

Scalable Algorithmic Methods for Simulating Heavy-Rain Events

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Abstract

We motivate and demonstrate simulation and evaluation of large-scale, fine-grained hydrodynamic flows, triggered by heavy-rain events. We show significant progress for simulating time-dependent, high-resolution runoff in large-scale heavy-rain scenarios, based on different geometry-based algorithmic speedup techniques. This enables us to address a second challenge: How can we deal with the instability of precipitation events, which are notoriously difficult to predict with good accuracy?

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1 Introduction

Throughout human history, natural disasters have been a significant threat [17]. Both frequency and extent of heavy-rain events have increased in recent time, as observed by [10] in 2020 for Germany. Thus, the development of efficient and stable tools for hydrodynamic modeling has been an active field for decades, both in research and in product development [12]. The use of high-resolution elevation models is important for capturing terrain details that can have a major impact on the runoff behavior of surface water [11]; however, the high-resolution simulation is computationally highly intensive, making it difficult to employ it for larger areas, especially in early warning systems [8, 13]. Accordingly, many existing tools offer different compromises between modeling details, preprocessing time, and computation time. Scalable approaches for these important tasks are based on combining a number of algorithmic tools, including methods from computational geometry. While previous success stories (most notably by Arge et al. [1–7, 14]) have made significant progress on stationary flood levels in largely flat terrain, the problem of flooding with time-dependent water flow in sloped terrain remains computationally demanding even with modern tools and commercial software.



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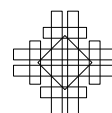
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Beyond all these efforts for scalable simulation methods, a second, potentially even bigger challenge looms: How can we deal with the unreliable nature of one of the most crucial inputs for any such model – the precipitation data, in time and space? Acquiring this time-dependent input with an accuracy similar to that of a finely resolved, static terrain is highly challenging, and even more difficult when it comes to forecasting such precipitation. As a consequence, computational methods from meteorology, computational physics or modern AI will likely continue to struggle to obtain reliable, fine-grained input, due to the instability of critical weather phenomena. This also implies that real-time intervention, as well as preemptive measures, will continue to suffer from a lack of reliable forecasting of the ensuing runoff.

2 Study Area and Hydraulic Modeling

While our methodological work is applicable to any region with sufficiently detailed terrain data, the main focus area of our work is a 370 km² polygonal domain centered on Goslar, Germany, and lies entirely within the federal state of Lower Saxony (Niedersachsen). Elevations increase from ca. 100 m above sea level (a.s.l.) in the Oker valley north of Goslar to almost 800 m a.s.l. in the southern sector according to Copernicus EU-DEM v1.1 [9].

Testing, improving and benchmarking of our simulations was performed with the commercial solver TUFLOW HPC version 2025.1.0, which is a 1D/2D hydraulic modeling software that solves the depth-averaged Navier-Stokes equations, also known as the shallow water equations, to simulate the flow of water over a terrain. TUFLOW uses an explicit finite volume solution with a square grid, whose cells might vary in size. Further details on the numerical scheme can be found in the TUFLOW manual [16] and in our full paper [15].

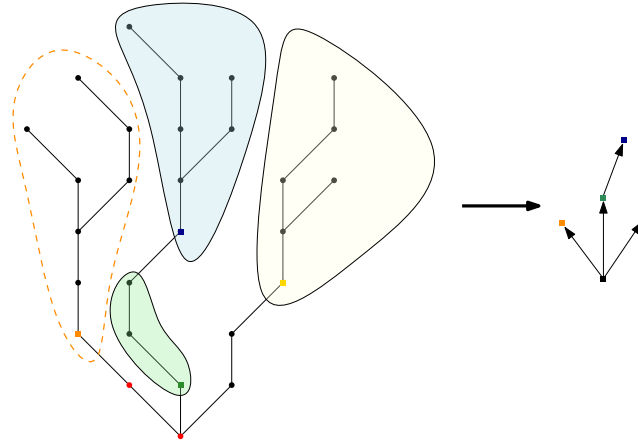
3 Enhancing Simulations

In general, there are two main challenges when simulating large areas with high resolution. Firstly, the memory footprint of the simulation becomes prohibitively large, making it infeasible to run the simulation on current hardware. Secondly, the runtime of the simulation also eventually grows beyond a reasonable time frame. This is often countered by using coarser resolution models, which can lead to a loss of accuracy in crucial areas.

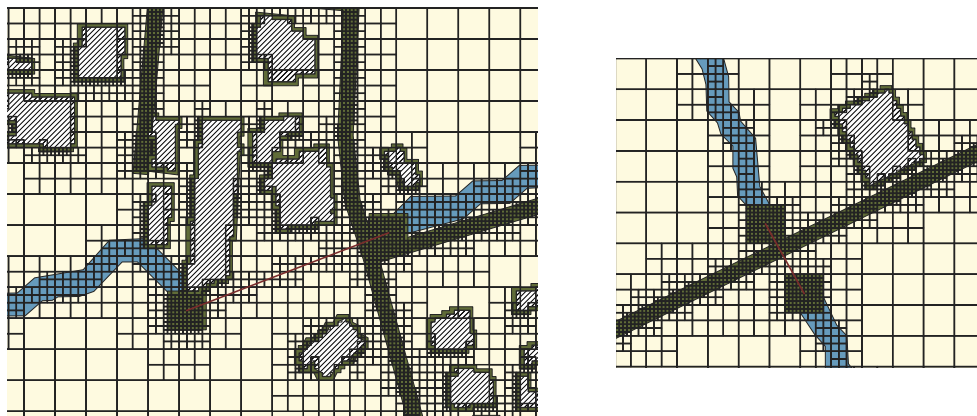
Our work [15] is based on two algorithmic improvements. Firstly, we have developed a subdivision algorithm that partitions the terrain into smaller regions that can be simulated independently, thus reducing the memory footprint of the simulation; see Figure 1. Secondly, we use a quadtree refinement approach that (given areas and desired resolution as inputs) automatically refines the mesh in critical regions. A key contribution of our work is the analysis of *what* regions require refinement and *how much* refinement is necessary to maintain accuracy while minimizing computational cost; see Figure 2. Both approaches can be combined to enable large-scale simulations on modern hardware.

4 Outcomes

There are two main outcomes of our work: (I) progress for simulating time-dependent, high-resolution runoff in large-scale heavy-rain scenarios, based on the two algorithmic approaches described in Section 3. In combination with state-of-the-art commercial software and powerful computing devices, these approaches can achieve simulation times that are significantly shorter than the duration of the simulated events for modestly sized regions (on the order of tens of square kilometers) at meter-scale resolution. The exact times depend on



■ **Figure 1** (Left) Subdividing a large hydrodynamic flow graph into smaller, dependency-aware polygonal regions bounded by an inflow threshold, enabling memory-efficient and parallelizable simulation. (Right) Dependency graph of the flow components after subdivision. Each node represents a component and edges indicate dependencies between them.



■ **Figure 2** Quadtree-refined meshes. Base resolution is 8 m, with refinements down to 1 m around streets, culverts, buildings (green) and 2 m around streams (blue). Culverts are marked in red.



Figure 4 A critical location near Goslar, identified by further sensitivity analysis. (Top left) Close-up of the intersection. (Top right) A culvert that runs below the intersection. (Bottom) Criticality of this intersection: maximum water depth and velocity from uniform-resolution simulations.

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