From Simulation to Digital Twin: GPU-Accelerated Shallow Water Equations for Real-Time Flood Decision Support

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Abstract

This study presents a high-performance computational framework that advances conventional flood simulation toward a real-time Digital Twin for water resource management. The framework is built upon the two-dimensional Shallow Water Equations (SWE), which provide a physics-based representation of surface water flow dynamics. While SWE models are widely used for hydrodynamic simulation, their application to high-resolution and large-scale domains is often constrained by significant computational demands, limiting their use in time-critical decision-making contexts. To overcome these limitations, this research develops a GPU-accelerated SWE solver that leverages massively parallel computation, enabling simultaneous updates of computational grid cells across the simulation domain. The model integrates high-resolution Digital Elevation Models (DEM), rainfall forcing, and surface roughness parameters derived from Manning's coefficient. An adaptive grid strategy is introduced to dynamically allocate finer spatial resolution in flood-prone urban areas while maintaining coarser grids in upstream or less sensitive regions, thereby optimizing the balance between computational efficiency and simulation accuracy. Beyond standalone simulation, the system is designed as a foundational component of a Digital Twin architecture by incorporating real-time data streams from rainfall stations and water-level sensors. This integration allows continuous synchronization between simulated and observed states, enhancing both predictive accuracy and situational awareness. The system outputs include spatially explicit flood depth and flow velocity maps, which can be visualized through geospatial platforms such as web-based dashboards and Google Earth (KMZ), facilitating intuitive interpretation by decision-makers. Performance evaluation demonstrates that the GPU-based implementation achieves substantial acceleration compared to traditional CPU-based models, reducing simulation time from several hours to minutes while preserving numerical stability under standard Courant–Friedrichs–Lewy (CFL) constraints. The proposed framework significantly improves the timeliness and resolution of flood forecasting, enabling decision support within operational timeframes. This work illustrates the practical potential of combining physics-based hydrodynamic modeling, high-performance computing, and real-time data integration to establish scalable Digital Twin systems for climate-resilient water management. The approach is particularly suited to complex hydrological environments, such as mixed urban–river–coastal systems, and provides a pathway toward next-generation intelligent flood management platforms.