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Strengthening Resilience in 4D: Geospatial Digital Twins for Navigating Urban Flood Dynamics

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Abstract:

Damages from floods account for over one-third of global economic losses and two-thirds of people affected by natural hazards in the past few decades (Xia et al., 2019). Recently, the frequency and intensity of floods have been on a constant rise, leading to increasing fatalities, injuries, infrastructural damages, and economic losses worldwide (World Disasters Report, 2020). This onset has primarily affected urban and peri-urban areas as they deal with the compounded effects of climate change, rapid urbanization, and environmental degradation (Duy et al., 2018). As urban areas continue to expand, the need for effective measures to reduce flood risks and increase flood resilience becomes more pronounced.

However, several challenges exist. Urban flood models need to address complex hydrodynamic behaviours by accurately coupling one-dimensional (1D) runoff, e.g., rivers and channels, with two-dimensional (2D) surface flows to capture the full scope of flood dynamics. Meanwhile, high-resolution, realistic modeling demands substantial computational power and precise data inputs. Furthermore, simulating “what-if” scenarios to anticipate the impacts of various intervention strategies and climate-driven precipitation changes requires advanced modeling frameworks that can predict and visualize these conditions across space and over time. Despite a robust body of literature on urban flood resilience, few studies have directly addressed these challenges.

The recent advances in hydrodynamic modeling and geospatial digital twin techniques offer a promising solution to the above challenges. On one hand, enhanced hydrodynamic models support the integration of 1D and 2D flow components, capturing both channelized runoff and surface water movement. On the other hand, geospatial digital twins further extend this capability by continuously updating model parameters with real-time or customized data, such as rainfall and water levels, and immersive geo-visualizations. This allows geospatial digital twins to adapt to evolving flood conditions and simulate “what-if” scenarios.

This research develops a geospatial digital twin integrating high-resolution geographic data, 1D-2D coupled hydrodynamic models, street-level flood simulation, and immersive visualization. The Galveston City in Texas, U.S., is selected as the experiment site because it has long faced the persistent challenge of frequent flooding. The objectives are three-fold: (1) developing a comprehensive Galveston geospatial digital twin for flood modeling that integrates topography, hydrography, and built environment; (2) utilizing the developed geospatial digital twin to simulate hyperlocal urban floods under 2yr, 10yr, 25yr, 50yr, 100yr return period rainfall scenarios; and (3) identifying at-risk zones under various rainfall scenarios. The geospatial digital twin model leverages advanced computational techniques, hydrologic-hydraulic model, real-time radar data, urban infrastructure information, and detailed topographical data to simulate flood scenarios with greater accuracy. We validate the flood simulation results of the geospatial digital twin using web harvested data of locations of flood impacts.

Results show that buildings inundated by more than one foot increased from 0.5% in a 2-year flood to 6.2% in a 100-year flood over 24 hours. Critical Infrastructure like Texas A&M University, Galveston Island Community Service center, Oppe Elementary Magnet Campus of Coastal Studies always face the highest flood depths for most simulated flood events. Road inundation above 1 foot increased by 6.69% from a 2-year flood to a 100-year flood. Figure 1 showcases a street-level flood simulation, detailing maximum flood depths, realistic water flow textures, velocity tracers, junction flood levels, and underground storm sewer dynamics for a comprehensive spatial analysis. In figure 2, the immersive visualization of the platform is showcased in the 4D visualization of flood depth and extent. The novelty

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of this study lies in the development and implementation of a realistic ultra-high spatiotemporal resolution flood model at the city scale, which can utilize sensor data collection to simulate floods in real-time. The proposed geospatial digital twin provides an environment to simulate and visualize street-level flood conditions, identify potential property damages, and inform the development of effective mitigation strategies and preparedness measures. It also serves as a collaborative digital platform for stakeholders, including city planners, emergency services, policymakers, and residents, to co-design and co-implement effective resilience-building solutions. These capacities enable city planners and emergency responders to assess, monitor, and forecast the potential impact of various mitigation strategies under different flooding scenarios. By leveraging these technical advances, we can develop effective tools and actionable insights that align with the risk reduction priorities. The proposed model serves as critical tool for proactive disaster management and urban planning, enhancing flood management and guiding infrastructure development. The framework can be leveraged to build geospatial digital twins for other communities.

Figure 1. Street level and underground flood simulation for a flood event in Galveston

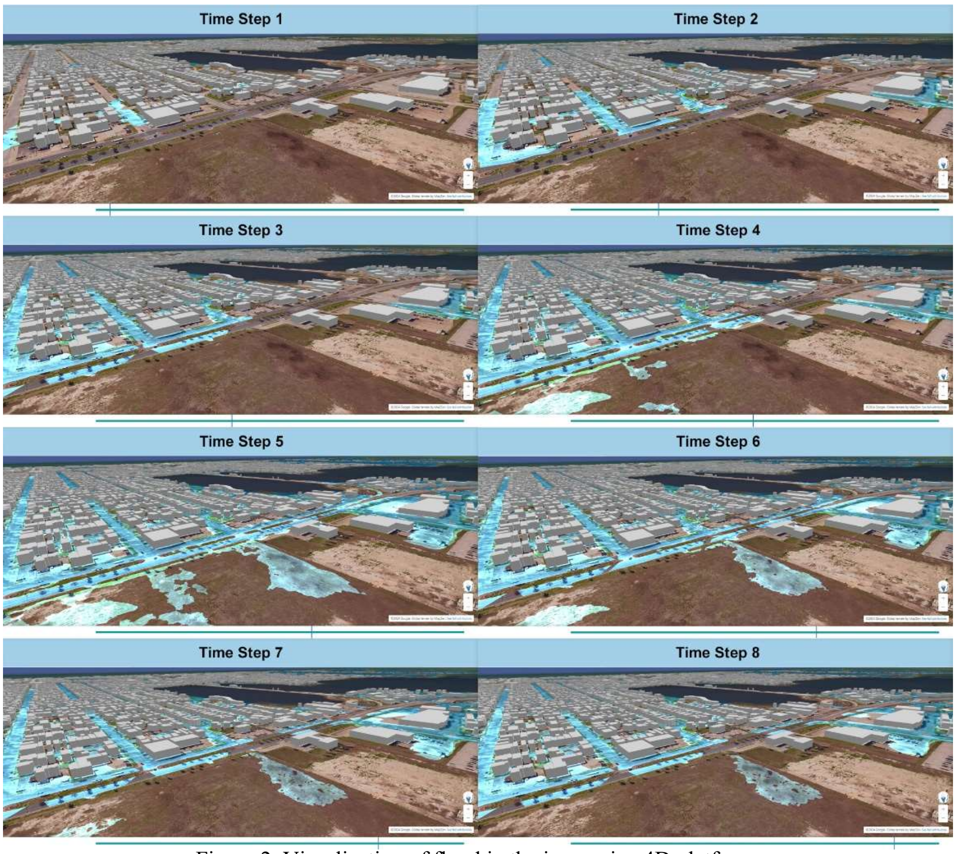

Figure 2. Visualization of flood in the immersive 4D platform.

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