological, infrastructural, and economic data sets into an integrated web-based operating environment. Secondly, the project focuses on designing and operationalizing a Role-Based Spatial Intelligence framework that can convert similar telemetry streams into distinct operational outputs linked with user-specific duties. Third, the study aims to assess the potential of adaptive intelligence filtering to potentially minimize cognitive overload, increase situational awareness and enable faster operational decision-making in urban flood crises.

The research contributes toward the development of next-generation disaster management systems that integrate not only data, but operational cognition and decision efficiency during high-consequence emergency events by integrating real-time telemetry acquisition, dynamic exposure modeling, transportation intelligence, and role-adaptive interface design within a unified digital twin architecture.

2. Literature Review

2.1. Urban Flood Decision Support Systems

Urban flood management is altering from static floodplain mapping to dynamic and data-driven decision support systems that can integrate real-time hydrological measurements, meteorological forecasts and geospatial analytics. Initial flood control systems mostly depended on deterministic hydraulic modeling and static hazard zonation methodologies meant for long-term planning rather than operational emergency coordination (Merz et al., 2007). These systems offered useful insights on flood vulnerability and inundation extents but were typically restricted in their capacity to assist fast evolving emergency response scenarios with continuously changing climatic and infrastructure circumstances.

The advent of Geographic Information Systems (GIS) has altered flood risk management by integration of spatial information including topography, land use, hydrology, infrastructure and demographic exposure into a single analytical setting (Goodchild, 2006). Gradually, web-based GIS platforms were developed into operational decision support systems (DSS) used by emergency managers to monitor flood conditions, coordinate evacuations, identify vulnerable infrastructure, and visualize hazard propagation in near real time (Turoff et al., 2004; Zerger and Wealands, 2004). Further progress in the analytical capacity of urban flood DSS frameworks was achieved with advances in remote sensing, radar rainfall estimates and hydrodynamic simulation that allowed a better prediction of inundation dynamics and change of the flood extent (Schumann et al., 2009).

Recent developments in cloud computing and online mapping technologies have enabled the use of interactive flood dashboards and geospatial operational platforms in Emergency Operation Centers (EOCs). These systems also tend to include stream gauge telemetry, National Weather Service warning products, transportation layers, social media feeds, and infrastructure status information into centralized operating interfaces (Kilsedar et al., 2023). Increasingly, city governments and disaster management organizations are using these platforms to increase situational awareness and interagency collaboration during flood catastrophes. Most contemporary systems, despite substantial breakthroughs in data integration and visualization, give priority to informational comprehensiveness rather than operational cognition and adaptive intelligence filtration.

One of the main drawbacks of traditional urban flood DSS platforms is the use of monolithic interface architectures that present the same spatial layers and streams of telemetry to all operational users regardless of their role specialization or decision responsibility (Comfort, 2007). Transportation coordinators, emergency managers, public work workers and infrastructure operators are thus often left to analyze very varied datasets by themselves, under stringent time restrictions. This operational structure might result in an excess of information density, scattered situational awareness and delayed tactical decision making during high-consequence flood occurrences (Chen et al. 2008). While the state-of-the-art flood DSS technologies have greatly improved the availability of data and the geospatial visualization capabilities, the adaptive role-specific intelligence transformation to reduce operational cognitive burden during emergency management has been little investigated.

2.2. Digital Twins in Smart Cities and Disaster Management

Digital twin technologies have emerged as a key paradigm in smart city research and cyber-physical systems engineering. Digital twins are virtual representations of physical systems that were originally developed in manufacturing and industrial monitoring applications and are continuously synchronized through real-time sensor integration, computational modeling, and bidirectional data exchange (Grieves and Vickers, 2017). The rapid development of Internet of Things (IoT) infrastructures, cloud analytics, and high-frequency sensing technologies has simplified the implementation of digital twins in transportation systems, energy networks, urban infrastructure management and environmental monitoring (Batty, 2018).

In the field of urban systems, the digital twin idea has gradually evolved towards the development of integrated spatial-temporal platforms for real-time modeling of the interactions between infrastructures, transportation systems, environmental processes and human activities (Deren et al., 2021). Smart city digital twins often include diverse data sources, such as traffic telemetry, environmental sensors, utility infrastructure statuses, and geographical databases, into virtual operating environments that are continually updated (Qi et al., 2021; Beck et al., 2010). These technologies provide simulation-based planning, infrastructure optimization, predictive maintenance and resilience evaluation under dynamic operational situations.

In recent years, there has been significant growth in the use of digital twin frameworks to disaster management and emergency response. Digital twins have been studied for earthquake resilience, wildfire monitoring, hurricane evacuation planning, and flood risk management (Lu et al., 2020; Fan et al., 2021). Digital twins are increasingly used in flood management applications to integrate hydrological telemetry, precipitation forecasts, hydraulic simulation outputs and inundation modelling into operational situational awareness systems that can assist emergency coordination and infrastructure protection (Dembski et al., 2020). However, despite this rapid technical advancement, current disaster-oriented digital twins are often still mainly focused on infrastructure and simulation. Many systems focus on high-fidelity physical representation, real-time sensor synchronization, and predictive modeling with comparably little emphasis on operational cognition, interface adaptability, and human-centered intelligence delivery (Fuller et al., 2020). As a result, many digital twin settings remain enhanced visualization or communication tools for education and awareness (Demiray et al., 2025), rather than adaptive operational intelligence platforms (Kadiyala et al., 2024).

This limitation becomes particularly significant within flood emergency operations where multiple operational stakeholders require fundamentally different forms of situational awareness. Emergency managers prioritize strategic operational posture and interagency coordination, while field crews require infrastructure-specific tactical directives and transportation coordinators focus on mobility continuity and evacuation routing. Current digital twin implementations rarely differentiate these operational requirements through adaptive role-specific intelligence transformation. Consequently, there remains a significant research gap regarding the integration of cognitive systems engineering principles within disaster-oriented digital twin architectures.

2.3. Cognitive Overload and Situational Awareness in Emergency Operation Centers

The principle of situational awareness has become a central pillar in the literature of emergency management, disaster informatics and cognitive systems engineering. Situational awareness is the sensing of items in the environment, comprehension of their significance and projection of their status soon (Endsley, 1995). The quickly changing operating situations, scattered sources of information and constrained decision-making deadlines make maintaining situational awareness in Emergency Operation Centers (EOCs) extremely problematic.

Flood emergency operations need staff to concurrently assess hydrological telemetry, weather predictions, transportation interruptions, infrastructure failures, shelter capacity, evacuation demands, and public information streams. During significant flood events, these information flows tend to grow faster than human operators can efficiently absorb them, resulting in cognitive overload and decision fatigue (Mendonça et al., 2007). Cognitive overload occurs when the quantity or complexity of the information exceeds an individual's processing capability, leading to poor understanding, delayed decision making and lower operational effectiveness (Wickens, 2008).

Research in disaster management has shown time and again that more information does not always lead to better operational performance. However, high information density might conceal important signals and increase analytical load during emergency response operations (Comfort and Haase, 2006). Emergency professionals tend to use heuristic simplifications and quick prioritizing tactics to deal with uncertainty and temporal stress in high-pressure circumstances (Turoff et al., 2004). Therefore, operational interfaces that do not emphasize vital information or that lessen the analytical complexity may impede rather than support emergency cooperation. Later work in human-computer interaction (HCI) has shown that interface design is important to operator cognition in high-consequence operational tasks (Norman, 2013). Poorly constructed dashboards, visual clutter and lack of information hierarchy can result in longer visual search time, less understanding accuracy and worse collaborative decision-making (Cummings, 2004).

In the context of crisis response, these consequences may directly influence evacuation timing, infrastructure protection, and public safety results. Therefore, investigators in GIScience and emergency management have called for adaptive geovisualization frameworks that may modify information display to user needs, operational situation, and job specialization (MacEachren et al., 2005). However, most of present DSS platforms still prioritize the complete spatial visibility rather than the selective cognitive filtering. This constraint highlights a need for new operational paradigms where geospatial intelligence technologies actively translate raw data into operationally useful, role-specific outputs that are meant to decrease cognitive burden and increase tactical responsiveness.

2.4. Role-Based Systems, Adaptive Interfaces, and Spatial Intelligence

Role-Based Access Control (RBAC) has long been established as a standard framework within enterprise software systems for regulating permissions and information access according to organizational responsibilities (Sandhu et al., 1996). Traditional RBAC systems primarily focus on cybersecurity, authentication, and authorization management by restricting access to datasets and functional capabilities based on predefined user roles. Although widely implemented across governmental and organizational infrastructures, RBAC frameworks are generally not designed to support adaptive intelligence transformation or operational cognition.

Parallel developments in adaptive interface research and intelligent information systems have explored mechanisms for dynamically tailoring interface content according to user behavior, task requirements, and contextual conditions (Brusilovsky and Millán, 2007). Adaptive interfaces attempt to improve usability and decision efficiency by reducing irrelevant information exposure and prioritizing task-relevant data streams. In spatial decision support contexts, adaptive visualization systems have demonstrated potential for improving geospatial comprehension and analytical efficiency through context-sensitive layer filtering and customized visualization strategies (Roth, 2013).

Within disaster management environments, however, the integration of adaptive interfaces with operational geospatial intelligence remains comparatively underdeveloped. Existing flood dashboards frequently provide identical operational environments to all users regardless of professional specialization, tactical responsibilities, or cognitive workload conditions. Transportation coordinators, urban planners, emergency managers, and field responders therefore interact with the same spatial layers, telemetry streams, and warning products despite requiring substantially different forms of situational awareness.

Recent research in disaster informatics has highlighted the importance of human-centered operational intelligence systems capable of supporting collaborative decision-making under uncertainty (Palen and Anderson, 2016). Nonetheless, relatively few studies have explored how role-specific geospatial intelligence transformation can be operationalized within real-time disaster response systems. Most adaptive emergency management systems focus primarily on information dissemination rather than analytical transformation of spatial intelligence into operationally differentiated outputs.

The concept of spatial intelligence extends beyond simple geospatial visualization toward the interpretation, contextualization, and operational translation of spatial relationships and environmental dynamics (Couclelis, 2005). In the context of flood emergency operations, spatial intelligence involves not merely displaying flood extents or infrastructure locations, but actively transforming hydrological conditions into actionable operational directives tailored to specific decision domains. This distinction is particularly important because emergency response effectiveness depends not solely on access to information, but on the ability to rapidly convert environmental data into operationally relevant decisions. Accordingly, the present study introduces the concept of Role-Based Spatial Intelligence (RBSI), which extends traditional role-based information systems beyond authorization control toward cognitively adaptive operational intelligence transformation. Unlike conventional RBAC systems that merely regulate access permissions, the RBSI framework dynamically converts identical telemetry streams into differentiated operational outputs aligned with the situational requirements of specific emergency response stakeholders.

2.5. Research Gap

Significant contributions to the development of urban flood decision support systems, GIS-based disaster management platforms and digital twin technologies have been made by previous studies. These initiatives have improved the ability to monitor hazards in real time, visualize data, predict floods, and coordinate response actions, notably through developments in sensor networks, cloud computing, and geospatial analytics. At the same time, research in human-computer interaction and cognitive systems engineering has demonstrated the necessity to handle the complexity of information and improve situational awareness in high-stakes operating contexts.

But there is a key gap at the confluence of these fields. Much of the current work on urban flood digital twins and GIS-based disaster management systems concentrates on data aggregation, system visualization, and simulation accuracy, but comparatively little attention has been paid to how decision-makers cognitively process and utilize information. In fact, many systems still utilize uniform interface designs that show the same high-density information to all users, regardless of their operational roles, responsibilities, or decision-making contexts.

This study addresses four major gaps in the literature: (a) absence of cognitively adaptive, role-based intelligence transformation in urban flood digital twin systems; (b) limited application of human-centered cognitive systems engineering principles into disaster informatics platforms; (c) lack of operational frameworks that can translate raw telemetry into actionable, role-specific spatial intelligence; and (d) absence of dynamic, real-time economic exposure modeling in active emergency response environments. In moving next generation urban flood decision support systems beyond simple data integration, proposed FloodOps Twin framework addresses these limitations by emphasizing adaptive intelligence delivery, role-specific situational awareness, and enhanced real-time decision-making support across a range of user groups.

3. Methodology

3.1. System Design Philosophy and Operational Framework

FloodOps Twin is a real-time urban flood decision support focused digital twin developed for Emergency Operation Center (EOC) needs with high cognitive stress and tight decision-making timescales. The framework's methodological basis rests on the notion that the success of emergency responses is determined not by the availability of data but by the operational conversion of diverse telemetry into role-specific, cognitively filtered actionable information. Hence, the architecture was designed based on three key methodological goals: (1) continuous real-time synchronization with live hydrological and meteorological telemetry sources, (2) dynamic spatial intelligence generation through automated analytical pipelines, and (3) role-adaptive information filtering through a Role-Based Spatial Intelligence (RBSI) framework.

The system architecture is a modular cyber-physical spatial intelligence pipeline, which includes six key components for data collection, telemetry synchronization, spatial processing, intelligence translation, role-adaptive interface rendering and operational interaction. The platform combines various environmental, infrastructural and socioeconomic data sources into a web-based unified operating environment that can accommodate dynamic emergency response procedures. Most flood dashboards nowadays are passive visualization systems. FloodOps Twin, in contrast, was built as an active intelligence mediation architecture that continually reads incoming data and translates environmental situations into operationally relevant commands.

Frontend was implemented with asynchronous JavaScript architecture, Leaflet.js for geospatial rendering, Chart.js for temporal telemetry visualization, RESTful API integration for live data synchronization and event driven DOM manipulation for adaptive interface generation. The solution submitted shows full role-adaptive display logic, asynchronous telemetry fetching and ability to alter operational dashboards. The general system design is developed as a real-time spatial-temporal intelligence pipeline in which live telemetry feeds are continually translated into operational outputs based on changing hydrological conditions and stakeholder-specific analytical requirements. The conceptual basis of this methodological approach is drawn from the literature on cyber-physical systems engineering, disaster informatics, geospatial decision support systems, and cognitive systems engineering (Batty, 2018; Fuller et al., 2020; Comfort, 2007).

3.2. System Architecture Overview

The FloodOps Twin framework includes five core computational subsystems: real-time telemetry acquisition; spatial-temporal flood intelligence engine; dynamic economic exposure modeling; tactical automation and transportation routing; and a Role-Based Spatial Intelligence (RBSI) interface. The methodological approach starts with continuous intake of live data streams on hydrology, meteorology, transportation and infrastructure through external APIs. These diverse data sets are standardized into uniform spatial-temporal operational objects and processed through many levels of analytical transformation. The intelligence products produced are dynamically filtered according to the individual user roles and exposed through an adaptable dashboard interface for varied operational purposes.

The system architecture is based on an asynchronous event-driven processing approach, where incoming telemetry data continually prompt downstream recalculations of important operational indicators. These include transit access, infrastructural vulnerability, economic impact evaluations and tactical response recommendations. It enables the digital twin to be tightly coupled with changes in environmental and infrastructural settings, while minimizing delays in actionable intelligence generation. The total system methodology architecture is conceptually described in Eq.1 as below:

$$I_r(t) = F_r(H(t), M(t), T(t), E(t), S_r) \qquad \text{Eq. 1}$$

where, $I_r(t)$ represents role-specific operational intelligence at time t, $H(t)$ denotes hydrological telemetry, $M(t)$ denotes meteorological telemetry, $T(t)$ represents transportation system conditions, $E(t)$ denotes economic exposure variables, and S_r represents stakeholder role definitions. This formulation reflects the central methodological principle of the RBSI framework shown in Fig 1 and Fig. 2: identical telemetry streams are transformed differently depending on operational role and decision context.

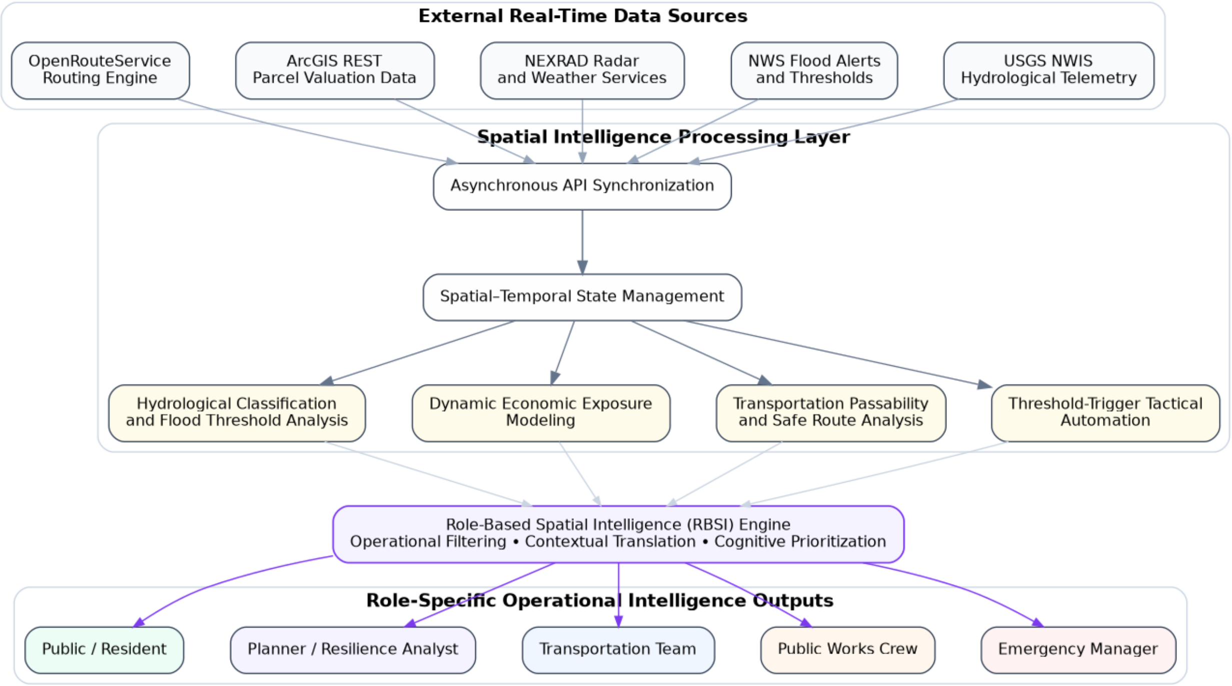


Figure 1: Generalized FloodOps Twin architecture illustrating real-time telemetry integration, spatial intelligence processing, dynamic operational analytics, and role-based intelligence dissemination within a modular urban flood digital twin framework.

3.3. Real-Time Hydrological Telemetry Acquisition

The hydrological telemetry subsystem continuously retrieves live stream gauge observations from the United States Geological Survey (USGS) National Water Information System (NWIS) Instantaneous Values API. The framework currently utilizes Iowa River station 05454500 as the primary hydrological reference node for Iowa City flood operations. Additional upstream and tributary gauges may be incorporated to support distributed watershed monitoring.

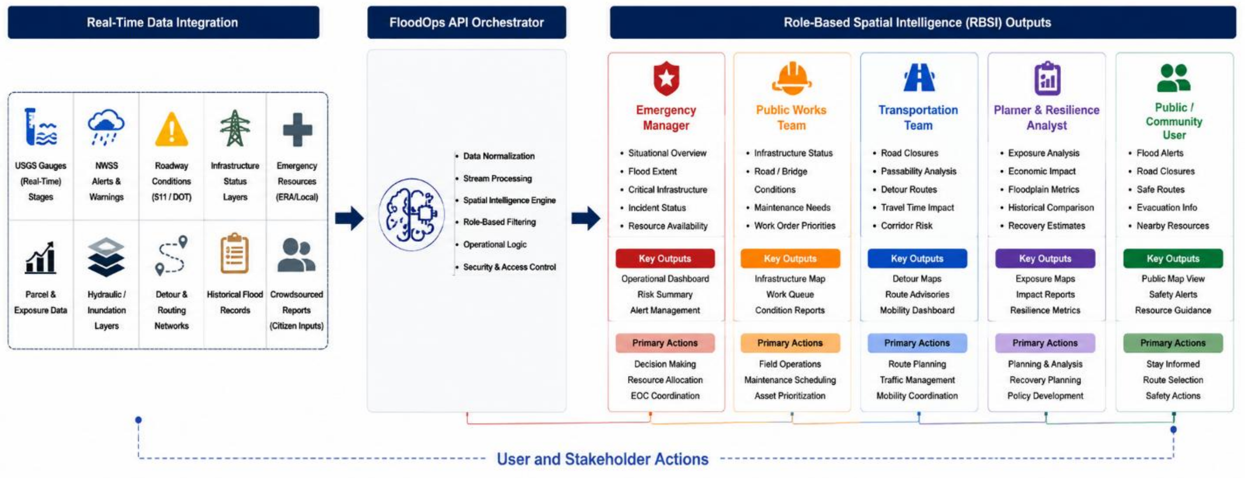


Figure 2: Conceptual Role-Based Spatial Intelligence (RBSI) framework demonstrating the transformation of shared urban flood telemetry into differentiated operational intelligence products for emergency management, public works, transportation coordination, resilience planning, and public communication.

The telemetry synchronization process retrieves river stage observations, discharge values, timestamp metadata, and flood category information through asynchronous JavaScript fetch operations executed at predefined temporal intervals. The uploaded implementation demonstrates direct integration with the USGS JSON telemetry endpoint. The general telemetry retrieval equation (Eq. 2) can be expressed as:

$$H(t) = \{S(t), Q(t), C(t), \tau(t)\} \qquad \text{Eq. 2}$$

where, $S(t)$ denotes river stage (ft), $Q(t)$ denotes discharge ($\frac{m^3}{s}$), $C(t)$ denotes flood classification category, $\tau(t)$ denotes timestamp synchronization.

Flood classification thresholds were derived from National Weather Service flood stage definitions including action, minor, moderate, and major flood categories. The uploaded implementation demonstrates threshold initialization values used within the operational framework. The flood category classification function (Eq. 3) is defined as:

$$f(x) = \begin{cases} Normal, S_t < S_a \\ Action, S_a \leq S_t < S_m \\ Minor, S_m \leq S_t < S_{mod} \\ Moderate,\ S_{mod} \leq S_t < S_{maj} \\ Major, S_t \geq S_{maj} \end{cases} \qquad \text{Eq. 3}$$

where, S_a is the action stage threshold, S_m denotes minor flood stage, S_{mod} shows moderate flood stage, and S_{maj} represents major flood stage. This classification framework supports dynamic operational escalation throughout the digital twin.

3.4. Meteorological Data Integration

Meteorological intelligence is integrated through multiple real-time sources including National Weather Service (NWS) alert feeds, NEXRAD radar products, and precipitation forecasts from Open-Meteo APIs. The system continuously retrieves active flood watches, warnings, and severe weather products through the NWS Alerts API. These warning products are dynamically parsed and spatially rendered within the Leaflet-based situational awareness interface. Radar visualization is implemented using Weather Surveillance Radar-1988 Doppler (WSR-88D) NEXRAD WMS layers obtained from the Iowa Environmental Mesonet infrastructure. These raster products provide near real-time precipitation intensity visualization integrated directly into the spatial intelligence environment. The rainfall accumulation process (Eq. 4) is represented as:

$$P_t = \int_{t_0}^{t_n} R(t)dt \qquad \text{Eq. 4}$$

where, P_t denotes cumulative precipitation accumulation and $R(t)$ represents rainfall intensity over time. Meteorological severity weighting (Eq. 5) is subsequently integrated into operational escalation scoring:

$$W_e = \alpha S_t + \beta P_t + \gamma F_t \qquad \text{Eq. 5}$$

W_e denotes emergency severity weighting, S_t represents river stage, P_t denotes rainfall accumulation, F_t represents forecasted crest projection, and α, β, γ are weighting coefficients. This combined hazard metric supports automated operational posture escalation.

3.5. Spatial Flood Intelligence Processing

The spatial intelligence engine continuously integrates hydrological telemetry with geospatial operational layers including road networks, infrastructure assets, FEMA flood zones, transportation corridors, and critical facilities. The framework utilizes Leaflet.js as the primary geospatial rendering engine due to its lightweight architecture, asynchronous layer control capabilities, and compatibility with RESTful geospatial services. Spatial objects are dynamically updated according to evolving telemetry conditions.

Operational inundation risk is estimated using stage-dependent heuristic threshold logic linked to transportation corridors and infrastructure elevations. Although the current implementation does not employ full hydrodynamic simulation coupling, the framework uses elevation-trigger approximations for operational decision support. The generalized inundation function (Eq. 6) is represented as:

$$I\ (x, y, t) = \begin{cases} 1, S_t \geq E\ (x, y) \\ 0, S_t < E(x, y) \end{cases} \qquad \text{Eq. 6}$$

$I(x, y, t)$ denotes inundation status at spatial coordinate (x, y), S_t denotes river stage at time t, and $E(x, y)$ represents local elevation threshold. This binary operational inundation representation supports real-time transportation and infrastructure intelligence generation.

3.6. Dynamic Economic Exposure Modeling

One of the major methodological innovations of FloodOps Twin involves dynamic economic exposure estimation through live integration with the Johnson County Assessor ArcGIS REST API. Unlike traditional flood exposure assessments that rely on static census datasets or precomputed floodplain summaries, the proposed framework continuously recalculates parcel-level exposure according to evolving flood conditions. Parcel geometries intersecting operational inundation extents are queried asynchronously from the ArcGIS REST service. Property valuation attributes including TotalValue_Assessed and property class categories are aggregated dynamically within the operational intelligence engine. The exposure model (Eq. 7) is defined as:

$$E_t = \sum_{i=1}^{n} V_i \cdot I_i\ (S_t) \qquad \text{Eq. 7}$$

where, E_t is for total economic exposure, V_i denotes assessed parcel value, and $I_i\ (S_t)$ denotes inundation status dependent on river stage. Exposure aggregation by land-use classification (Eq. 8) is represented as:

$$E_c = \sum_{i \in c} V_i \qquad \text{Eq. 8}$$

where, E_c denotes class-specific economic exposure, c represents parcel classification categories such as residential, commercial, industrial, or public infrastructure.

3.7. Tactical Automation and Threshold-Trigger Logic

The tactical automation subsystem transforms hydrological conditions into operational directives using heuristic threshold-trigger logic algorithms. These algorithms were designed to reduce manual interpretation burden for field crews and transportation operators during high-tempo emergency operations. The operational trigger framework (Eq. 9) is represented as:

$$A_k = \begin{cases} 1, S_t \geq T_k \\ 0, S_t < T_k \end{cases} \qquad \text{Eq. 9}$$

Here, A_k denotes activation state of operational action k, T_k denotes predefined threshold stage. Examples include roadway closure activation, HESCO barrier deployment, pump station inspections, drainage intervention tasks, and emergency detour activation. The uploaded implementation demonstrates corridor-specific threshold definitions used for transportation intelligence generation. The generated work orders are dynamically rendered within role-specific operational dashboards and spatially synchronized with map interactions through DOM event listeners.

3.8. Dynamic Transportation Routing and Corridor Passability

Transportation intelligence is generated through corridor passability analysis combined with OpenRouteService API integration. Each roadway segment is associated with operational elevation thresholds corresponding to projected inundation susceptibility. Passability is represented (Eq. 10) as:

$$P_r = \begin{cases} 1, S_t < T_r \\ 0, S_t \geq T_r \end{cases} \qquad \text{Eq. 10}$$

where, P_r denotes passability state and T_r denotes roadway flood threshold. When corridors become impassable, the routing subsystem recalculates evacuation or emergency access paths using graph-based shortest-path algorithms constrained by inundated segments. General routing optimization (Eq. 11-12) is expressed as:

$$R^* = \arg \underset{R}{min} \sum_{e \in R} \omega_e \qquad \text{Eq. 11}$$

subject to:

$$e \notin I_f \qquad \text{Eq. 12}$$

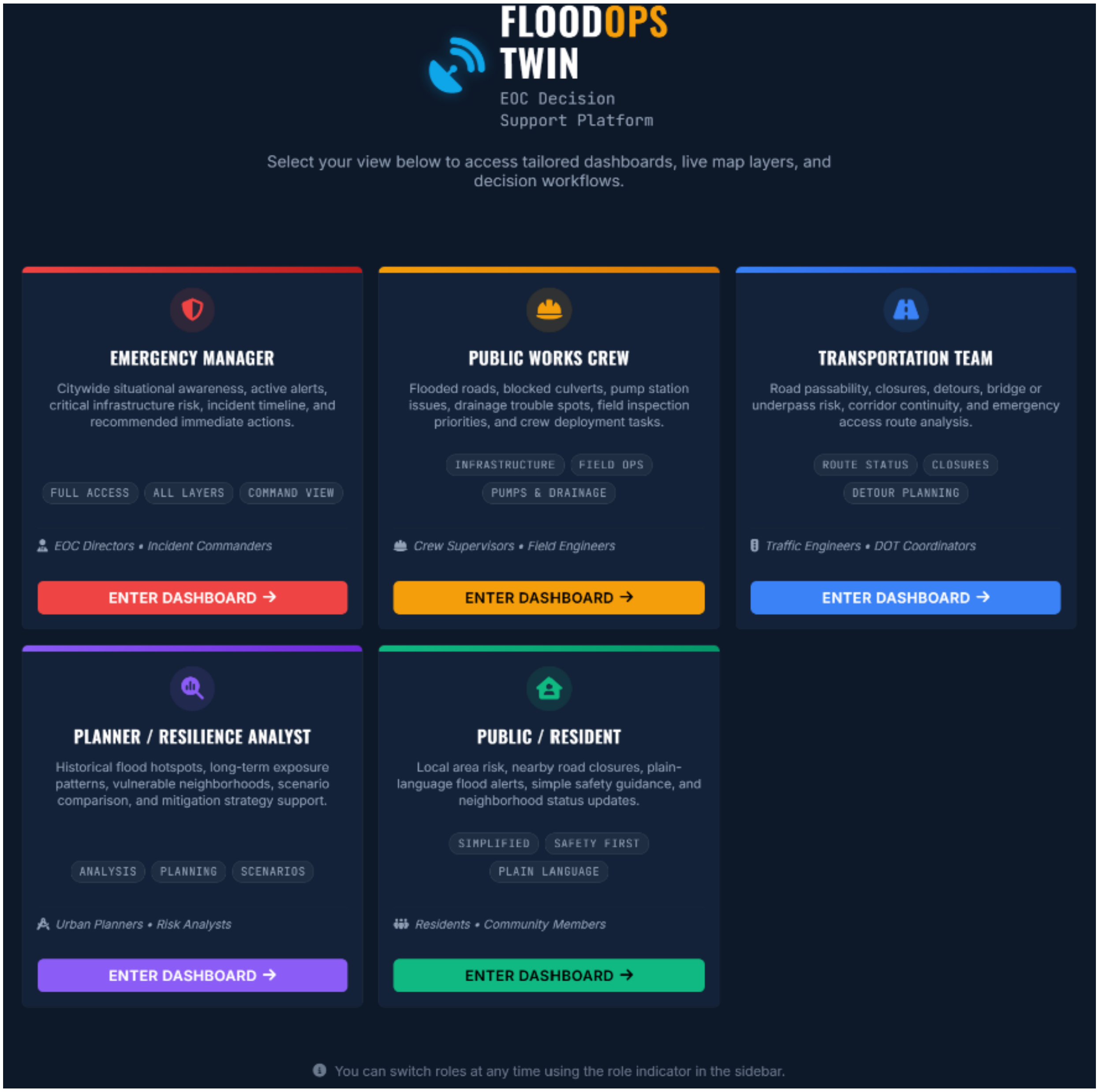
where R^*denotes optimal evacuation route, w_e denotes segment traversal cost, and I_f denotes flooded corridor set.

3.9. Role-Based Spatial Intelligence (RBSI) Interface Methodology

The Role-Based Spatial Intelligence framework constitutes the primary methodological innovation of FloodOps Twin. Unlike conventional dashboards that expose all users to identical telemetry environments, the RBSI subsystem dynamically transforms operational outputs according to stakeholder role. Role-specific intelligence transformation (Eq. 13) is defined as:

$$I_r = G(D, S_r) \qquad \text{Eq. 13}$$

where, I_r denotes role-specific intelligence, D represents raw telemetry datasets, S_r denotes stakeholder role, G denotes transformation operator. Operational roles currently implemented include Emergency Manager, Public Works Crew, Transportation Team, Planner/Resilience Analyst, and Public User. The uploaded implementation demonstrates role-specific dashboard rendering (Fig. 3), navigation restructuring, adaptive layer control, and interface transformation logic. This adaptive methodology reduces information redundancy and selectively prioritizes operationally relevant intelligence streams according to user responsibilities.



FLOODOPS TWIN

EOC Decision Support Platform

Select your view below to access tailored dashboards, live map layers, and decision workflows.

EMERGENCY MANAGER

Citywide situational awareness, active alerts, critical infrastructure risk, incident timeline, and recommended immediate actions.

FULL ACCESS · ALL LAYERS · COMMAND VIEW

EOC Directors • Incident Commanders

ENTER DASHBOARD →

PUBLIC WORKS CREW

Flooded roads, blocked culverts, pump station issues, drainage trouble spots, field inspection priorities, and crew deployment tasks.

INFRASTRUCTURE · FIELD OPS · PUMPS & DRAINAGE

Crew Supervisors • Field Engineers

ENTER DASHBOARD →

TRANSPORTATION TEAM

Road passability, closures, detours, bridge or underpass risk, corridor continuity, and emergency access route analysis.

ROUTE STATUS · CLOSURES · DETOUR PLANNING

Traffic Engineers • DOT Coordinators

ENTER DASHBOARD →

PLANNER / RESILIENCE ANALYST

Historical flood hotspots, long-term exposure patterns, vulnerable neighborhoods, scenario comparison, and mitigation strategy support.

ANALYSIS · PLANNING · SCENARIOS

Urban Planners • Risk Analysts

ENTER DASHBOARD →

PUBLIC / RESIDENT

Local area risk, nearby road closures, plain-language flood alerts, simple safety guidance, and neighborhood status updates.

SIMPLIFIED · SAFETY FIRST · PLAIN LANGUAGE

Residents • Community Members

ENTER DASHBOARD →

You can switch roles at any time using the role indicator in the sidebar.

Figure 3: Role-Based Spatial Intelligence (RBSI) interface with five stakeholders and roles

3.10. Human-Computer Interaction and Spatial Synchronization

The framework incorporates bidirectional spatial synchronization between tabular intelligence panels and geospatial map interfaces. DOM event listeners continuously synchronize operational selections with Leaflet spatial rendering operations. Examples include selecting work orders to automatically zoom to spatial coordinates, selecting road closures to highlight inundated corridors, and dynamically updating infrastructure panels through spatial interaction. This bidirectional synchronization reduces interface navigation complexity and minimizes spatial search overhead during emergency operations. The interaction latency framework may be conceptualized (Eq. 14) as:

$$L_d = L_s + L_i + L_c \qquad \text{Eq. 14}$$

where, L_d denotes total decision latency, L_s denotes spatial search latency, L_i denotes information interpretation latency, and L_c denotes coordination latency. The RBSI methodology aims to minimize L_i and L_s through adaptive intelligence filtering and synchronized spatial interaction.

3.11. Transition from Generalized Framework to Operational Demonstration

The methodology presented above defines a generalized role-adaptive urban flood intelligence framework independent of any specific municipality. The architecture, telemetry synchronization workflows, economic exposure modeling procedures, routing algorithms, and Role-Based Spatial Intelligence (RBSI) mechanisms are designed to operate using locally available hydrological, transportation, infrastructure, and parcel datasets. To demonstrate practical applicability, the framework was implemented and evaluated using Iowa City, Iowa as a representative urban flood environment. The following section first presents the generalized operational outputs produced by the RBSI framework and subsequently demonstrates their application through a case study based on the historical context of the 2008 Iowa River flood.

4. Results and Discussion

4.1. Role-Based Spatial Intelligence (RBSI) Operational Results

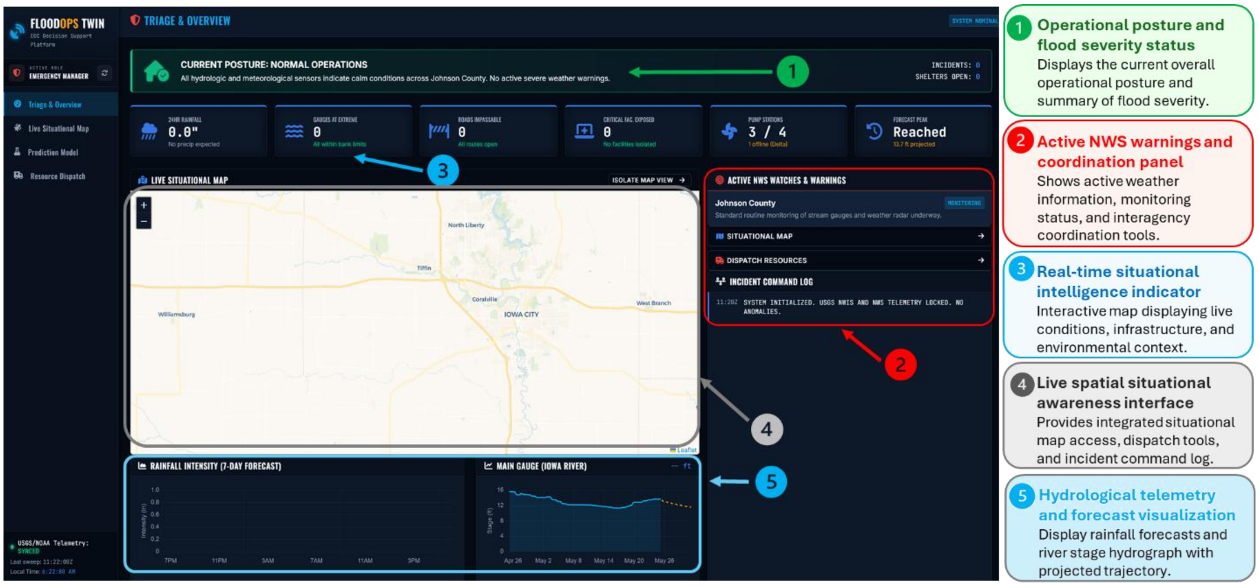
The primary objective of the FloodOps Twin framework is to transform a shared urban flood telemetry environment into differentiated operational intelligence products tailored to stakeholder responsibilities. Unlike conventional flood dashboards that expose all users to the same information environment, the proposed Role-Based Spatial Intelligence (RBSI) framework continuously filters, prioritizes, and restructures synchronized environmental information according to operational role. The resulting intelligence environments maintain a common situational awareness foundation while reducing information redundancy and emphasizing role-specific decision support. The following sections present the generalized operational outputs generated by the RBSI framework independent of any specific municipality or flood event.

4.1.1. Emergency Manager Operational Environment

The Emergency Manager environment is designed to support strategic situational awareness and executive-level coordination during evolving flood conditions. The interface shown in Fig. 4 aggregates hydrological telemetry, infrastructure status indicators, transportation conditions, resource availability, and warning information into a unified operational overview intended to facilitate rapid decision-making.

4.1.2. Public Works Operational Environment

The Public Works environment focuses on infrastructure-oriented operational intelligence. Within this environment, hydrological conditions are translated into actionable infrastructure management tasks related to drainage systems, roadway assets, utility protection, and field operations. The interface (Fig. 5) integrates infrastructure layers, operational monitoring tools, and field coordination resources into a single spatially synchronized environment. As environmental conditions evolve, the framework prioritizes infrastructure monitoring activities and supports localized operational response by transforming environmental telemetry into infrastructure-specific intelligence products.



All hydrologic and meteorological sensors indicate calm conditions across Johnson County. No active severe weather warnings.

Standard routine monitoring of stream gauges and weather radar underway.

11:20Z SYSTEM INITIALIZED. USGS NWIS AND NWS TELEMETRY LOCKED. NO ANOMALIES.

① **Operational posture and flood severity status**
Displays the current overall operational posture and summary of flood severity.

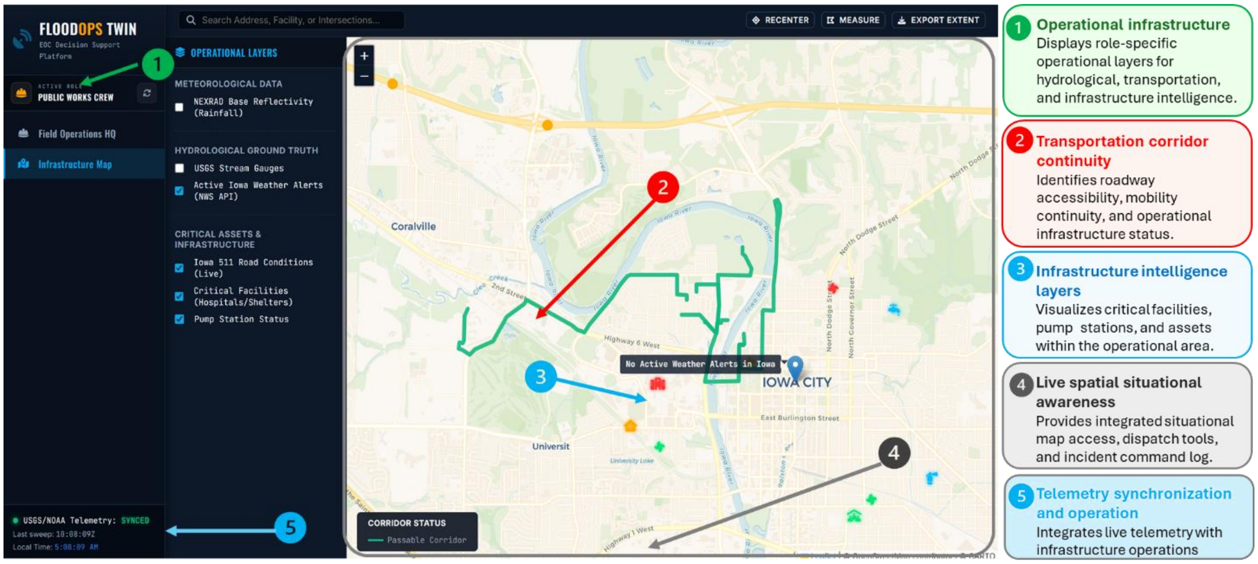
② **Active NWS warnings and coordination panel**
Shows active weather information, monitoring status, and interagency coordination tools.

③ **Real-time situational intelligence indicator**
Interactive map displaying live conditions, infrastructure, and environmental context.

④ **Live spatial situational awareness interface**
Provides integrated situational map access, dispatch tools, and incident command log.

⑤ **Hydrological telemetry and forecast visualization**
Display rainfall forecasts and river stage hydrograph with projected trajectory.

Figure 4: Annotated Emergency Manager dashboard in the FloodOPS Twin platform illustrating the triage and overview interface. The dashboard integrates real-time hydrological telemetry, operational posture indicators, active weather alerts, situational



① **Operational infrastructure**
Displays role-specific operational layers for hydrological, transportation, and infrastructure intelligence.

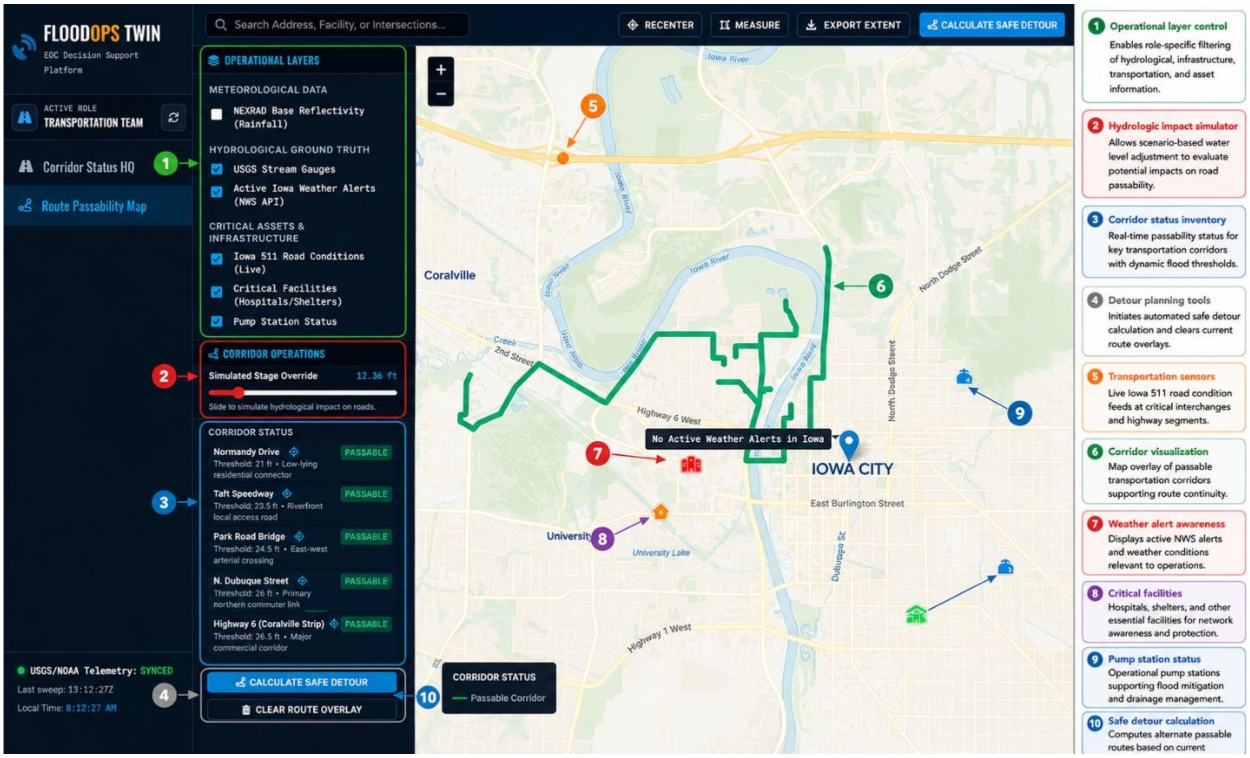
② **Transportation corridor continuity**
Identifies roadway accessibility, mobility continuity, and operational infrastructure status.

③ **Infrastructure intelligence layers**
Visualizes critical facilities, pump stations, and assets within the operational area.

④ **Live spatial situational awareness**
Provides integrated situational map access, dispatch tools, and incident command log.

⑤ **Telemetry synchronization and operation**
Integrates live telemetry with infrastructure operations

Figure 5: Annotated Public Works operational interface demonstrating infrastructure monitoring, transportation corridor awareness, operational layer filtering, and synchronized spatial intelligence within the FloodOps Twin framework.



☐ NEXRAD Base Reflectivity (Rainfall)
☑ USGS Stream Gauges
☑ Active Iowa Weather Alerts (NWS API)
☑ Iowa 511 Road Conditions (Live)
☑ Critical Facilities (Hospitals/Shelters)
☑ Pump Station Status

Simulated Stage Override 12.36 ft
Slide to simulate hydrological impact on roads.

Normandy Drive Threshold: 21 ft • Low-lying residential connector	PASSABLE
Taft Speedway Threshold: 23.5 ft • Riverfront local access road	PASSABLE
Park Road Bridge Threshold: 24.5 ft • East-west arterial crossing	PASSABLE
N. Dubuque Street Threshold: 26 ft • Primary northern commuter link	PASSABLE
Highway 6 (Coralville Strip) Threshold: 26.5 ft • Major commercial corridor	PASSABLE

USGS/NOAA Telemetry: SYNCED
Last sweep: 13:12:27Z
Local Time: 8:12:27 AM

① **Operational layer control** Enables role-specific filtering of hydrological, infrastructure, transportation, and asset information.

② **Hydrologic impact simulator** Allows scenario-based water level adjustment to evaluate potential impacts on road passability.

③ **Corridor status inventory** Real-time passability status for key transportation corridors with dynamic flood thresholds.

④ **Detour planning tools** Initiates automated safe detour calculation and clears current route overlays.

⑤ **Transportation sensors** Live Iowa 511 road condition feeds at critical interchanges and highway segments.

⑥ **Corridor visualization** Map overlay of passable transportation corridors supporting route continuity.

⑦ **Weather alert awareness** Displays active NWS alerts and weather conditions relevant to operations.

⑧ **Critical facilities** Hospitals, shelters, and other essential facilities for network awareness and protection.

⑨ **Pump station status** Operational pump stations supporting flood mitigation and drainage management.

⑩ **Safe detour calculation** Computes alternate passable routes based on current

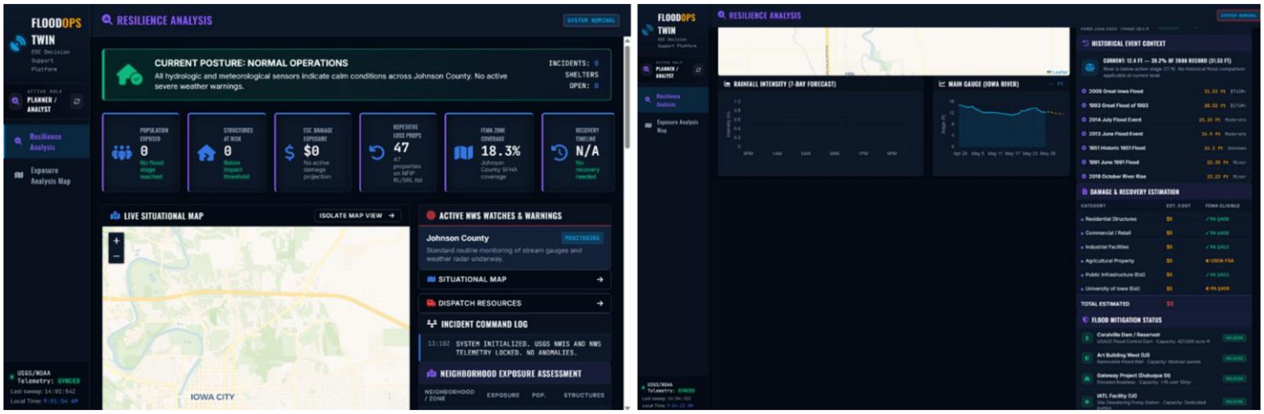
Figure 6: Annotated Transportation Team operational interface within the FloodOps Twin framework demonstrating role-specific corridor intelligence, dynamic roadway passability assessment, hydrologic impact simulation, infrastructure-aware operation.

4.1.3. Transportation Operational Environment

The Transportation environment emphasizes mobility continuity, corridor accessibility, and evacuation support (Fig. 6). The system continuously evaluates roadway passability using synchronized hydrological conditions and corridor-specific flood thresholds. Transportation intelligence products include roadway accessibility status, corridor vulnerability indicators, detour generation, and route continuity assessment. By focusing on transportation-specific operational requirements, the framework supports emergency mobility planning while minimizing the need for transportation personnel to manually interpret complex hydrological conditions.

4.1.4. Planner and Resilience Analyst Operational Environment

The Planner and Resilience Analyst environment focuses on vulnerability assessment, economic exposure estimation, and resilience-oriented intelligence generation (Fig. 7). Unlike tactical operational environments, this interface emphasizes longer-term planning considerations including floodplain exposure, repetitive-loss properties, historical benchmark datasets (Ebert-Uphoff et al., 2017) infrastructure vulnerability, and recovery-oriented assessment. A notable capability of this environment is the integration of dynamic parcel-level economic exposure estimation through synchronized property valuation datasets. Consequently, the platform provides planners with continuously updated spatial intelligence products that support both operational awareness and long-term resilience planning.



CURRENT POSTURE: NORMAL OPERATIONS
All hydrologic and meteorological sensors indicate calm conditions across Johnson County. No active severe weather warnings.

INCIDENTS: 0
SHELTERS OPEN: 0

Standard routine monitoring of stream gauges and weather radar underway.

```
13:10Z  SYSTEM INITIALIZED. USGS NWIS AND NWS
        TELEMETRY LOCKED. NO ANOMALIES.
```

Figure 7: Planner and Resilience Analyst operational interfaces demonstrating resilience-oriented spatial intelligence, historical flood context analysis, dynamic exposure estimation, and recovery-focused operational analytics.

4.1.5. Public Communication Operational Environment

The Public Communication environment provides a simplified representation of flood intelligence intended for non-technical users. Complex telemetry streams, infrastructure indicators, and operational terminology are translated into accessible information focused on public safety and situational awareness. The interface emphasizes roadway closures, evacuation guidance, transportation accessibility, and neighborhood-level safety information (Fig. 8). By reducing technical complexity while maintaining situational relevance, the framework seeks to improve accessibility and support informed decision-making among residents during evolving flood conditions.

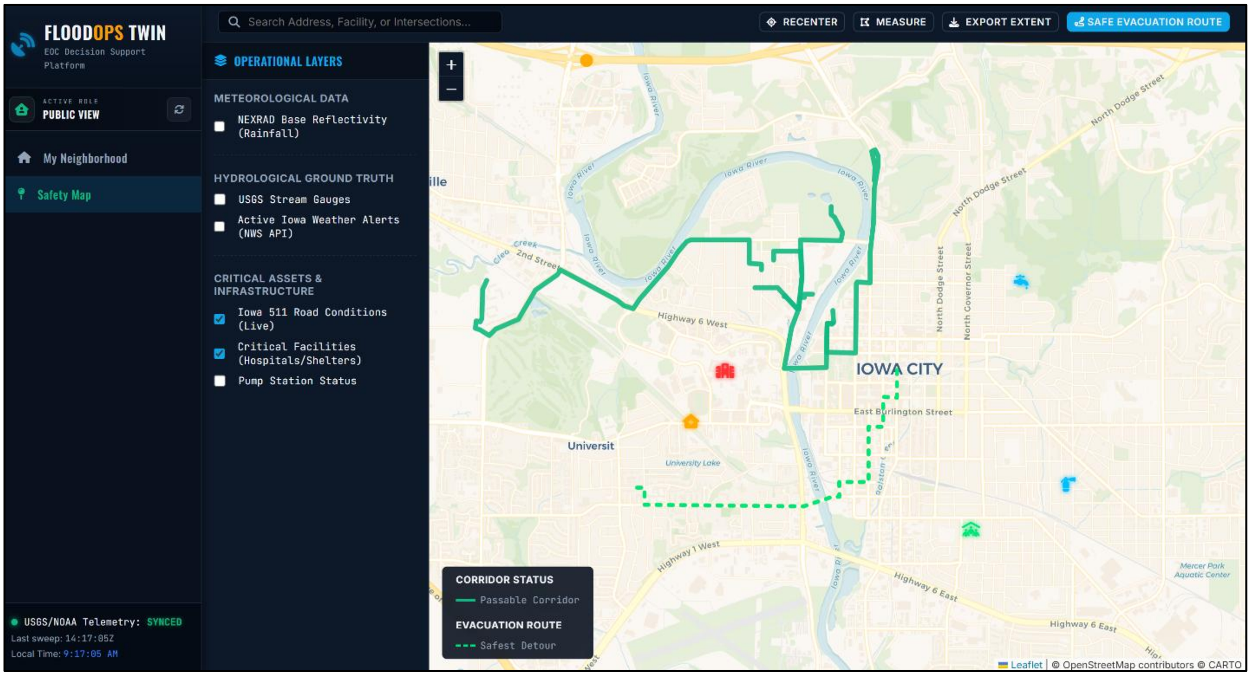
4.2. Iowa City Case Study Demonstration

4.2.1. Study Area and Simulation Environment

To demonstrate the practical applicability of the proposed framework, FloodOps Twin was implemented using Iowa City, Iowa as a representative urban flood environment. Iowa City was selected due to the historical significance of the 2008 Iowa River flood and the availability of hydrological, infrastructure, transportation, and socioeconomic datasets relevant to flood operations. During the 2008 event, prolonged rainfall and extreme river-stage escalation resulted in widespread flooding across eastern Iowa, producing substantial impacts to transportation systems, public infrastructure, institutional facilities, and residential communities (USGS, 2010; Iowa Flood Center, 2025). The case study therefore provides a realistic operational environment for evaluating how role-adaptive spatial intelligence can support flood response activities under historically grounded flood conditions.

4.2.2. Operational Escalation Scenario

The Iowa City implementation continuously synchronized real-time hydrological telemetry obtained from USGS stream gauge services with National Weather Service alerts, transportation status layers, infrastructure datasets, and parcel-level exposure information. Simulated river-stage escalation was subsequently used to evaluate how operational intelligence products evolved as flood severity increased. As flood stages approached predefined operational thresholds, the framework dynamically updated infrastructure indicators, transportation accessibility assessments, economic exposure estimates, and public communication products. This process demonstrated the ability of the platform to continuously adapt operational outputs according to changing environmental conditions while maintaining synchronization across all stakeholder environments.



METEOROLOGICAL DATA
☐ NEXRAD Base Reflectivity (Rainfall)

HYDROLOGICAL GROUND TRUTH
☐ USGS Stream Gauges
☐ Active Iowa Weather Alerts (NWS API)

CRITICAL ASSETS & INFRASTRUCTURE
☑ Iowa 511 Road Conditions (Live)
☑ Critical Facilities (Hospitals/Shelters)
☐ Pump Station Status

USGS/NOAA Telemetry: SYNCED
Last sweep: 14:17:05Z
Local Time: 9:17:05 AM

Figure 8: Public operational interface demonstrating simplified flood-risk communication, safe evacuation routing, transportation corridor awareness, and neighborhood-level situational guidance within the FloodOps Twin framework. The interface integrates synchro.

4.2.3. Cross-Role Intelligence Transformation

The case study illustrates the central principle of the RBSI framework: identical environmental conditions can generate substantially different intelligence products depending on operational context. For example, increasing river stages were interpreted as escalation indicators within the Emergency Manager environment, infrastructure priorities within the Public Works environment, mobility constraints within the Transportation environment, exposure metrics within the Planner environment, and safety guidance within the Public Communication environment. Despite these differences, all operational environments remained synchronized through a common telemetry foundation. This capability enables the framework to support differentiated operational workflows without fragmenting situational awareness across agencies and stakeholders. The Iowa City demonstration therefore highlights the potential of role-adaptive digital twin architectures to support cognitively efficient urban flood operations while preserving a shared operational understanding of evolving flood conditions.

5. Discussion

The results demonstrate that the FloodOps Twin framework can transform a shared flood telemetry environment into differentiated operational intelligence products tailored to stakeholder responsibilities. Unlike conventional flood dashboards that present identical information to all users, the proposed Role-Based Spatial Intelligence (RBSI) framework selectively filters and restructures synchronized hydrological, transportation, infrastructure, and exposure data according to operational context. This distinction is important because emergency managers, transportation coordinators, public works personnel, planners, and residents often require fundamentally different information despite responding to the same flood event.

A key contribution of the framework is its emphasis on contextual intelligence transformation rather than centralized visualization alone. Existing flood decision-support systems frequently focus on increasing information availability and situational awareness through integrated dashboards and geospatial visualization platforms. While such approaches improve data accessibility, they may also increase cognitive burden by requiring users to independently interpret large volumes of environmental and operational information. The FloodOps Twin framework addresses this challenge by translating synchronized telemetry into role-specific operational products, allowing stakeholders to focus on information most relevant to their decision-making responsibilities while maintaining a shared understanding of evolving flood conditions.

The Iowa City case study further demonstrated how identical environmental conditions can generate substantially different operational outputs depending on stakeholder needs. Rising river stages were interpreted as operational escalation indicators for emergency managers, infrastructure priorities for public works personnel, corridor accessibility constraints for transportation teams, exposure metrics for planners, and simplified safety guidance for public users. This capability highlights the potential value of role-adaptive digital twins for supporting coordinated flood response without fragmenting situational awareness across agencies.

The proposed framework also contributes to emerging research on urban digital twins and disaster informatics. Much of the current digital twin literature emphasizes sensor integration, infrastructure representation, and real-time monitoring capabilities (Fuller et al., 2020; Ketzler et al., 2020). In contrast, FloodOps Twin focuses on how synchronized urban telemetry can be operationally interpreted and transformed to support human-centered emergency management workflows. The framework therefore extends digital twin applications beyond infrastructure monitoring toward operational intelligence generation.

Several limitations should be acknowledged. First, the current study evaluated the framework as an operational simulation and decision-support environment rather than through formal usability testing. Consequently, reductions in cognitive workload, decision latency, and operational efficiency were not quantitatively measured. Second, the current implementation utilizes threshold-based operational logic rather than fully coupled hydrodynamic flood modeling. Although this improves responsiveness and interpretability, future implementations may benefit from integration with real-time hydraulic forecasting and probabilistic inundation models. Future research should also explore human-subject evaluations, predictive analytics, and AI-assisted decision-support capabilities to further enhance adaptive flood intelligence systems.

6. Conclusion

This study presented FloodOps Twin, a role-adaptive urban flood digital twin designed to transform synchronized environmental telemetry into stakeholder-specific operational intelligence. The proposed Role-Based Spatial Intelligence (RBSI) framework integrates real-time hydrological observations, meteorological information, transportation conditions, infrastructure datasets, and parcel-level exposure indicators within a unified spatial decision-support environment. Unlike conventional flood dashboards that expose all users to the same information environment, the framework dynamically adapts intelligence products according to operational responsibilities.

The framework was demonstrated using Iowa City, Iowa and the historical context of the 2008 Iowa River flood. Results showed that shared telemetry streams could be transformed into differentiated operational environments supporting emergency management, public works coordination, transportation planning, resilience analysis, and public communication. By maintaining a common situational awareness foundation while reducing information redundancy, the framework provides a mechanism for delivering more contextually relevant operational intelligence during rapidly evolving flood events.

The findings suggest that future urban flood management systems may benefit from emphasizing intelligence transformation rather than information accumulation alone. As cities become increasingly data-rich and operational environments continue to grow in complexity, role-adaptive digital twins offer a promising approach for supporting more efficient, scalable, and human-centered emergency management. Future work should focus on formal usability assessment, integration of predictive flood forecasting models, and incorporation of AI-driven analytics to further strengthen operational decision support within urban flood digital twin environments.

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