International Cartographic Association
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A variable hydrological element construction and visualization system for advancing the spatial resolution in hydrodynamic simulation process

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Keywords: variable hydrological elements, tile-based map platform, data aggregation, hydrodynamic simulation

Abstract:

Hydrodynamic simulation processes are crucial for applications in disaster prediction, pollutant management, and climate change impact assessment. Traditionally, hydrodynamic models employ uniform grids or triangulated irregular networks (TIN) to represent hydrological units within watersheds (Abbott & Refsgaard, 2012; Yoon & Kang, 2004). Uniform grids, while having fixed spatial resolutions, necessitate high precision to approximate actual hydrological conditions accurately, often leading to excessive data volumes and computational redundancy (Wang et al., 2010). In contrast, TIN can represent complex hydrological features using non-uniform elements but is susceptible to error accumulation during continuous calculations. To address these challenges, the Variable Hydrological Element (VHE) framework has been introduced as a promising solution (JURETIĆ & GOSMAN, 2009). By utilizing subdividable grid structures and prioritizing higher-resolution elements in critical watershed areas, VHE effectively balances computational efficiency and simulation precision (Yang et al., 2025).

Traditional systems for VHE construction and preprocessing often relied on client-based, geo-contextually isolated visualization modules that enabled user interaction with hydrological elements (Yang et al., 2025; Zhao et al., 2023). The inherent lack of geographical information in such isolated environments made it difficult to accurately determine whether an element required higher resolution and, consequently, necessitated subdivision. This limitation significantly hampered the efficiency and effectiveness of VHE editing workflows. Therefore, integrating VHE construction methods with map platforms, which effectively represent geographical features through cartographical methods, is a logical and necessary step to enhance the process (Sarajzadeh, 2021).

However, several significant challenges arise when integrating VHE construction methods with map platforms: (1) **Coordinate System Discrepancies:** Most hydrological models operate within local projected coordinate systems, rendering direct display of VHEs on maps (which commonly utilize global projected coordinate systems like Web Mercator) is problematic or impossible (Merwade et al., 2008). (2) **Performance Burden:** Geographical problems are often large-scale. Accurately covering the entire research area and ensuring reliable simulation results require a substantial number of VHEs. Rendering these elements and supporting dynamic topological editing operations (such as subdivision and deletion) imposes a heavy computational load on the system powered by Web map platforms. (3) **Efficient Data Aggregation:** VHEs require not only topological information but also attributes derived from the covered geographical areas. This necessitates the system's capability to acquire, visualize, and aggregate relevant geographical information (e.g., elevation, land use, etc.). Strategies for effectively organizing this information within a layer-based rendering structure and facilitating interaction with VHEs are critical.

This research introduces and implements a comprehensive system for VHE construction and visualization that integrates with mapping capabilities. The system is designed to manage and display VHEs alongside supporting geographic data, including raster and vector features, Digital Elevation Models (DEMs), and 3D oblique photography. To ensure coordinate adaptability and rendering accuracy, the system incorporates a transformation layer positioned between the VHE data representation and the Graphics Processing Unit (GPU) resources. Addressing the computational complexity, the system employs the Actor Architecture (Hewitt, 2010) to accelerate this crucial transformation process. Furthermore, to enhance rendering performance, the system adopts a memory address consistency strategy, aligning

https://doi.org/10.5194/ica-abs-10-262-2025

VHE rendering data and attribute data between CPU and GPU memory for hardware-accelerated visualization and interaction with less storage and faster picking. Leveraging this system, VHEs and their topological relationships can be generated, managed, and edited within a geographically rich environment, thereby significantly improving the reliability of hydrodynamic simulations. Moreover, the integrated geographic data facilitates accurate and automated attribute assignment for VHEs through efficient data aggregation workflow. The system's performance in data aggregation, VHE generation, and subdivision efficiency was validated using Yuen Long, Hong Kong, China, as the experimental site. The results unequivocally demonstrate the system's reliability and effectiveness in generating and visualizing VHEs, providing robust and essential support for advanced hydrodynamic simulations.

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https://doi.org/10.5194/ica-abs-10-262-2025