City-Scale Digital Twin Framework for Flood Impact Analysis: Integrating Urban Infrastructure and Real-time Data Analytics

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Abstract

Urban areas are increasingly vulnerable to flooding due to climate change and rapid urbanization. Traditional mapping and decision-support tools lack the capability to integrate real-time data or analyze cascading disruptions across interconnected urban systems. Digital twins offer a promising solution by enabling real-time monitoring, simulation, and optimization of urban environments. This study presents a comprehensive city-scale digital twin framework that integrates flood forecasting, transportation networks, and critical infrastructure systems into a unified, real-time cyberinfrastructure. By leveraging data from sensors, hydrological models, and geographic information systems (GIS), the framework enables interactive, three-dimensional simulations to assess flood impacts and their cascading effects on urban mobility and infrastructure. Using Waterloo, Iowa, as a case study, we demonstrate the framework's ability to simulate flood scenarios, assess transportation disruptions, and generate actionable insights for disaster preparedness. The results highlight the framework's potential to enhance urban resilience by providing a holistic understanding of interdependent urban systems, supporting data-driven decision-making, and advancing flood risk management strategies.

Keywords: Digital twin, decision support, hydrological data, flood impact, urban infrastructure.

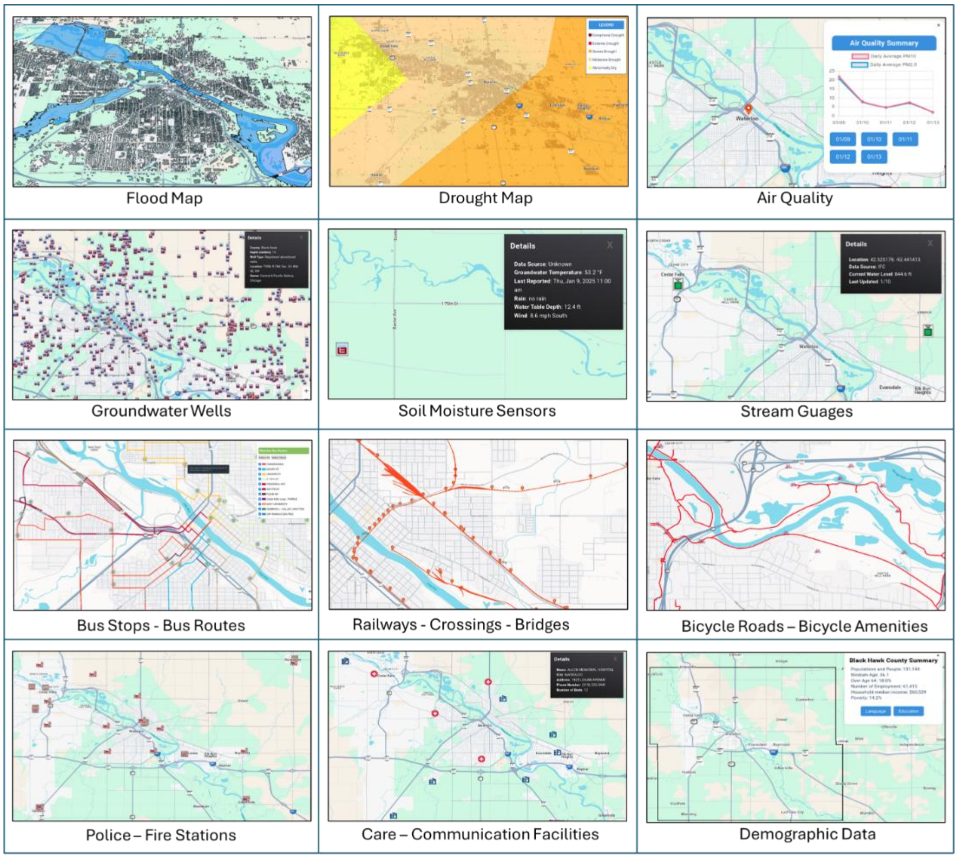
Software Availability

Name	City-Scale Digital Twin Framework
Developers	Sümeyye Kaynak, Baran Kaynak
Software required	Web Browser
Program language	JavaScript, HTML, CSS
Availability and cost	The code is open-source, licensed under the MIT License, and freely accessible on GitHub.
Code repository	https://github.com/uihilab/CityDigitalTwin

Highlights:

- Integrates multiple urban data sources (hydrological, transportation, and infrastructure) for comprehensive flood analysis.
- Incorporates real-time data, urban systems, and geospatial modeling to enhance flood impact assessment.
- Optimizes emergency response planning through real-time traffic rerouting and facility accessibility analysis.
- Provides faster and more scalable flood damage estimation compared to traditional models.
- Delivers actionable insights to improve urban resilience and disaster preparedness.

Graphical Abstract:



Flood Map
Drought Map
Air Quality
Groundwater Wells
Soil Moisture Sensors
Stream Guages
Bus Stops - Bus Routes
Railways - Crossings - Bridges
Bicycle Roads – Bicycle Amenities
Police – Fire Stations
Care – Communication Facilities
Demographic Data

1. Introduction

The concept of digital twins has emerged as a transformative technological advancement, particularly in the realm of smart cities (Deren et al., 2021; Ford & Wolf, 2020). Initially developed for product lifecycle management in the manufacturing sector, digital twins have evolved to encompass applications across diverse industries, including transportation (Kaewunruen et al., 2021; Lv et al., 2022), energy (Enders & Hoßbach, 2019), agriculture (Pylianidis et al., 2021), healthcare (Elayan et al., 2021; Jimenez et al., 2020), as well as artificial intelligence (AI) (Kharchenko et al., 2020), Internet of Things (IoT) (Kaur et al., 2020), and big data (Tao et al., 2018). At its core, a digital twin is a dynamic, virtual representation of a physical asset, system, or process, continuously updated with real-time data from sensors and other sources (Armstrong, 2020; Sermet et al., 2020). This enables accurate monitoring, simulation, and optimization of the physical entity it replicates (Qian et al., 2022).

As cities expand and urban environments grow more complex, the ability to simulate and analyze real-world systems has become an indispensable tool for urban planners and decision-makers (Dembski et al., 2020; Beck at al., 2009). When applied at a city scale, digital twins can revolutionize how cities manage resources, plan for growth, and respond to critical hazards. Cities consist of interconnected systems, including infrastructure, transportation networks, utilities, environmental monitoring, and public services (Ghaith et al., 2021). Managing these systems efficiently is a significant challenge, especially as traditional approaches often rely on siloed systems for each domain (e.g., transportation, energy, or environmental data), which fail to capture interdependencies across systems.

With the increasing frequency and intensity of natural disasters due to climate change, cities face heightened risks from events like floods, storms, and heatwaves (Henriksen et al., 2023). Accurate modeling of interdependencies among city infrastructures is essential for developing effective preparedness and mitigation plans (Yildirim et al., 2023). This has led to advancements in digital twin technology, enabling virtual replication of city systems to analyze their behavior under various scenarios (Ivanov et al., 2020). A city digital twin integrates all urban infrastructure systems, including intra- and inter-dependencies, as well as human-infrastructure interactions (Mudiyanselage et al., 2024). Applying natural hazards, such as flooding, to these digital twins allows for real-life simulations, enabling city officials to evaluate response strategies and minimize potential impacts (Ford & Wolf, 2020; Lu et al., 2020).

The development of a city-scale digital twin requires extensive data inputs collected from various sources, such as sensors, IoT devices, surveillance cameras, and satellites (Ramu et al., 2022; Demir et al., 2015). Several cities have successfully employed digital twins for specific purposes. For instance, the digital twin of Zurich, under development since 1990, facilitates urban planning in response to expected population growth (Schrotter & Hürzeler, 2020). Similarly, Helsinki's digital twin, initiated in the 1980s for urban development, now serves as a platform for city management and design (Ruohomäki et al., 2018). Singapore's Virtual Singapore exemplifies the use of digital twins to optimize urban systems and improve resilience against environmental risks like flooding (National Research Foundation, 2014). These examples illustrate the potential of digital twins as comprehensive platforms for enhancing urban resilience. However, many existing frameworks are limited in scope, often focusing on specific domains such as transportation or environmental monitoring, without fully integrating all aspects of urban life into a multi-layered model.

Flooding is one of the most disruptive natural disasters, particularly for cities with dense populations and vulnerable infrastructure (Borowska-Stefańska et al., 2017; McDermott, 2022). Between 1980 and 2022, the United States experienced 37 flood disasters, each causing 50 or more fatalities and over one billion dollars in damages (Smith, 2020). Despite efforts to mitigate flood risks (Yildirim et al., 2022), flooding remains a persistent and growing threat due to factors such as poor urban planning, climate change, and increasing population density (Kundzewicz et al., 2014). Effective flood forecasting (Krajewski et al., 2021) and real-time analysis of flood impacts on critical city systems can provide invaluable insights for emergency response and disaster preparedness (Sit et al., 2021). This evolving risk requires urgent actions to develop long and short-term plans and strategies for effective food risk management (Reisinger et al., 2020; Tanir et al., 2024). Flood risk management requires a detailed understanding of hazards, exposure, and vulnerability (Reisinger et al., 2020; Cikmaz et al., 2023). Identifying at-risk areas and assessing the potential consequences of flooding are key steps in minimizing damage and ensuring urban resilience (Alabbad et al., 2023; 2024; Tingsanchali, 2012).

WebGL technology has become a widely adopted standard for rendering interactive 3D graphics within web browsers, enabling visualization of urban environments with features such as route optimization, traffic analysis, infrastructure mapping and water delineation (Sit et al., 2019). Similarly, widely used web-based mapping technologies provide navigation and real-time traffic updates, yet their capabilities are often limited when it comes to integrating multi-layered urban data or simulating the cascading impacts of disruptions like flooding. For instance, while these tools can display flooded areas or reroute users around disruptions, they typically lack the ability to model how flooding affects emergency response times, public transit availability, or utility network stability. By contrast, city-scale digital twins, such as the Snap4City framework, offer a comprehensive approach by integrating real-time data on flooding with additional layers like 3D building models, traffic flow representations, and interactive icons for points of interest (Adreani et al., 2024). This enables urban planners and decision-makers to dynamically analyze interconnected systems and proactively respond to flood-related scenarios, extending the capabilities of WebGL-based visualizations with predictive insights and multi-data integration.

Despite progress in digital twin technology, current digital twin frameworks often face significant limitations. First, they tend to focus on specific domains, such as transportation or environmental monitoring, without integrating other critical urban infrastructures (Alperen et al., 2021; Rezaei et al., 2023; Zheng et al., 2022). For example, a transportation-focused digital twin may lack real-time environmental data, such as flood forecasts or air quality measurements, which limits its ability to provide a comprehensive view of urban resilience. Second, many existing frameworks are constrained by their data management capabilities. Integrating and processing large, heterogeneous datasets from sources such as sensors, GIS systems, and hydrological models remains a significant technical challenge (Argyroudis et al., 2022). Lastly, visualization capabilities in many digital twin platforms are static or two-dimensional, limiting their effectiveness for interactive scenario analysis (Fuller et al., 2020; Demir et al., 2009).

To address these limitations, our study proposes a comprehensive digital twin framework designed to integrate flood related datasets with transportation networks and other critical infrastructure systems. Unlike existing models, the framework provides a holistic, multi-layered view of urban systems, enabling decision-makers to analyze the cascading impacts of disruptions. For example, the framework can simulate how flooded roads affect amenities, public transit accessibility, and even energy grid stability. This integrated approach ensures that city planners can visualize the interdependencies of urban systems and develop more effective disaster preparedness and response strategies. The framework leverages advanced data integration techniques to process real-time feeds from diverse sources, such as sensors, hydrological models, GIS systems, and IoT networks. By incorporating different flood maps and urban mobility analysis, the framework enables dynamic analysis of flood impacts under various scenarios. Furthermore, it features enhanced visualization capabilities, offering interactive, three-dimensional models that allow city officials to explore flood scenarios in real time. This level of detail helps bridge the gap between flood risk assessment and actionable insights for urban planning.

To demonstrate the applicability of our framework, we developed a digital twin for Waterloo, Iowa—a city that faces significant flood risks due to its proximity to rivers and low-lying areas. By integrating data from hydrological models, GIS systems, and real-time sensors, the digital twin of Waterloo provides a comprehensive tool for simulating flood impacts and analyzing transportation and infrastructure disruptions. For instance, it can simulate how flood waters would render certain road networks impassable, disrupt public transit routes, and delay emergency services. This allows city planners to evaluate the effectiveness of various mitigation strategies and make data-driven decisions to enhance urban resilience. The primary objectives of this framework are to (1) integrate flood maps into critical urban infrastructure datasets to assess vulnerability; (2) analyze cascading failures across transportation and public services due to flooding; and (3) provide actionable insights to support urban resilience and disaster preparedness.

The remainder of this manuscript is structured as follows: The Methodology section describes the design and architecture of our digital twin framework, including its Data Layer, Application Layer, and User Interface Layer, which enable real-time flood impact analysis. Results and Discussion section presents the case study of Waterloo, demonstrating the framework's capabilities through four key use cases: urban system visualization, flood impact on transportation, facility accessibility analysis, and community-level damage estimation. These analyses highlight how the framework integrates real-time data to assess urban vulnerabilities and optimize emergency response. Finally, the Conclusion and Future Work section summarizes the study's key contributions to urban flood resilience and disaster preparedness, while also outlining potential advancements for future research.

2. Methodology

This study presents city-scale digital twin platform designed to access flood impacts and support resilience planning. The platform integrates diverse geospatial and real-time data sources into unified system, enabling dynamic modeling, simulation, and visualization of urban environments. The City-Scale Digital Twin Framework is tested with a case study for Waterloo, Iowa, given its significant historical flood events and the availability of urban and hydrological data. The framework is structured into three main layers: Data Layer, Application Layer, and User Interface Layer, as illustrated Figure 1.

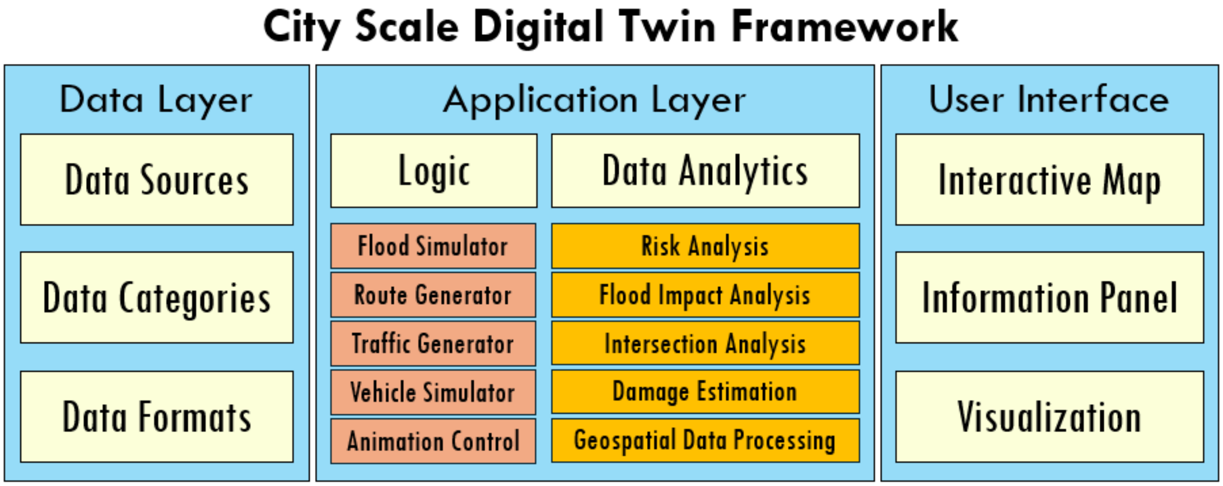


Figure 1. Diagram of the City Scale Digital Twin Framework

2.1. Data Layer

The Data Layer is responsible for acquiring, processing, and standardizing multi-source datasets, ensuring real-time accessibility and seamless integration into the digital twin system. Data is obtained from sensors, APIs, remote sensing platforms, and public datasets, which are processed to maintain spatial and temporal accuracy. The real-time data is continuously fetched from APIs and sensor networks to ensure up-to-date environmental and infrastructure monitoring. Heterogeneous datasets, such as GeoJSON, KML, and Shapefile, are standardized into a unified format to facilitate efficient aggregation and processing. The framework supports multi-format data handling, allowing seamless filtering, grouping, and transformation based on analytical needs. By integrating diverse datasets, the digital twin provides a holistic representation of urban systems, allowing for real-time monitoring, predictive modeling, and scenario analysis.

The framework incorporates a diverse range of data categorized into four key domains: Infrastructure, Weather and Environment, Transportation, and Public Services as shown in Table 1. Each category consists of various datasets that capture different aspects of urban functionality and resilience. Infrastructure data includes static and semi-dynamic datasets that represent the physical and built environment of the city. These datasets provide the foundational elements for flood impact analysis by identifying key assets and their spatial relationships. The infrastructure data used in the digital twin framework includes critical physical structures such as buildings, bridges, railway crossings, power plants, and wastewater treatment facilities. This static data acts as the base for modeling and analyzing the physical structures of a city.

Weather and environmental data provide real-time and forecasted conditions to support flood impact assessments and predictive modeling. These dynamic datasets enable the integration of climate variables, air quality indicators, and hydrological conditions into the digital twin framework. The environmental data sources include weather forecasts, air quality data, drought maps, flood maps, and real-time sensor readings. High-resolution flood hazard maps from the Iowa Flood Information System (IFIS) provide real-time flood extent data, depth estimations, and historical flood records. Hydrological and environmental sensors placed along rivers, stormwater drainage systems, and urban monitoring stations collect real-time data on water levels, precipitation, and soil moisture conditions and further enhance environmental monitoring capabilities.

Table 1. Data categories and sources

Category	**Data**	**Source**
Infrastructure	Buildings, Bridges, Bicycle amenities, Railway crossing, Railway bridge, Electric power plants, Wastewater treatment plants, Groundwater wells	IOWA DOT, IFIS
Weather & Environment	Weather forecast, Air quality, Drought, Flood maps, Sensor data	Open-Meteo, waqi.info, U.S. Drought Monitor, IFIS
Transportation	Road network, Public transit, Bicycle network	OpenStreetMap, IOWA DOT
Public Services	Demographics, Schools, Police stations, Fire stations, Care facilities, Communication facilities	U.S. Census Bureau, IOWA Geospatial Data Clearinghouse, IOWA Black Hawk County

Transportation data a critical component of the digital twin framework, providing a comprehensive view of urban mobility and allowing for the simulation of flood-induced disruptions in mobility networks. These datasets provide a detailed understanding of how roadways, public transit, and alternative transportation modes interact with flood events. The transportation data sources include road networks, public transit networks, railway networks, and bicycle networks. The road network data from OpenStreetMap (OSM) includes detailed information on streets, highways, and intersections. Bus and rail transit routes from Iowa DOT provide insights into public transportation accessibility.

Public services data provide essential insights into the accessibility and resilience of critical facilities during flood events. This dataset category focuses on key services such as emergency response, healthcare, education, and demographic distributions. The dataset is a static data and include demographic data, schools and educational institutions, police and fire stations, hospitals and health care facilities, senior centers, and communication facilities. Demographic information from the U.S. Census Bureau provides population distribution, socioeconomic indicators, and household characteristics. Additionally, Black Hawk County GIS data provides the locations of law enforcements, fire departments, hospitals, clinics, medical center, telecommunication towers, broadcasting stations, and care centers, facilitating accessibility analysis and facility mapping.

To ensure interoperability across different datasets, the digital twin framework normalizes and integrates data into a common format. Geospatial datasets are stored in formats such as GeoJSON, Shapefile (SHP), and KML to maintain spatial accuracy and facilitate visualization. Real-time sensor feeds and API-based data sources are ingested into the system at regular intervals, allowing continuous updates to flood extent, traffic conditions, and infrastructure status. The processed data is structured into a multi-layered system, where each dataset is linked to relevant simulation models and visualization components. By combining infrastructure, environmental, transportation, and public services data, the digital twin enables a detailed analysis of how flood events disrupt urban systems. The comprehensive nature of these datasets ensures that the framework can support a wide range of applications, from emergency response planning to long-term urban resilience strategies.

2.2. Application Layer

The Application Layer serves as the computational backbone of the digital twin, responsible for processing, analyzing, and simulating data to generate actionable insights. It is composed of two core modules: Logic, and Data Analytics & Core Functions. Each of these components plays a distinct role in the operational workflow of the digital twin system.

2.2.1. Application Logic

The Logic module governs data ingestion, processing, and simulation workflows. The core components are Data Importer, Flood Simulator, Route Generator, Traffic Generator, Vehicle Simulator, Animation Control. These interconnected sub-modules enable realistic, data-driven simulations of flood scenarios and urban dynamics.

The Data Importer acts as the primary gateway for bringing external data into the digital twin system. It standardizes geospatial and numerical datasets into a common format, ensuring compatibility with internal processing pipelines. This module preprocesses datasets by filtering redundant information, normalizing metadata, and applying georeferencing where necessary. For instance, road network data imported from OpenStreetMap undergoes transformation into the internal RoadModel format, which is later used in transportation simulations.

The Flood Simulator is responsible for integrating hydrological data and generating flood extent predictions under different scenarios. It operates using user-defined parameters, such as return periods (e.g., 25-year, 100-year, and 500-year floods), real-time precipitation data, and historical flood records. The module identifies flood-affected regions by overlaying flood extent maps onto urban infrastructure layers, enabling dynamic risk assessments.

The Route Generator is a critical component that recalculates transportation accessibility when flooding disrupts normal routes. Using Dijkstra’s algorithm, it computes the optimal paths for vehicles by treating the road network as a graph, where intersections serve as nodes and road segments act as edges. The module generates alternative travel routes based on user defined traffic and environmental conditions.

The Traffic Generator creates realistic traffic simulations by assigning vehicle movements to road networks based on predefined patterns. Users can specify parameters such as traffic density, congestion levels, and vehicle distribution through an interactive interface. The resulting output consists of time-stamped vehicle routes and traffic flow patterns, forming the basis for realistic movement simulations.

The Vehicle Simulator models the behavior of different vehicle types, including cars, buses, and trains, under normal and flood conditions. Each vehicle follows a distinct movement logic based on predefined parameters such as speed, looping and directional pattern. Public transit vehicles, such as buses, are programmed to follow scheduled routes, while private vehicles respond dynamically to traffic conditions.

The Animation Control module translates simulation outputs into visually engaging animations. It processes movement data frame-by-frame, updating vehicle positions, road accessibility, and environmental conditions in real-time. The animations are optimized using Deck.gl’s ScenegraphLayer, which ensures efficient rendering of dynamic elements such as moving vehicles and fluctuating flood extents.

2.2.2. Data Analytics and Core Functions

The Data Analytics and Core Functions module provides advanced analytical tools to assess the impacts of flooding on transportation, infrastructure, and public services. This module integrates historical and real-time datasets to generate predictive insights, allowing stakeholders to develop informed mitigation strategies. The key analytical functions are given below:

The Risk Analysis module evaluates the severity and spatial extent of flood impacts across urban infrastructure systems. This analysis combines historical and simulated flood data, and transportation network information to estimate potential disruptions. The system categorizes affected regions based on flood severity, enabling decision-makers to prioritize interventions for high-risk areas.

The Flood Impact Analysis module assesses the consequences of flooding on mobility and infrastructure. By overlaying flood maps onto urban datasets, the system identifies road segments, transit routes, and key facilities at risk. The analysis considers multiple factors, including flood depth, infrastructure resilience, and alternative routing options, to generate a holistic understanding of flood-induced disruptions. Figure 2 illustrates in detail how this module works. The process begins with the Data module, which collects and structures road and flood condition data. This data is then passed to the Simulator module, where road accessibility is adjusted based on flood risk levels. The adjusted data is transformed into animations and visualizations, which are presented to users via the User Interface module.

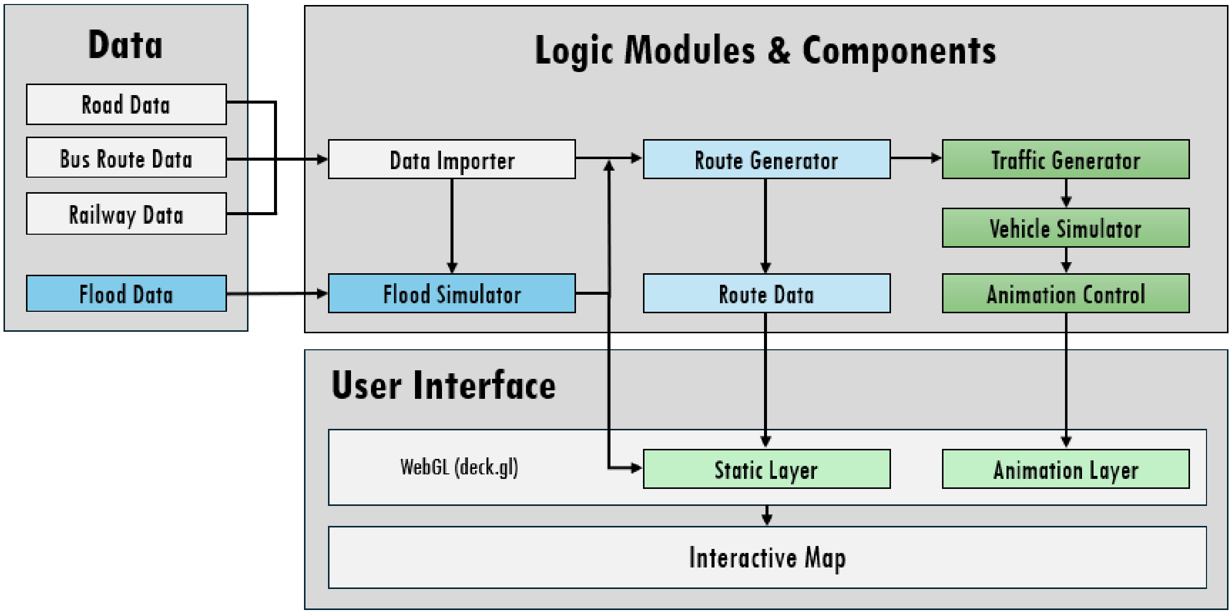


Figure 2. Flood Impact on Transportation Analysis Process Diagram

The Intersection Analysis function examines spatial overlaps between flood zones and critical infrastructure, such as power substations, hospitals, and emergency service hubs. Using geospatial algorithms, the system identifies vulnerable locations (i.e., school, bus stop, power grid node, etc.) and quantifies the potential impact on urban services. This analysis is instrumental in guiding emergency response planning and resource allocation.

The Damage Estimation module utilizes depth-damage curves and high-resolution flood maps to quantify potential losses associated with flood events. The system estimates structural and content damage for buildings based on inundation depth, construction type, and land use classification. Real-time hydrological data from USGS and the IFIS enhances the accuracy of damage predictions, enabling emergency responders to develop targeted recovery plans.

Geospatial data processing functions ensure that datasets are structured, queried, and visualized effectively. The digital twin system leverages PostGIS for spatial analysis, allowing efficient retrieval of data layers related to roads, buildings, flood zones, and public services. Advanced spatial queries enable users to assess the impact of flooding on specific areas, facilitating interactive decision-making.

2.3. User Interface Layer

The User Interface (UI) Layer serves as the primary interaction point for users, facilitating seamless exploration of data, analysis results, and real-time simulations. Designed to be intuitive, responsive, and interactive, the UI ensures that urban planners, emergency responders, and decision-makers can efficiently access and interpret flood impact scenarios. The interface integrates multiple visualization and control components, allowing users to manipulate data layers, interact with simulation outputs, and derive actionable insights.

2.3.1. Architecture and Components

The UI Layer consists of three major components (shown in Figure 3): Menu System, Interactive Map, and Information Panel, each structured to enhance user engagement and improve accessibility to critical data.

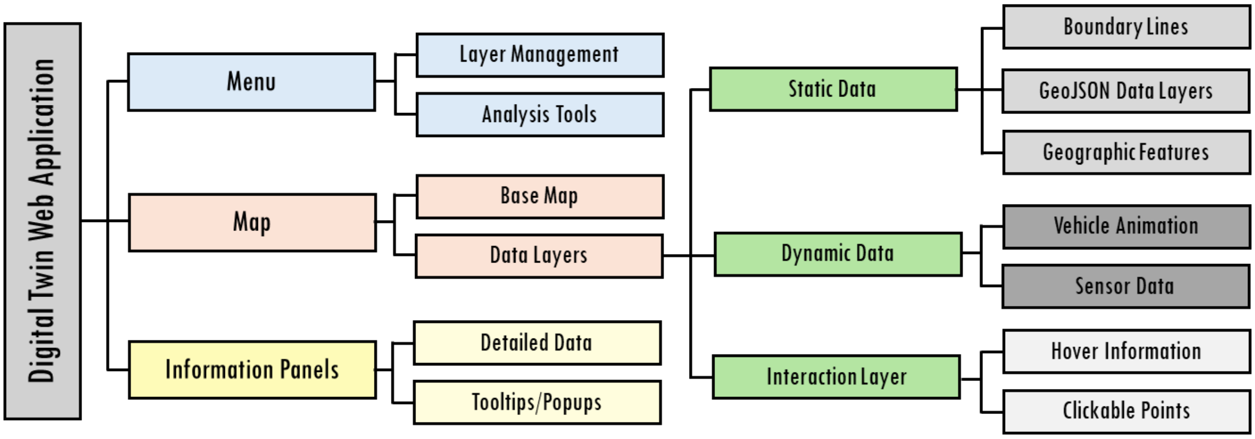


Figure 3. Digital Twin application user interface hierarchy diagram

The Menu System acts as the control center of the digital twin interface, providing a structured way for users to navigate the platform and interact with different data layers and analytical tools. It allows users to toggle data layers on or off, customizing the visual representation based on their analysis needs. Base layers include the default Google Maps background and static urban infrastructure layers such as roads, bridges, and buildings. Flood layers display real-time flood maps with selectable return periods, such as 25-year, 100-year, and 500-year floods. Transportation layers provide overlays for road networks, public transit routes, and alternative transportation options such as bike lanes. Public services layers show the locations of critical facilities such as hospitals, emergency services, and schools. Each layer is visually distinct, ensuring clarity in complex multi-layered analyses, and users can activate multiple layers simultaneously to explore interdependencies between different urban systems.

In addition to layer management, the menu system provides access to analytical tools that enable users to perform scenario-based simulations and custom queries. The flood impact simulation tool allows users to select a flood scenario and observe its impact on transportation and infrastructure. The traffic rerouting simulation computes and visualizes real-time rerouting of vehicles in response to road closures, ensuring efficient mobility even under flood conditions. The facility accessibility analysis identifies how flooding affects access to key services such as hospitals and emergency shelters. The damage estimation module provides quantitative assessments of potential structural and economic losses based on selected flood depths. Each tool integrates seamlessly with the visualization components, ensuring that users can see the immediate results of their analyses.

The Interactive Map serves as the central visualization platform, providing a dynamic interface where users can explore flood impacts, transportation disruptions, and facility accessibility. The map is powered by Google Maps API and enhanced with WebGL-based rendering using Deck.gl, ensuring high-performance visualizations in real-time. The base map serves as a foundational geographic reference, providing street-level details, terrain features, and navigation tools. Overlaid on this base map are multiple data layers that dynamically update based on user selections. These layers include flood zones, which display flood extents and water depth using gradient color schemes, allowing users to differentiate between low-risk and high-risk areas. Road closures and affected routes highlight roads that become impassable due to flooding, dynamically updating based on scenario selections. Vehicle simulations animate vehicle movement across the transportation network, showcasing how flooding disrupts mobility patterns. The facility impact visualization highlights facilities affected by flooding, color-coded based on risk levels.

The Information Panel serves as a data-rich dashboard that presents detailed statistics, summaries, and visual analytics. This component is crucial for interpreting the results of flood impact simulations and transportation analyses. The panel is divided into three main sections: summary insights, graphical data representations, and custom reports. The summary insights section provides key metrics related to the selected flood scenario, including the total number of affected road segments, public transit disruptions, facility accessibility impacts, and projected damage costs. This high-level summary gives users a quick overview of the flood’s anticipated effects.

2.3.2. Visualization Components

The Visualization module is responsible for rendering simulation outputs, enabling users to explore flood scenarios, traffic conditions, and infrastructure disruptions interactively. By integrating WebGL technology with the Deck.gl library, the platform ensures real-time, browser-based visualizations that allow stakeholders to interactively analyze urban systems.

The system distinguishes between static and dynamic data layers to optimize performance and minimize computational overhead. Static layers, such as road networks, bridges, and buildings, remain unchanged throughout the simulation and are rendered only once. These layers provide a foundational representation of the urban environment and serve as a base for all simulations. Dynamic layers, including traffic flows, flood extent, and vehicle movements, update continuously to reflect changing conditions. By separating these layers, the system ensures that only elements affected by real-time updates are re-rendered, leading to enhanced computational efficiency and improved visualization responsiveness.

To further optimize performance, the visualization module employs several rendering techniques that enhance user experience. One such technique is viewport filtering, which ensures that only elements within the user’s screen view are rendered, significantly reducing processing load. As users pan or zoom across the platform, rendering is dynamically adjusted to maintain smooth interactions without unnecessary computations. Additionally, animation frame interpolation is used to provide seamless transitions between different simulation states, preserving visual continuity even during complex analyses. This technique smooths abrupt changes in flood extent and vehicle movement, resulting in a more realistic and immersive simulation.

A key component of the visualization module is the integration of animated vehicle movements, which represent the effects of flooding on transportation networks. The Vehicle Simulator processes movement data for different vehicle types, including buses, private cars, and trains, and translates their behavior into 3D animations. These animations are displayed using Deck.gl's ScenegraphLayer, which renders 3D vehicle models and dynamically updates their position based on simulation parameters. Each vehicle type follows predefined movement logic, incorporating factors such as speed adjustments, rerouting decisions, and congestion responses. The system integrates Google Maps as the base map layer, ensuring intuitive navigation and a familiar geographic context. The interactive interface allows users to toggle between different flood scenarios, inspect affected infrastructure, and analyze alternative transportation routes.

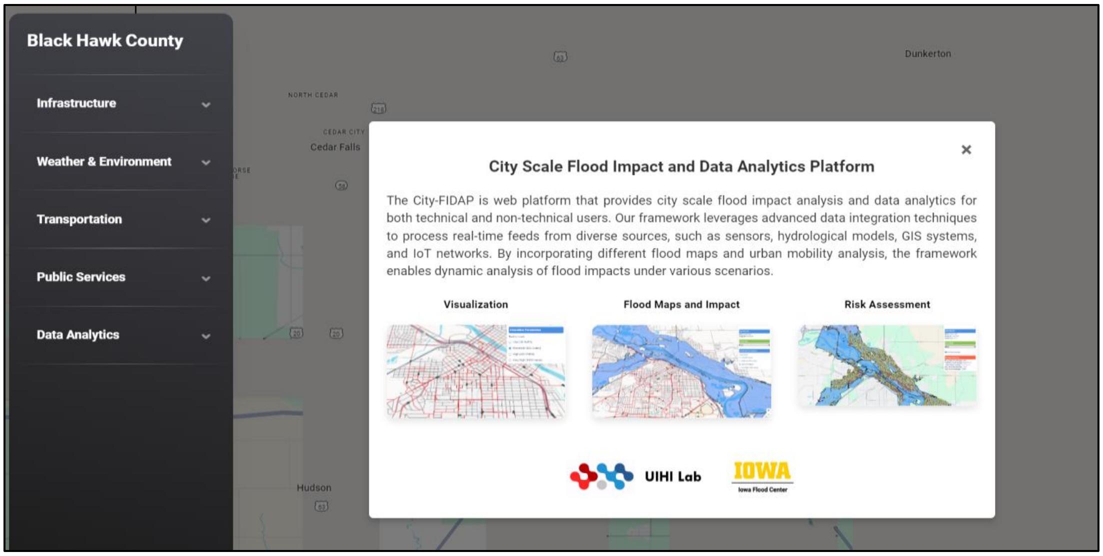
3. Results and Discussions

The developed framework is designed to provide comprehensive city scale flood impact analysis, integrating real-time data and simulation tools to support urban resilience planning. The framework enables users to visualize flood scenarios, analyze transportation disruptions, and assess the accessibility of critical infrastructure under different flood conditions. The main interface of the framework allows the user to select different attributes and data analytic tools (see Figure 4). This section presents four key use cases that demonstrate the framework's capabilities, with a focus on urban system visualization, flood impact on transportation, facility accessibility, and community-level damage assessment. Each use case is applied to Waterloo, Iowa, a city with a history of significant flooding events, to validate the framework's effectiveness in real-world scenarios.

3.1. Case Study Area

The State of Iowa is among the most flood-prone areas in the United States, with numerous river systems that frequently cause inundation in urban and agricultural regions. Waterloo, located in Black Hawk County, is particularly vulnerable to riverine flooding due to its proximity to the Cedar River. Historically, major flood events, such as the 2008 Iowa flood, have caused widespread damage to infrastructure, displaced thousands of residents, and resulted in billions of dollars in losses (USGS, 2010). During the catastrophic 2008 flood, 85 counties in Iowa were declared federal disaster areas, with Waterloo and Cedar Falls experiencing severe inundation. The Cedar River reached its second-highest crest on record, submerging roads, damaging critical infrastructure, and overwhelming emergency response systems (NWS, 2009).

The study area focuses on Black Hawk County, encompassing Waterloo and Cedar Falls, which together account for over 80% of the county's population. Waterloo's urban infrastructure includes a mix of residential, commercial, and industrial zones, along with vital public services such as hospitals, schools, police and fire stations, wastewater treatment plants, and power facilities. This diversity makes Waterloo an ideal test case for assessing the digital twin's capability to simulate and analyze flood-related disruptions



City Scale Flood Impact and Data Analytics Platform

The City-FIDAP is web platform that provides city scale flood impact analysis and data analytics for both technical and non-technical users. Our framework leverages advanced data integration techniques to process real-time feeds from diverse sources, such as sensors, hydrological models, GIS systems, and IoT networks. By incorporating different flood maps and urban mobility analysis, the framework enables dynamic analysis of flood impacts under various scenarios.

Figure 4. Main landing page of city scale digital twin framework

3.2. Use Case 1: Visualization of Urban Systems and Facilities

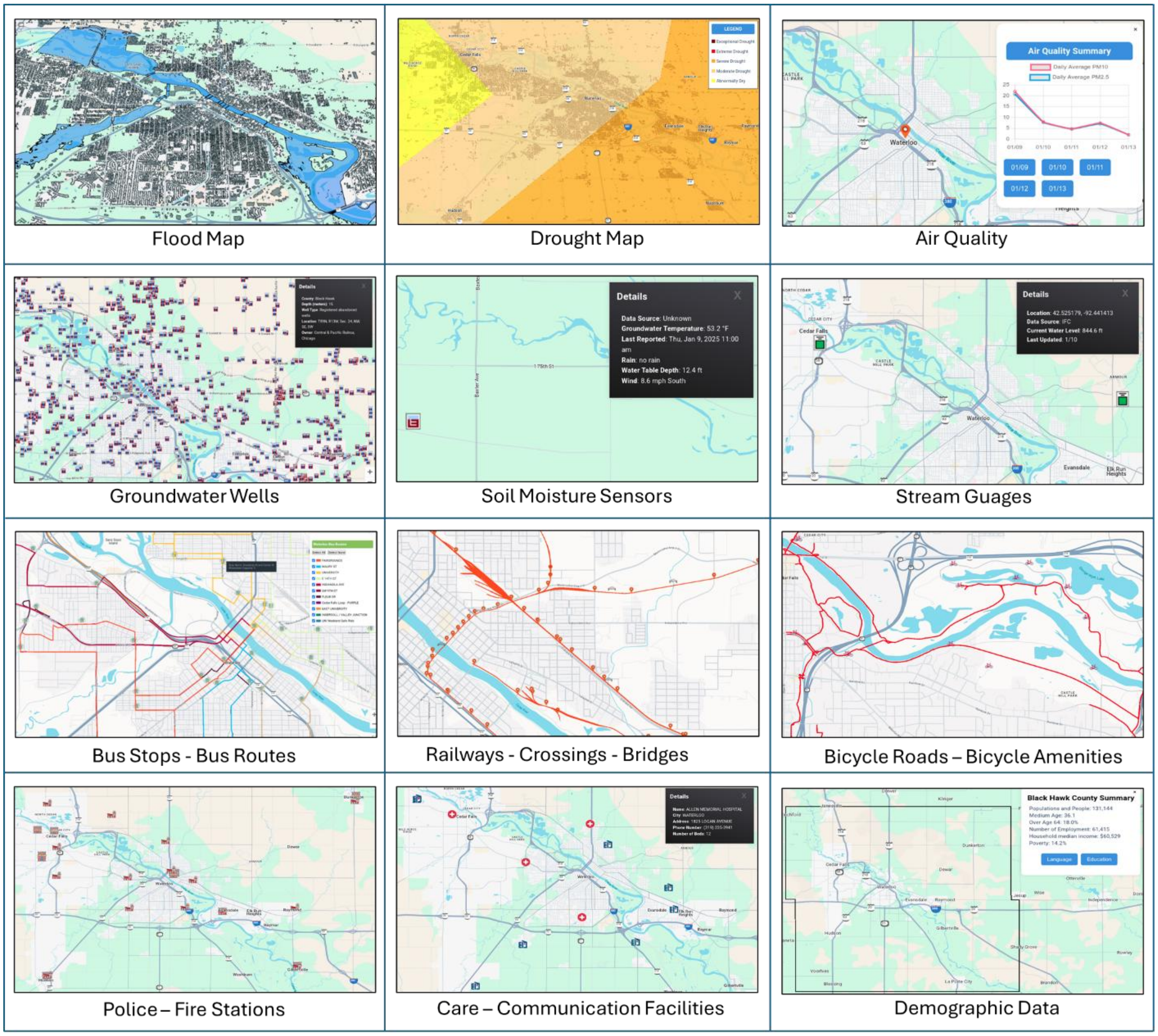
The City-Scale Digital Twin Framework provides an interactive map-based environment that enables users to visualize multiple layers of urban infrastructure and environmental data. The system integrates Google Maps as a base layer and allows users to overlay datasets related to transportation networks, critical facilities, and environmental conditions. The visualization platform supports the display of real-time data feeds, such as weather conditions, air quality, and sensor data, allowing users to analyze urban dynamics in different scenarios.

The framework enables users to explore the spatial distribution of facilities such as schools, hospitals, police stations, and emergency shelters, as well as the road and transit networks that connect them. Figure 5 illustrates a sample visualization where users can select different data layers to assess urban accessibility. By integrating multi-source datasets into an interactive map, the system enhances situational awareness and decision-making capabilities for urban planners and emergency managers.

3.3. Use Case 2: Flood Impact on Transportation

Flooding can severely disrupt transportation networks by submerging roads, damaging bridges, and forcing the suspension of public transit services. This use case examines the impact of flooding on the transportation infrastructure within the Waterloo area, focusing on how floodwaters affect road accessibility and public transit operations. The digital twin integrates flood maps, road and train network data, and bus routes to create a comprehensive transportation simulation under different flood scenarios.

The analysis is conducted based on flood maps corresponding to different flood scenarios provided by IFIS. The system allows users to select between various flood return periods (e.g., 25-year, 100-year, and 500-year floods) and visualize the extent of road inundation. Once a flood scenario is selected, the framework dynamically computes the affected road segments, marking them as impassable on the map. Then, it determines intersections between the flood-affected regions and the city's road network. This assessment includes highways, local roads, bus routes, and railway lines to identify areas at risk.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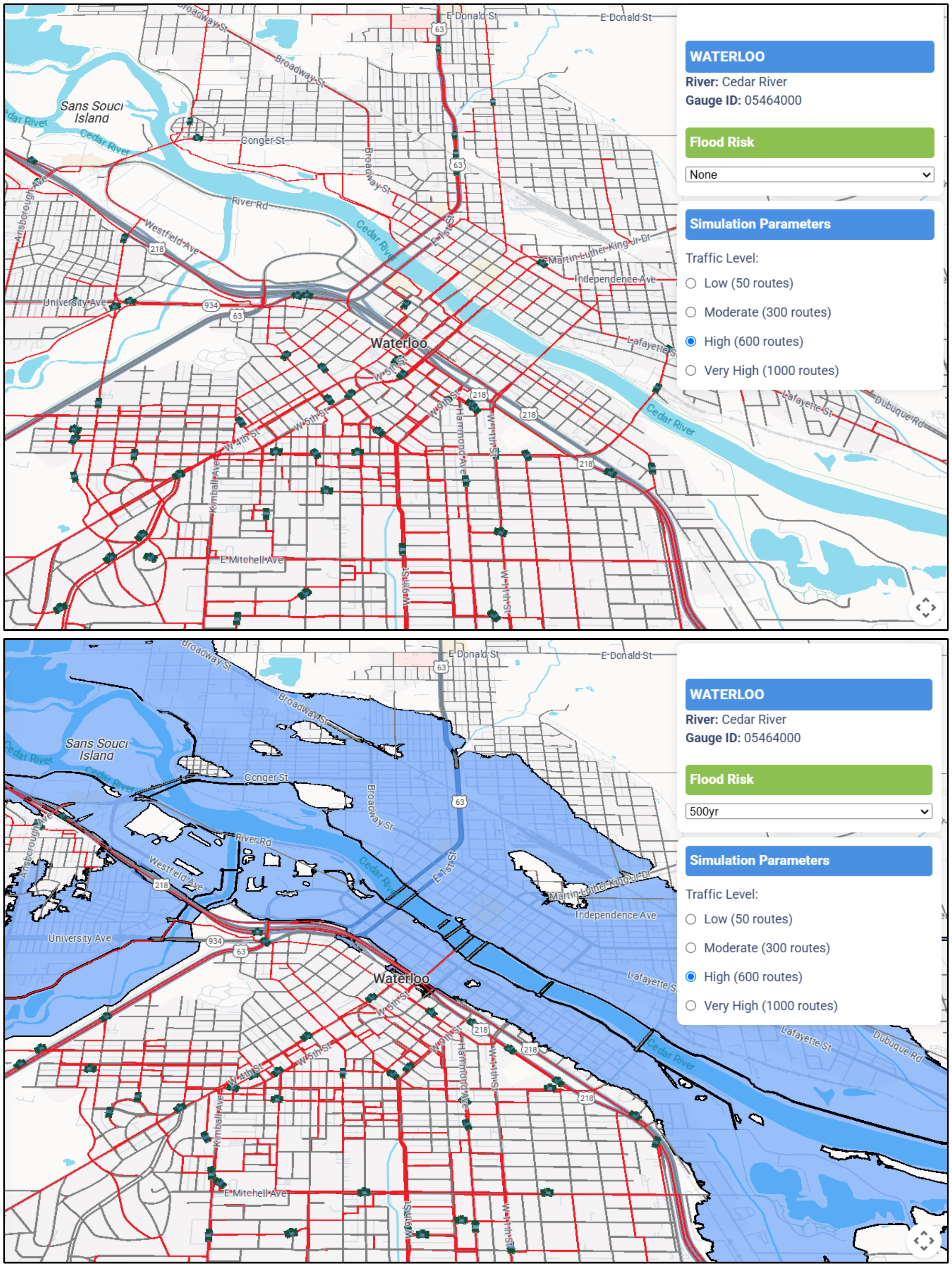
Care – Communication Facilities
Demographic Data

Figure 5. Visual representation of different data belongs to different urban systems or facilities

The Route Generator module then recalculates optimal paths for vehicles, buses, and emergency responders, ensuring that rerouted traffic follows the shortest viable detours. This computation is based on Dijkstra’s algorithm, which processes the road network as a graph and identifies the most efficient alternative routes. Figure 6 shows a view of how flooding affects the road network in Waterloo under normal conditions and 500-year flood risk scenario. The simulation results indicate that major transportation corridors near the Cedar River are highly vulnerable to flooding, with severe traffic disruptions observed during extreme flood events.



WATERLOO

River: Cedar River

Gauge ID: 05464000

Flood Risk

None

Simulation Parameters

Traffic Level:

- ○ Low (50 routes)
- ○ Moderate (300 routes)
- ● High (600 routes)
- ○ Very High (1000 routes)

WATERLOO

River: Cedar River

Gauge ID: 05464000

Flood Risk

500yr

Simulation Parameters

Traffic Level:

- ○ Low (50 routes)
- ○ Moderate (300 routes)
- ● High (600 routes)
- ○ Very High (1000 routes)

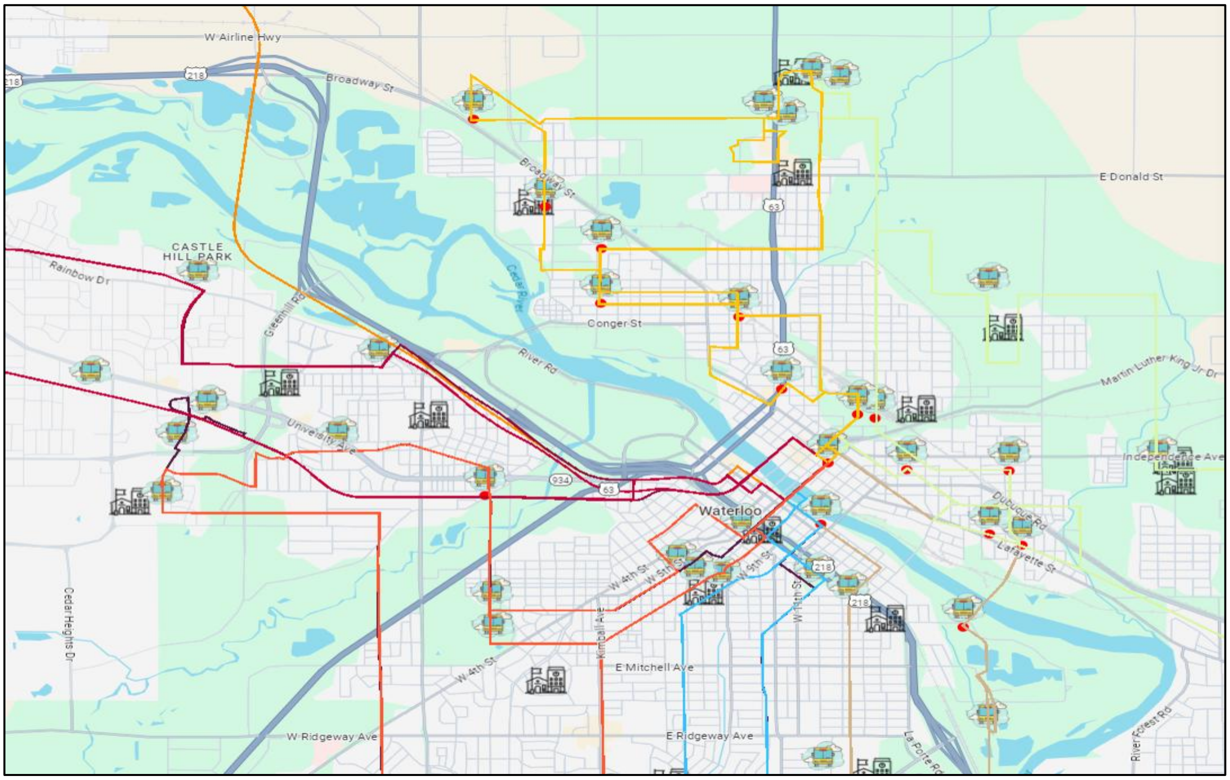
Figure 6. Visualization of flood impact on the road network with dynamic traffic rerouting

The 500-year flood scenario, in particular, results in widespread road closures, forcing significant rerouting of both private and public transportation systems. The railway network also experiences service disruptions, requiring alternative train routing or temporary suspension of operations. The interactive map interface allows users to analyze alternative transportation routes and adjust traffic simulation parameters in real time, improving preparedness for flood-related mobility challenges.

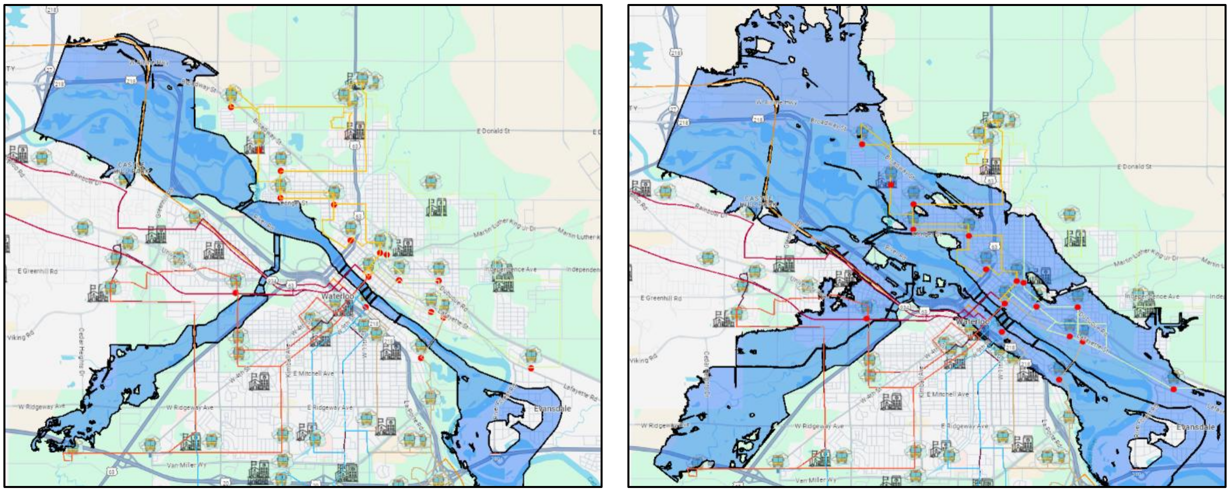
3.4. Use Case 3: Facility and Infrastructure Accessibility During Flooding

Flooding not only disrupts road networks but also affects the accessibility of critical urban facilities and amenities, such as hospitals, fire stations, and schools. This use case demonstrates how flooding impacts access to these essential services by modeling facility accessibility under different flood conditions. The City-Scale Digital Twin Framework enables users to analyze the connectivity between public facilities and the surrounding road network, highlighting areas that may become isolated due to flooding. The primary goal is to create an interactive, layered visualization that allows users to evaluate transit coverage and accessibility for these facilities effectively.

The system integrates facility location data with flood maps, overlaying different flood return period scenarios to assess the extent of service disruptions. The map integrates multiple data layers, including the locations of schools, bus routes, and bus stops, to provide a comprehensive view of the city's transportation network. Schools are prominently represented using distinct icons, ensuring easy identification and quick reference for users. Bus routes are displayed as colored lines, clearly illustrating the connectivity between different city areas and the schools. Additionally, bus stops are marked with smaller icons strategically placed along the bus routes, offering detailed information about access points for public transportation near schools.



(a)



(b) (c)

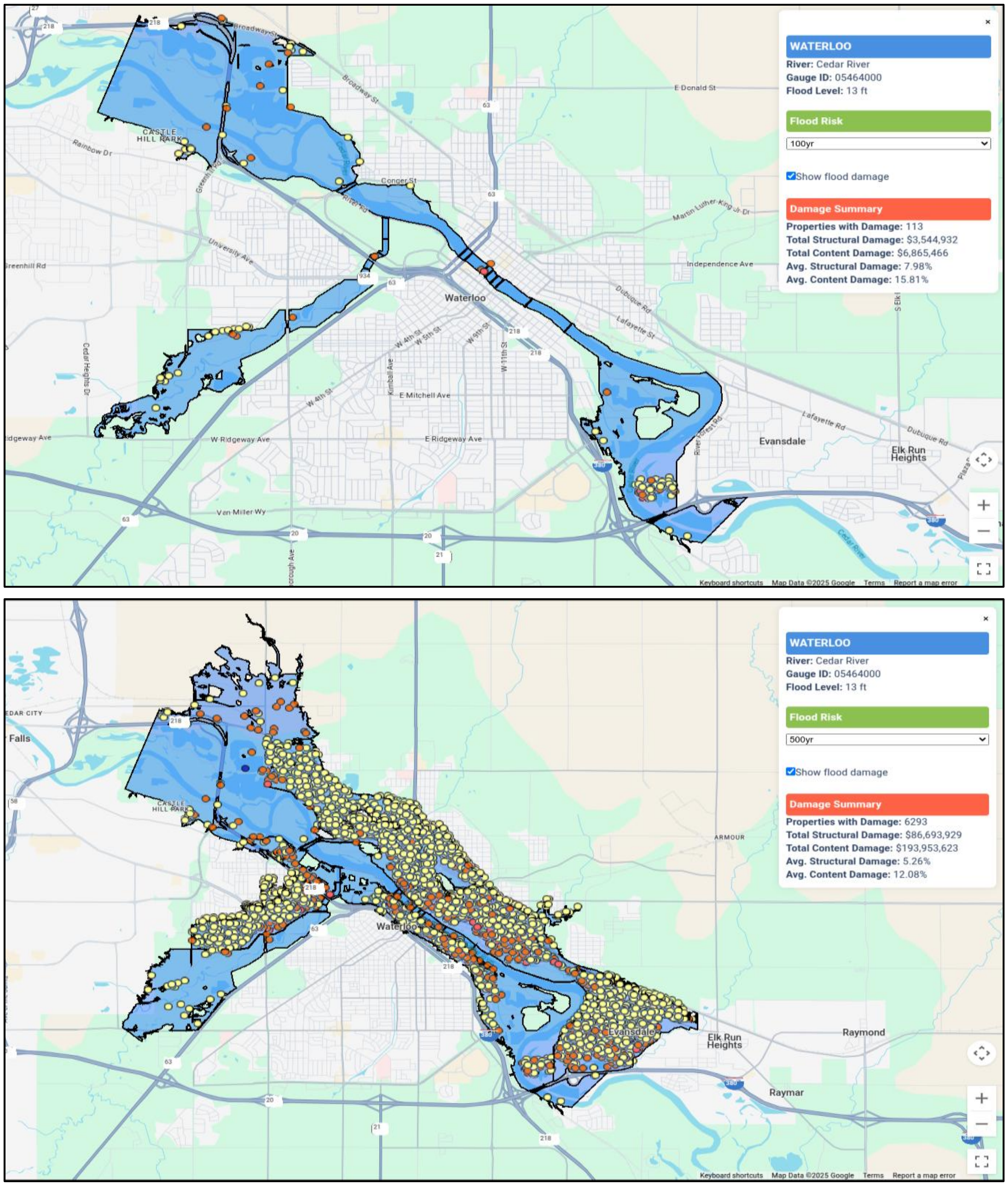
Figure 7. (a) Visualization of school accessibility dynamics under normal conditions; flood impact on school accessibility under (b) 100-year and (c) 500-year flood scenario

Figure 7 (a) provides a visualization of school accessibility under normal conditions, showing well-connected transit and road networks. Figure 7 (b) and (c) illustrate the accessibility challenges posed by 100-year and 500-year flood events, respectively. As flood severity increases, more schools become isolated, with road access significantly reduced. Beyond education facilities, the framework applies similar accessibility assessments to emergency services, evaluating how flooding affects response times for police, fire, and medical services. By dynamically updating road closures and alternative routes, the system supports emergency preparedness efforts, enabling first responders to plan contingency routes and prioritize high-risk areas. The interactive flood impact analysis ensures that stakeholders can quickly assess facility vulnerabilities and take proactive mitigation measures.

3.5. Use Case 4: Community Level Damage Analysis

The flood damage analyzing module in our digital twin framework integrates hydrological models, structural data, and economic impact assessments to estimate potential flood-related losses. The main goal is to develop a comprehensive damage assessment model for residential, commercial, and public infrastructure so as to support quick response actions, urban planning, and prioritization of resources in the city. The system utilizes depth-damage curves derived from HAZUS, alongside high-resolution floodplain maps and real-time hydrological data from the Iowa Flood Information System (IFIS). All datasets are maintained in a PostgreSQL database with the use of PostGIS extensions, which allows for efficient spatial queries and fast processing of data. This approach enables a detailed assessment of property and infrastructure damage across Waterloo.

The damage estimation model processes flood depth data and correlates it with structural vulnerability classifications to compute expected losses. Flood maps and raster datasets provide the ability to determine the inundation depth at specific building locations, which are then used to calculate structural and content damages using depth-damage curves for the regional building types. The severity of each damaged structure is calculated and categorized based on established thresholds, enabling appropriate resource allocation strategies. Figure 8 presents damage estimations for 100-year and 500-year flood scenarios, categorizing buildings based on the severity of expected impacts. Unlike the HAZUS software which take around 3 hours to process analysis, this can be loaded in less than a second using flood raster maps. Color-coded circular markers represent different damage levels, with yellow indicating low damage, orange for moderate damage, red for high damage, and purple for catastrophic damage.



WATERLOO
River: Cedar River
Gauge ID: 05464000
Flood Level: 13 ft

Flood Risk
100yr

☑ Show flood damage

Damage Summary
Properties with Damage: 113
Total Structural Damage: $3,544,932
Total Content Damage: $6,865,466
Avg. Structural Damage: 7.98%
Avg. Content Damage: 15.81%

WATERLOO
River: Cedar River
Gauge ID: 05464000
Flood Level: 13 ft

Flood Risk
500yr

☑ Show flood damage

Damage Summary
Properties with Damage: 6293
Total Structural Damage: $86,693,929
Total Content Damage: $193,953,623
Avg. Structural Damage: 5.26%
Avg. Content Damage: 12.08%

Figure 8. Damage estimations for (upper) 100-year and (lower) 500-year flood scenarios

To support disaster response planning, the system provides detailed statistical summaries, including the total number of affected properties, estimated structural damage costs, and projected content losses. Table 2 presents a comparative analysis of 100-year and 500-year flood events, highlighting the scale of potential economic damage. This summary includes critical indicators such as the number of properties experiencing structural or content damage, offering an immediate sense of the scale of impact.

Additionally, the system calculates the total structural damage, representing the aggregated monetary loss associated with physical damage to buildings, and the total content damage, which accounts for the cumulative monetary value of lost or damaged contents within affected properties. The framework also computes the average structural damage percentage across all impacted properties, offering insights into the severity of physical damage on a per-property basis. Similarly, the average content damage percentage reflects the mean value of content loss relative to the affected properties. By integrating real-time and historical data, the digital twin framework ensures that decision-makers have accurate and actionable insights for flood mitigation and recovery efforts.

Table 2. Damage Summary of 100-year and 500-year flood impact

	100-year flood	**500-year flood**
Affected properties/buildings	113	6,293
Total structural damage	$3,544,932	$86,693,929
Total content damage	$6,865,466	$193,953,623
Average structural damage	7.98%	5.26%
Average content damage	15.81%	12.08%

4. Conclusion and Future Work

This study presents a City-Scale Digital Twin Framework to enhance urban flood resilience by integrating real-time flood forecasting, transportation analysis, and infrastructure impact assessments. Applied to Waterloo, Iowa, the framework successfully simulated flood-related disruptions, showing its effectiveness in visualizing flood extent, modeling traffic disruptions, assessing infrastructure vulnerabilities, and estimating potential damages. The results highlight that severe flooding significantly disrupts transportation networks, public transit, and emergency response accessibility, requiring dynamic rerouting and alternative access planning. The damage estimation module provides a data-driven approach for assessing economic losses, supporting decision-makers in prioritizing disaster response and recovery efforts.

The City-Scale Digital Twin Framework contributes to the field by offering an interactive, real-time decision-support tool that integrates multi-source geospatial data, real-time hydrological models, and advanced visualization techniques. Unlike traditional static flood maps, this framework enables continuous monitoring and predictive analysis, bridging the gap between theoretical flood models and actionable urban planning strategies. It advances the smart city concept by demonstrating how digital twins can improve urban resilience, optimize emergency response, and support infrastructure planning. The framework's modular design allows scalability, making it applicable to different urban environments beyond flood risk management, such as climate resilience planning, transportation optimization, and disaster mitigation.

To further enhance the system, future developments should focus on improving real-time data integration, expanding machine learning-based flood forecasting, and refining transportation simulations to include multi-modal mobility data. Enhancing damage estimation with high-resolution flood models and socio-economic vulnerability indicators would provide more detailed risk assessments. The system could also benefit from cloud-based deployment and mobile accessibility, enabling emergency responders and city officials to access real-time flood impact insights remotely.

Future research can explore the application of digital twin technology beyond flooding, integrating multi-hazard simulations for extreme weather events such as hurricanes, wildfires, and heat waves. Incorporating behavioral and socio-economic models would improve evacuation planning and risk communication strategies. Advancements in artificial intelligence and self-learning digital twins could further automate emergency response planning and optimize urban resilience strategies. Additionally, testing the framework in diverse urban environments would enhance its adaptability for different climate and infrastructure conditions, supporting broader adoption in smart city planning and disaster risk reduction initiatives.

In conclusion, the City-Scale Digital Twin Framework provides an innovative approach to urban flood risk assessment, leveraging real-time data, interactive visualization, and predictive analytics to support proactive disaster management. Its ability to simulate, analyze, and visualize urban flood impacts in real time makes it a valuable tool for policymakers and urban planners seeking to enhance disaster preparedness and resilience strategies. As cities continue to face increasing climate-related challenges, digital twin technology will play a crucial role in enabling data-driven, adaptive, and sustainable urban development.

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