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Hyper-resolution 1D-2D urban flood modelling using LiDAR data and hybrid parallelization

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Coupled 1D-2D modelling is a widely used approach to predict water movement in complicated surface and subsurface drainage systems in urban or peri-urban areas. In this study, a hybrid parallel code, H12, is developed for 1D-2D coupled urban flood modelling. Hybrid-1D-2D, or H12, enables street-resolving hyper-resolution simulation over a large area by combining Open Multi-Processing (OpenMP) and Message Passing Interface (MPI) parallelization. Variable grid sizing is adopted for detailed geometric representation of urban surfaces as well as efficient computation. To assess the capability of H12, simulation experiments were carried for the Johnson Creek Catchment (~40 km^2) in Arlington, Texas. The LiDAR-derived digital elevation model (DEM) and detailed land cover map at 1-m resolution are used to represent the terrain and urban features in flood modelling. Hybrid parallelization achieves up to a 79-fold reduction in simulation time compared to the serial run and is more efficient than either OpenMP or MPI alone especially in hyper-resolution simulations.

1. Introduction

Floods are one of the most destructive natural hazards (Michel-Kerjan and Kunreuther, 2011). With urbanization and climate change, the frequency and magnitude of floods are changing in many parts of the world (Hirabayashi et al., 2013; Karen R. Ryberg et al., 2014; Mallakpour and Villarini, 2015). In particular, urban flooding is becoming increasingly costly and difficult to manage due to a greater concentration of population and assets in urban centers. Urban flooding is a phenomenon affected by various factors such as rainfall, topography, and hydrologic and hydraulic processes on land surface and in subsurface. Dual drainage, i.e., the concurrent water flow not only in sewer pipes but also on land surface at the same location, is a unique and important aspect of urban hydrology and has been studied by many researchers (Bazin et al., 2014; Djordjević et al., 1999, 2014; Fraga et al., 2015; Leandro et al., 2009; Teng et al., 2017). Among the numerous modelling approaches, coupled 1D-2D modelling is one of the most widely used to simulate dual drainage through one-dimensional sewer flow, two-dimensional surface flow and the exchange between the 1D and 2D domains in which the above flows occur (Adeogun et al., 2015; Chen et al., 2015; Djordjević et al., 2014; Fraga et al., 2015; Leandro et al., 2009; Noh et al., 2016a).

Since surface flow is strongly influenced by topography, availability of accurate digital elevation models (DEM) at appropriate resolutions is central to accurately simulating flooding (Abily et al., 2016; Bierkens et al., 2015; Bates et al., 2003; Leitão et al., 2009). Mark et al. (2004) also pointed out that the use of high-resolution geomorphological data is critical to accounting for the effects of man-made structures such as buildings, roads and curbs on the urban surface. Recently, remote sensing technology has revolutionized high-resolution water modelling (Fewtrell et al., 2008; Liu et al., 2015). In particular, light detection and ranging (LiDAR) systems have been widely used for flood inundation modelling which can capture floodplain topography at 1-m or finer resolution with high horizontal and vertical accuracy (Gallegos et al., 2009; Marks and Bates, 2000; Mason et al., 2007, 2014; Neal et al., 2009a; Ozdemir et al., 2013; Schubert et al., 2008). However, as discussed by Dottori et al. (2013), overconfidence can be placed in such high-resolution data when in reality accuracy is not necessarily improved by higher resolution due to uncertainty sources. In

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addition, since the laser beam measures the distance to the first object on its path, the DEMs from LiDAR may be different from the actual surface boundary for water movement. For instance, if vegetation canopy and man-made structures such as bridge or elevated roads are not properly treated in the raw LiDAR data, the resulting flood simulation is not likely to be realistic. Although there remain various issues on the tradeoff among model resolution, model complexity, data and parameter uncertainty, and computational feasibility (Abily et al., 2016; Bates et al., 2003; Fewtrell et al., 2008; Mignot et al., 2006; Neal et al., 2012), hyper- or high-resolution data sets are radically changing computer models and their use, increasing their complexity and range of applications (Beven, 2007; Dottori et al., 2013). Although there is no formal distinction between hyper- and high-resolutions, we use the term “hyper-resolution” for grid sizes of 1-m or finer and “high-resolution” for grid sizes which are coarser than 1 m. In addition, within the manuscript, we use the terms “fine” and “coarse” to differentiate grid sizes in relative terms within high- and hyper-resolutions.

Hyper- or high-resolution 2D inundation modelling is, however, computationally expensive for many real world applications (Neal et al., 2010). For example, 1-m resolution modelling of a 40 km^2 area (40×10^6 grids) requires more computational grids than 500-m resolution modelling of the contiguous United States (CONUS) (32×10^6 grids). In addition to the dimensionality of the computational grid, a small time step of 0.05 s or less is required for convergence (e.g., Courant-Friedrichs-Lewy (CFL) condition) for dynamic or diffusive wave modelling which renders hyper-resolution modelling more challenging for practical implementation. As such, some form of parallelization is necessary for hyper-resolution flood modelling. Parallel computing methods include Message Passing Interface (MPI) in a distributed memory system (Gropp et al., 1996), Open Multi-Processing (OpenMP) in a shared memory (Chapman et al., 2007) and co-processor parallelism which utilizes graphics processing units (GPU) (Ament et al., 2011) or many-core processors such as Intel Xeon Phi (Intel, 2017).

There have been significant advances in parallel 2D inundation modelling (Gallegos et al., 2009; Neal et al., 2010, 2009b; Sampson et al., 2015; Sanders et al., 2010; Shen et al., 2015). Sanders et al. (2010) developed a parallel Godunov-type shallow water code, ParBrezo, using MPI and evaluated it for urban dam break flood and storm surge inundation cases. Neal et al. (2010) compared three parallelization methods based on OpenMP, MPI and accelerator cards, and found that MPI is slightly more efficient than OpenMP and shows high scalability with a large number of cores. Leandro et al. (2014) developed a 2D parallel diffusive wave model for flood plain inundation with the Matlab parallel computing toolbox and Fortran OpenMP. Sampson et al. (2015) used OpenMP parallelized LISFLOOD-FP and reach decomposition to simulate inundation over the entire globe at 90-m resolution.

Each parallelization method has positives and negatives. Though straightforward to implement, OpenMP is limited in scalability by the size of the shared memory system. MPI is scalable for high-dimensional problems but at the expense of reduced computational efficiency due to increasing communications among the CPUs. Despite large potential, co-processor parallelism is highly device-dependent and improves performance only for specific types of calculations. In recent years, a number of studies have demonstrated that hybrid parallelization that combines the above may be an effective solution for drastically reducing computational time for high-dimensional problems in various research areas (Borges et al., 2014; Gorobets et al., 2013; Ibanez et al., 2016; Mininni et al., 2011; Satarić et al., 2016; Wan and Lin, 2013). However, to the best of the authors' knowledge, there has been no investigation into hybrid parallelization for 1D-2D flood modelling presumably due to the convoluted nature of dual drainage which requires extensive coupling.

In this study, a hybrid parallel code, Hybrid-1D-2D, or H12 for short, is developed for coupled 1D-2D urban flood modelling to enable street-resolving hyper-resolution simulation for a large area by combining OpenMP and MPI. The code developed uses variable grid sizing for detailed geometric representation of urban land surfaces and computational efficiency. In order to assess the capability of hyper-resolution 1D-2D modelling in a realistic setting, H12 is applied for the Johnson Creek Catchment (~40 km^2) in Arlington, Texas. We used LiDAR-derived DEM with 1-m resolution for topography. The LiDAR-derived DEM is post-processed to remove vegetation canopy and to capture flow paths below urban objects such as elevated roads, overpasses and bridges. The value of hyper-resolution 1D-2D modelling is discussed in comparison with low-resolution modelling results. In addition, performance of hybrid parallelization over OpenMP and MPI is analyzed.

The rest of this paper is organized as follows: Section 2 describes the study area and data used. Section 3 describes the coupled 1D-2D urban flood model and development of the parallel code, H12, including the variable sized scheme, profiling of the serial code and structure of the hybrid parallel code. Section 4 presents simulation results at two different resolutions, compares run-times and efficiency with different parallelization methods, and discusses challenges of hyper-resolution urban flood modelling and parallel computing. Section 5 summarizes the main findings.

2. Study area and data used

In this section, we describe hydrologic and hydraulic characteristics of the study domain and the procedure of LiDAR data processing for hyper-resolution 1D-2D urban flood modelling.

2.1. Study area

The study domain is the Johnson Creek catchment (40.2 km^2) located in Arlington, Texas (Fig. 1). The Johnson Creek (length: 21 km) originates near Interstate 20 in eastern Tarrant County, TX, and flows northeasterly to drain into the Trinity River in Grand Prairie in Dallas County. The major land cover types include residential area, road, parking lot and lawn. There are 7017 sewer pipes connected with 3615 inlets, 3259 storm fittings, 549 manholes, 286 culverts and 415 outfalls in the model domain. The total lengths of sewer pipes and culverts are 190.7 and 5.8 km, respectively. According to the previous study (Asquith and Roussel, 2004), 500-year return period rainfall for 1 and 2-h durations is about 117 and 71 mm/h, respectively, which was used for code evaluation and benchmarking.

2.2. Hyper-resolution LiDAR-derived land surface

Hyper-resolution DEM was obtained from LiDAR point data. The LiDAR data used in this study was created in April 2009 with the Leica ALS-50 system. The system was flown at an average flying altitude of 1400 m above ground with an average point spacing of 0.57 m. The resulting LiDAR data have a vertical accuracy of 0.07 m and a horizontal accuracy of 1 m at 95% confidence level. Given the density of the raw data, 1 m was considered the finest resolution retrievable for the study area. Initially, a 1-m bare-earth DEM was created from the ground-return LiDAR points using a natural neighbor interpolation method (Sibson, 1981) with ArcGIS 10.4 (www.esri.com). Then, solid urban features such as houses and buildings which obstruct flow of storm water were added to the bare-earth DEM for numerical flood modelling. We obtained the building footprint GIS layer from the City of Arlington and