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Benchmarking urban flood models of varying complexity and scale using high resolution terrestrial LiDAR data

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ABSTRACT

This paper describes benchmark testing of a diffusive and an inertial formulation of the de St. Venant equations implemented within the LISFLOOD-FP hydraulic model using high resolution terrestrial LiDAR data. The models are applied to a hypothetical flooding scenario in a section of Alcester, UK which experienced significant surface water flooding in the June and July floods of 2007 in the UK. The sensitivity of water elevation and velocity simulations to model formulation and grid resolution are analyzed. The differences in depth and velocity estimates between the diffusive and inertial approximations are within 10% of the simulated value but inertial effects persist at the wetting front in steep catchments. Both models portray a similar scale dependency between 50 cm and 5 m resolution which reiterates previous findings that errors in coarse scale topographic data sets are significantly larger than differences between numerical approximations. In particular, these results confirm the need to distinctly represent the camber and curbs of roads in the numerical grid when simulating surface water flooding events. Furthermore, although water depth estimates at grid scales coarser than 1 m appear robust, velocity estimates at these scales seem to be inconsistent compared to the 50 cm benchmark. The inertial formulation is shown to reduce computational cost by up to three orders of magnitude at high resolutions thus making simulations at this scale viable in practice compared to diffusive models. For the first time, this paper highlights the utility of high resolution terrestrial LiDAR data to inform small-scale flood risk management studies.

1. Introduction

Recent studies on the effects of urbanization on the hydrologic response of drainage networks have examined the impact of urban drainage on flooding in terms of drainage network structure (Meierdiercks et al., 2010), drainage network efficiency (Aronica and Lanza, 2005), drainage pathway distribution (Leitão et al., 2009) and model resolution (Schubert et al., 2008; Fewtrell et al., 2008). The proliferation of recent modelling efforts is a direct consequence of large pluvial flood events over urban areas (e.g. Dead Run in Baltimore, US in July 2004 (Ntelekos et al., 2008) or flooding in Hull, UK in summer 2007) and the associated perceived increased risk from such high rainfall events. Indeed, the Environment Agency of England and Wales (EA) estimated that two-thirds of the 57,000 homes affected in the June and July 2007 floods in the UK were flooded from surface water runoff exceeding the capacity of the drainage system (DEFRA, 2008). In addition, the Pitt Review (Pitt, 2008) noted that although the UK's understanding of flooding risks from coastal and fluvial sources is well advanced, information related to surface water flooding risk is limited.

Leitão et al. (2009) note that bearing in mind the current industrial best practice, there is considerable scope and need for improving the methods for quantifying risk from surface water flooding in urban areas. A number of studies have assessed the importance of model resolution for simulating surface water propagation (Schubert et al., 2008; Fewtrell et al., 2008; Gallegos et al., 2009), while others have investigated the necessary process representation for such flooding events (Hunter et al., 2008; Pender and Néelz, 2010) and some authors have considered the sub-surface drainage component coupled to a surface flow model (Hsu et al., 2000). The first set of studies initially concluded that the representation of the minimum distance between buildings is of paramount importance for the representation of surface flow, which equates to ~5–10 m. Gallegos et al. (2009), however, note that three computational elements are required across a street in a dynamic unstructured model to provide an appropriate compromise between computational cost and accuracy, albeit that this led to a model resolution of ~5 m in their application. The studies addressing process representation in models suggest that while simplified diffusive models provide plausible results, there can be significant

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differences in flood extent between the diffusive models and more complex dynamic models in steep catchments where the flow is inertia dominated (Hunter et al., 2008). Few studies have considered the joint influence of model resolution and process representation for urban flood events. In addition, although Schubert et al. (2008) considered mesh resolutions finer than 1 m, the underlying digital elevation models (DEMs) used to drive these studies have all been derived from topographic sampling products collected at ~2 m resolution or coarser. As such, most work has concentrated on assessing the need to resolve buildings within urban DEMs rather than considering the detailed street network and micro-topography; Gallegos et al. (2009) being the notable exception.

Airborne LiDAR systems have been enhanced in the last 10 years from systems with laser pulse rates of ~10–100 kHz leading to footprint improvements from ~3 m to ~25 cm, reducing vertical elevation errors in the process down to ~5 cm root mean square error (RMSE). More recently, terrestrial LiDAR systems have started to be employed to capture even more detailed (i.e. ~1–3 cm horizontal resolution) 3D point cloud data for applications in engineering, transportation and urban planning (Barnea and Filin, 2008; Lichti et al., 2008). Despite the fact that anecdotal and modelling evidence of urban flooding processes suggests that small scale features (i.e. kerbs, road camber and drains) can have a significant impact on flood propagation, such high resolution data from terrestrial laser scanners has yet to be used in urban hydraulic models. In addition, such small scale features can be difficult to distinguish in airborne LiDAR products as they may be smaller than the resolution of the instrument and because airborne instruments necessarily have a downward look direction. Terrestrial LiDAR systems mounted on moving vehicles may provide a solution for resolving such small scale features over side areas appropriate for flood risk management. In this paper, the utility of the high resolution terrestrial LiDAR data for simulating surface water flooding is analyzed. This provides a mechanism to evaluate the role of the street network, as opposed to purely building location, in modulating the propagation of surface water in urban areas. In addition, using numerical models of varying complexity provides a method for assessing the important physical processes and analyzing the interplay between model resolution and numerical complexity at such small scales.

2. Data availability and collection

2.1. Site and event description

During the floods of July 2007 in the United Kingdom, Alcester in Warwickshire experienced considerable flooding from the Rivers Alne and Arrow, in addition to flooding from surface water derived from excess rainfall as the local drainage system was overwhelmed. The combination of high river levels and high rainfall accumulations (60–80 mm in 12 h) led to flooding of 110 properties although the Environment Agency (EA) in the UK estimates that a further 200 properties were successfully protected by the current defences. Furthermore, the EA estimates that ~260 properties in Alcester lie within the 1-in-100 year floodplain. In response to this flooding, the EA plans to raise the height of the flood wall in Alcester to ensure that it is above the July 2007 river levels and there are additional plans to install two new pumping stations to alleviate the flood risk from surface water. The section of Alcester chosen for this study lies in an area susceptible to flooding both from the River Arrow and surface water overwhelming the drainage system. The area is 0.11 km^2 consisting of four streets and a number of cul-de-sacs feeding off them (Fig. 1).

Although the area is prone to flooding from fluvial and pluvial sources, there are no reliable estimates of flood volumes for an observed flood event in the area. Therefore, the inflow boundary conditions for this test case were derived using the depth–duration–frequency curves for estimating rainfall from the Flood Estimation Handbook (FEH, Institute of Hydrology (1999)). The EA in England and Wales is currently mapping surface water flooding risk using a 1-in-200 year return period 30-min rainfall storm. For this study, we assume that the 200-year 30-min rainfall (47 mm) is collected over a drainage area of 100 × 100 m upstream of the inflow point (see Fig. 1) to represent the flow coming from a blocked sewer draining a small catchment (Fig. 2). The final assumption in this study is that the drainage system is operating at capacity such that water on the surface does not interact with the drains at the road side. The lack of observed data of the flooding at this test site means that the ensuing modelling exercise takes the form of a sensitivity analysis.

2.2. LiDAR collection and processing

The terrestrial laser scanning system used for gathering the ultra high resolution elevation data for Alcester was the LYNX Mobile Mapper™ system distributed by Optech Incorporated and the data were collected by the Environment Agency Geomatics Group. The LYNX Mobile Mapper™ consists of two 100 kHz LiDAR instruments, each with 360° field of view, mounted on a rigid platform on the back of a Land Rover. Two GPS receivers are mounted on the roof of the car as well, one at the front and one on the rigid platform at the back. The GPS system uses the principle of real time kinematic (RTK) navigation whereby the roving LYNX unit calculates a relative position based on a known base station with positional accuracies of ±5 cm leading to vertical accuracies of ±5 cm. The system is capable of recording four simultaneous measurements per laser pulse which results in a point cloud density of ~1 point per centimetre when driving at ~30 mph.

The terrestrial LiDAR point cloud is processed into a DEM using proprietary processing algorithms developed by the EA drawing on experience from years of processing airborne LiDAR data in addition to work by Mason and others (Cobby et al., 2003; Mason et al., 2003, 2007). The key aspect of LiDAR segmentation is to separate ground laser hits from surface object returns. This is achieved using classification algorithms in an iterative procedure in order to progressively remove surface objects from the underlying surface topography. In this particular case, the TerraScan software package was used. The resulting surface was aggregated to a raster DEM at 10 cm resolution. The 10 cm resolution DEM (11,606,900 cells) was then further resampled to Δx = 25 cm (1,856,000 cells), 50 cm (464,000), 1 m (116,000), 2 m (29,000) and 5 m (4640) to investigate the scale dependency of flooding at this site.

3. Modelling framework

Hunter et al. (2008) demonstrated the need to benchmark hydraulic models of varying complexity to fully understand the effect of process representations on the simulation of flood flows through urban environments. Further evidence from the authors suggests it proved difficult to ensure that each model interpreted the model inputs and boundary conditions in the same way. Similarly, work on the EA benchmarking study (Pender and Néelz, 2010) suggests participants encountered similar problems of ensuring consistency between models in the construction of each test case. Incorporating different numerical solution schemes into a single computational code reduces any such ambiguity in model setup. Therefore, the LISFLOOD-FP model is used here as there are a number solution schemes of varying complexity implemented within the same numerical code (see Bates and De Roo, 2000; Hun-