

# 1 Evaluating scale and roughness effects in urban flood 2 modelling using terrestrial LIDAR data

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## 9 **Abstract**

10 This paper evaluates the results of benchmark testing a new inertial formulation of the St.  
11 Venant equations, implemented within the LISFLOOD-FP hydraulic model, using different  
12 high resolution terrestrial LiDAR data (10cm, 50cm and 1m) and roughness conditions  
13 (distributed and composite) in an urban area. To examine these effects, the model is applied to  
14 a hypothetical flooding scenario in Alcester, UK, which experienced surface water flooding  
15 during summer 2007. The sensitivities of simulated water depth, extent, arrival time and  
16 velocity to grid resolutions and different roughness conditions are analysed. The results indicate  
17 that increasing the terrain resolution from 1 m to 10 cm significantly affects modelled water  
18 depth, extent, arrival time and velocity. This is because hydraulically relevant small scale  
19 topography that is accurately captured by the terrestrial LIDAR system, such as road cambers  
20 and street kerbs, is better represented on the higher resolution DEM. It is shown that altering  
21 surface friction values within a wide range has only a limited effect and is not sufficient to  
22 recover the results of the 10 cm simulation at 1 m resolution. Alternating between a uniform  
23 composite surface friction value ( $n=0.013$ ) or a variable distributed value based on land use has  
24 a greater effect on flow velocities and arrival times than on water depths and inundation extent.  
25 We conclude that the use of extra detail inherent in terrestrial laser scanning data compared to  
26 airborne sensors will be advantageous for urban flood modelling related to surface water, risk  
27 analysis and planning for Sustainable Urban Drainage Systems (SUDS) to attenuate flow.

28 **Keywords:** Hydraulic modelling, Terrestrial LiDAR, Distributed roughness, Surface water,  
29 Urban flooding

## 1   **1   Introduction**

2   Urban flood events are increasing in frequency and severity as a consequence of: (1) reduced  
3   infiltration capacities due to continued watershed development (Hsu et al. 2000); (2) increased  
4   construction in flood prone areas due to population growth (Brown et al. 2007; Mason et al.  
5   2007); (3) the possible amplification of rainfall intensity due to climate change; (4) sea level  
6   rise which threatens coastal development; and (5) poorly engineered flood control infrastructure  
7   (Gallegos et al. 2009). These factors will contribute to increased urban flood risk in the future,  
8   and as a result improved modelling of urban flooding has been identified as a research priority  
9   (Wheater, 2002; Gallegos et al. 2009; Tsubaki & Fujita, 2010; Fewtrell et al. 2011; Sampson et  
10   al. 2012). Surface water flood, which is one of the main sources of urban flooding after fluvial  
11   and coastal, occurs when natural and man-made drainage systems have insufficient capacity to  
12   deal with the volume of rainfall. The Environment Agency of England and Wales (EA)  
13   estimated that of the 55,000 properties affected by the UK June 2007 floods, around two thirds  
14   were flooded as a result of excess surface water runoff (DEFRA, 2008). Moreover, it is  
15   estimated that 80,000 properties are at very significant risk from surface water flooding (10%  
16   annual probability or greater), causing on average £270 million of damage each year. As a  
17   result, the 2007 event showed that the necessity of researches on surface water flooding risk  
18   besides fluvial and coastal risk (Pitt, 2008).

19   Current active research areas in surface water flooding include the representation of micro-scale  
20   topographic and blockage effects (e.g. kerbs, road surface camber, wall, buildings) and the  
21   development of numerical schemes capable of representing high-velocity shallow flow at fine  
22   spatial resolutions over low friction surfaces in urban environments. Over the last decade,  
23   studies investigating the role of topography in urban flood models have typically employed  
24   airborne LiDAR terrain models of ~50cm – 3 m horizontal resolution (Mason et al. 2007;  
25   Brown et al. 2007; Fewtrell et al. 2008; Hunter et al. 2008; Gallegos et al. 2009; Neal et al;  
26   2009; Tsubaki & Fujita, 2010). However, small scale features which have significant impact on  
27   the flood propagation and especially surface water flooding in urban environments (Hunter et  
28   al. 2008; Fewtrell et al. 2011; Sampson et al. 2012) cannot be distinguished in airborne LiDAR  
29   data. Because of that, terrestrial laser scanners have started to be employed to capture even  
30   more detailed (i.e. ~1 – 3 cm horizontal resolution) 3D point cloud data for applications in  
31   engineering, transportation and urban planning (Barnea and Filin, 2008; Lichti et al. 2008).  
32   Fewtrell et al. (2011) analysed the utility of high resolution terrestrial LiDAR data in simulating

1 surface water flooding and found that the road cambers and kerbs represented in the high  
2 resolution grid terrestrial LiDAR DEM had a significant impact on simulated flows. Sampson  
3 et al. (2012) also highlighted that inclusion of small scale topographic features resolved by the  
4 terrestrial laser scanner improves the representation of hydraulic connectivity across the  
5 domain. Variable mesh generation provides an alternative to high resolution grids for  
6 representing detailed features in urban environments (Yu & Lane, 2006a; Schubert et al. 2008),  
7 and a detailed comparison between variable mesh models and grid-based models for inundation  
8 modelling is given by Neal et al. (2011).

9 The benchmarking of two-dimensional (2D) hydraulic models and the influence of floodplain  
10 friction on rural floodplains are now relatively well understood as a result of various model  
11 applications over the last two decades (Gee et al. 1990; Bates et al. 1998; Horritt, 2000; Bates  
12 & De Roo, 2000; Horritt & Bates, 2002; Nicholas and Mitchell, 2003; Hunter et al. 2005;  
13 Werner et al. 2005; Néelz et al. 2006). A number of studies have documented the application  
14 of 2D hydraulic models, such as numerical solutions of the full 2D shallow-water equations,  
15 2D diffusion wave models, and analytical approximations to the 2D diffusion wave using  
16 uniform flow formulae, to complex urban problems (Aronica & Lanza, 2005; Mignot et al.  
17 2006; Guinot & Soares-Fraza, 2006; Hsu et al. 2000; Yu & Lane, 2006a; Yu & Lane, 2006b;  
18 Fewtrell et al. 2008; Néelz & Pender, 2010). Practical application of full-dynamic shallow water  
19 models to large areas to resolve flows at high resolution is often limited due to the extremely  
20 high computational cost. On the other hand, most simplified formulations lack the generality  
21 needed to capture the wide range of flow conditions usually taking place in urban areas. To  
22 address this issue, Bates et al. (2010) derived a simplified or ‘inertial’ shallow water model  
23 which represents a good balance between computational performance and the representation of  
24 the most relevant physical processes needed to model urban flood propagation. Solutions using  
25 the new equation set are shown to be grid-independent and to have an intuitively correct  
26 sensitivity to friction. However small instabilities and increased errors on predicted depth were  
27 noted by Bates et al. (2010) under low friction conditions ( $n < 0.03$ ) that may be typical of skin  
28 frictions in urban areas. Fewtrell et al. (2011) tested diffusive and inertial equations using  
29 terrestrial LiDAR data and a high single composite friction value ( $n=0.035$ ) in urban areas.  
30 They noted that the computational cost is considerably reduced in the inertial formulation  
31 compared to a diffusive wave approximation in high resolution model simulations. In terms of  
32 friction parameters, whilst many flood inundation models have commonly used a uniform  
33 roughness coefficient for the floodplain (Bates & De Roo 2000; Horritt & Bates, 2002), some

1 researchers have used spatially-distributed friction in both rural and urban areas (Werner et al.  
2 2005; Wilson and Atkinson, 2007; Schubert et al. 2008; Gallegos et al. 2009). For the urban  
3 case, Gallegos et al. (2009) noted that a spatially uniform resistance parameter lead to poor  
4 stream flow accuracy compared to a spatially distributed parameter. This was confirmed by  
5 Schubert et al. (2008) who found that flood extent, flood depth and arrival times were sensitive  
6 to roughness parameter spatial distributions for a test case in Glasgow, UK. An unresolved  
7 question however is how topographic and friction effects interact and are influenced by the  
8 model grid scale at terrestrial LiDAR resolutions. At such scales terrain data at 1-3cm point  
9 spacing begin to resolve explicitly some of the structural elements responsible for generating  
10 frictional losses at coarser grid scales. Looking at model sensitivity to friction on a variety of  
11 fine spatial resolution grids parameterized using terrestrial LiDAR data can shed light on: (1)  
12 whether micro terrain features generate frictional losses at coarser grid scales; (2) whether such  
13 frictional losses can be easily parameterized in coarser scale models; and (3) which terrain  
14 features cannot be treated in this way and need to be explicitly represented in the model grid.

15 In densely urbanized areas where relatively smooth surfaces are found, the simulation of surface  
16 water floods using a very fine resolution DEM (below 1m) and very low friction values (below  
17  $n=0.020$ ) may also cause numerical instabilities to arise in shallow water models as these strictly  
18 only apply to slopes with gradients  $< 10\%$ . An inevitable consequence of capturing finer  
19 resolution DEM data and surveying topography from sideways looking terrestrial laser scanners  
20 rather than nadir pointing airborne LiDAR systems is that small scale features such as kerbs  
21 and walls are much better resolved. A 10cm kerb height drop when sampled at typical airborne  
22 LiDAR resolutions (1-2m) does not create gradients above 10%, and such features are often not  
23 even correctly seen by the sensor (Sampson et al., 2012). However, the same feature when  
24 sampled using a sideways looking terrestrial laser system with ~1-3cm point spacing will be  
25 easily resolved, and when the raw point cloud terrain data are re-sampled on up to 1m grids  
26 slopes can be generated which breach the assumptions of the shallow water equations. On a  
27 10cm grid a 10cm vertical drop results in a bed gradient of 50% which can be very difficult for  
28 many shallow water based models to deal with (Hunter et al. 2008; Gallegos et al. 2009; Neal  
29 et al. 2011). In terms of numerical stability and accuracy de Almeida et al. (2012) proposed and  
30 tested a new numerical scheme for the simplified shallow water model of Bates et al. (2010)  
31 able to improve stability significantly. Yet this has still to be evaluated for use in urban areas  
32 surveyed with terrestrial laser DEM data and simulated with sub metre scale model grids.

1 The primary aim of this paper is therefore to apply and test the new numerical scheme proposed  
2 by de Almeida et al. (2012) using different surface friction configurations (spatially distributed  
3 or single composite value) on high resolution DEMs derived from terrestrial LiDAR. We start  
4 by describing the data and methods, including a description of the test site, data sources and the  
5 improved formulation of LISFLOOD-FP, before applying this model to varying resolution  
6 terrestrial LiDAR DEMs with distributed and composite surface friction values. The results are  
7 then presented and discussed in terms of water depths, extents, arrival times and velocities  
8 before the conclusion are drawn and implications stated.

## 9 **2 Data and Method**

### 10 **2.1 Site and event description**

11 Alcester in Warwickshire experienced extensive flooding the Rivers Alne and Arrow during  
12 the floods of July 2007 in the United Kingdom, with the closest gauges on the River Arrow  
13 recording flows with a return period of 1 in 200 years. Moreover, the local drainage system  
14 was overwhelmed by excess rainfall (60 – 80 mm rainfall over a 12 hour period). The  
15 combination of these two events led to flooding of 150 properties with both fluvial and surface  
16 water, although the Environment Agency of England and Wales (EA) estimate that a further  
17 200 properties were successfully protected by the current flood defences. Furthermore, the EA  
18 estimates that ~260 properties in Alcester lie within the 1-in-100 year floodplain ( $\geq 1\%$  chance  
19 of fluvial flooding each year) and substantial areas of the town are at risk from surface water.  
20 In response to this flooding, the height of the flood wall in Alcester has been increased to  
21 ensure that it is above the July 2007 river levels and two new pumping stations have been  
22 installed to expel water from the town when the drainage system capacity is exceeded (EA,  
23 2011). The section of Alcester chosen for this study lies in an area susceptible to flooding both  
24 from the River Arrow and surface water overwhelming the drainage system. The motivation  
25 for the terrestrial LiDAR collection, therefore, was to understand the detailed hydraulics of  
26 water flow in this region. The test site has an area of 0.1 km<sup>2</sup> and consists of 4 streets with a  
27 number of cul-de-sacs feeding off them (Fig 1).

28 [Fig. 1 about here]

29 Although the area selected is prone to flooding from fluvial and surface water sources, there  
30 are no reliable estimates of flood volumes for an observed flood event in the area. As the aim  
31 of this study is to determine scale and roughness effects for terrestrial LiDAR data in urban

1 modelling, rather than to develop a detailed understanding of flood risk at Alcester, the model  
2 boundary conditions need to be sufficiently realistic to approximate a typical surface water  
3 flood but do not need to precisely reflect the actual conditions at the site. Therefore, the inflow  
4 boundary conditions for this test case were derived using the depth-duration-frequency method  
5 for estimating rainfall from volume 2 of the UK Flood Estimation Handbook, with local  
6 parameters derived from the accompanying Flood Estimation Handbook CD-ROM (FEH,  
7 Institute of Hydrology (1999)). For this study, we assume that the 200-year 30-minute rainfall  
8 (47 mm) is collected over a drainage area of  $100 \times 100$  m upstream of the inflow point (see Fig  
9 1) to represent the flow coming from a blocked culvert opening draining a small catchment.  
10 The accumulated volumes have been transformed into the simple 30 minute inflow hydrograph  
11 shown in Fig 2, where we assume inflow to increase linearly from 0 m<sup>3</sup> s<sup>-1</sup> to peak rate over  
12 the initial 7.5 min of the event, remaining at the peak rate for the subsequent 15 min before  
13 falling linearly back to 0 m<sup>3</sup>s<sup>-1</sup> over the final 7.5 min. The final assumption in this study is that  
14 the drainage system is operating at capacity such that water on the surface does not interact with  
15 the drains at the road side. Whilst observed data of the flooding would be of value, its absence  
16 does not limit the present study whose aim is to understand scaling effects for terrestrial laser  
17 data using a sensitivity analysis.

18 [Fig. 2 about here]

## 19 **2.2 Terrestrial LiDAR data collection and processing**

20 The high resolution elevation data of Alcester used in this study were collected by the  
21 Environment Agency Geomatics Group using the LYNX Mobile Mapper™ system distributed  
22 by Optech Incorporated. The LYNX Mobile Mapper™ consists of two 100 kHz LiDAR  
23 instruments, each with 360° field of view, mounted on a rigid platform on the back of a Land  
24 Rover. Two GPS receivers are mounted on the roof of the car, one at the front and one on the  
25 rigid platform at the back. In addition, an inertial measurement unit (IMU) is centred on the  
26 rigid platform and a sensor is mounted on the wheel to record rotations and steering direction  
27 in order to provide dead reckoning estimates of position if the GPS signal is weak. The GPS  
28 system uses the principle of real time kinematic (RTK) navigation whereby the roving LYNX  
29 unit calculates a relative position based on a known base station with accuracies of +/-5 cm.  
30 The system is capable of recording 4 simultaneous measurements per laser pulse which results  
31 in 1GB/second of point cloud data generation (<http://www.optech.ca/lynx.htm>).

1 The terrestrial LiDAR point cloud is processed into a DEM using proprietary processing  
 2 algorithms developed by EA. The main purpose of LiDAR segmentation is to separate ground  
 3 hits from surface objects such as vegetation and buildings returns. However in terrestrial  
 4 LiDAR surveys there is an additional need to separate long range points caused by reflection  
 5 off car surfaces and the interior of buildings from the ground pulse hits. This is achieved using  
 6 classification algorithms in an iterative procedure in order to progressively remove surface  
 7 objects from the underlying surface topography (see for detail Sampson et al. 2012). The  
 8 resulting surface was aggregated to a raster DEM at 10 cm resolution (3,616,663 cells) then  
 9 resampled to 50 cm (144,659 cells) and 1m (36,242 cells) using a simple nearest neighbour  
 10 resample method (Fewtrell et al. 2008) to investigate the scale dependency of flooding at this  
 11 site.

## 12 **2.3 Model description**

13 LISFLOOD-FP is a software package designed to model the propagation of water over complex  
 14 topography typically represented by raster data. The package is a mature system that has  
 15 undergone extensive development and testing since conception (e.g. Bates and De Roo 2000;  
 16 Hunter et al., 2005; Bates et al., 2010). The current version (Version 5.7.6) consists of a  
 17 collection of numerical schemes implemented to solve a variety of mathematical  
 18 approximations of the 2-D shallow water equations of different complexity (ranging from an  
 19 extremely simple diffusive wave model to a shock capturing Godunov-type scheme based on  
 20 the Roe Riemann solver which solves the full shallow water equations (Roe, 1981; Toro, 1999,  
 21 2001; LeVeque, 2002; Villanueva and Wright, 2005)). Among these different formulations, that  
 22 proposed by Bates et al. (2010) has attracted increasing attention for modelling flood  
 23 propagation over large urban areas. It solves a simplified inertial version of the Saint-Venant  
 24 equations (e.g. Ponce, 1990; Xia, 1994; Aronica et al., 1998; Bates et al., 2010; de Almeida et  
 25 al., 2012) which neglects the convective acceleration term in the momentum conservation  
 26 equation, yielding a system of three partial differential equations:

$$27 \quad \frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0 \quad (1)$$

$$28 \quad \frac{\partial q_x}{\partial t} + gh \frac{\partial(h+z)}{\partial x} + \frac{gn^2|q_x|q_x}{h^{7/3}} = 0 \quad (2)$$

$$29 \quad \frac{\partial q_y}{\partial t} + gh \frac{\partial(h+z)}{\partial y} + \frac{gn^2|q_y|q_y}{h^{7/3}} = 0 \quad (3)$$

1 where  $q$  [ $L^2 T^{-1}$ ] is the discharge per unit width,  $h$  [L] is the water depth,  $z$  [L] is the bed  
 2 elevation,  $g$  [ $LT^{-2}$ ] is the acceleration due to gravity,  $n$  [ $TL^{-1/3}$ ] is the Manning friction  
 3 coefficient,  $x$  [L] and  $y$ [L] are the horizontal coordinates and  $t$  [T] is the time. These equations  
 4 were originally solved using a simple finite difference scheme applied to a staggered structured  
 5 grid of square cells, which leads to a system of three explicit equations in two horizontal  
 6 dimensions (Bates et al. 2010). Previous applications of this formulation have reported  
 7 problems of numerical instability in domains with relatively low friction (typically  $n < 0.03$ ),  
 8 which imposes particular limitations to simulations of urban areas, where smooth surfaces are  
 9 typically abundant.

10 de Almeida et al. (2012) proposed a modification of the Bates et al. (2010) numerical scheme  
 11 that significantly stabilizes the solution in these low friction scenarios. The resulting model  
 12 provides a robust solution to flood propagation problems over complex topographies at very  
 13 low computational cost. In this scheme, water flux at the interfaces of two adjacent cells (i.e.  $q_x$   
 14 and  $q_y$ ) is calculated using the following discretization of the simplified momentum  
 15 conservation equation (Eqs. 2 and 3):

$$16 \quad q_{i-1/2}^{\eta+1} = \frac{\theta q_{i-1/2}^{\eta} + \frac{(1-\theta)}{2}(q_{i-3/2}^{\eta} + q_{i+1/2}^{\eta}) - gh_f \frac{\Delta t}{\Delta x} (y_i^{\eta} - y_{i-1}^{\eta})}{1 + \frac{g \Delta t n^2 q_{i-1/2}^{\eta}}{h_f^{7/3}}} \quad (4)$$

17 where  $h_f$  is defined as the difference between  $\max(y_i, y_{i-1})$  and  $\max(z_i, z_{i-1})$ , and  $(\theta)$  is a spatial  
 18 weighting factor that is used to control the amount of numerical diffusion added to the  
 19 numerical scheme to stabilize numerical oscillations (de Almeida et al., 2012). The particular  
 20 value of  $\theta$  used in the simulations is selected as the maximum (i.e. closest to unity) that provides  
 21 solutions free from spurious numerical oscillations. The subindex  $i$  denotes the centre of a  
 22 computational cell and  $i-1/2$  and  $i-3/2$  the three cell interfaces used by the numerical scheme to  
 23 compute flow discharges in the  $x$  direction. The superindex  $\eta$  and  $\eta + 1$  denote the indices of  
 24 two time steps of the computation. Water depths inside cells are subsequently updated by  
 25 substituting these flows into the discretized mass conservation equation (Eq. 1):

$$26 \quad y_{i,j}^{\eta+1} = y_{i,j}^{\eta} + \frac{\Delta t}{\Delta x} (q_{i-\frac{1}{2}}^{\eta+1} - q_{i+\frac{1}{2}}^{\eta+1} + q_{j-\frac{1}{2}}^{\eta+1} - q_{j+\frac{1}{2}}^{\eta+1}) \quad (5)$$

27 where the subindex  $j$  is used to denote the  $y$  position of the centre of the cell. The stability is  
 28 controlled by the Courant-Freidrichs-Levy conditions (e.g. Cunge, 1980) for shallow water  
 29 flows:

1 
$$C_r = \frac{\lambda \Delta t}{\Delta x} \tag{6}$$

2 where the dimensionless Courant Number ( $C_r$ ) needs to be less than 1 for stability and  $\lambda = \sqrt{gh}$   
3 is the wave celerity for the simplified inertial formulation. Eq. 6 provides a necessary but not  
4 sufficient condition for model stability, and the model estimates the time step as:

5 
$$\Delta t = \alpha \frac{\Delta x}{\sqrt{gh_{max}}} \tag{7}$$

6 where  $h_{max}$  is the maximum depth within the computational domain and  $\alpha$  is a coefficient that  
7 provides a further limitation on the maximum time step. The current version of the model uses  
8 a default value for  $\alpha$  of 0.7, although this can be tuned by the user. Further details of the model  
9 can be found in Bates et al (2010), de Almeida et al (2012) and de Almeida et al (*in press*).

## 10 **2.4 Model Applications**

11 In order to evaluate scale and roughness effects on urban surface flood modelling, different  
12 resolution DEMs produced from terrestrial LiDAR data and Manning's n data were prepared  
13 before applying the new inertial model (de Almeida et al. 2012). For the DEM data, 50cm and  
14 1m resolution DEMs were derived based on the 10 cm resolution terrestrial LiDAR DEM which  
15 was used as the benchmark terrain. Figure 3 shows that significant information (e.g. kerb and  
16 road surface camber) contained within the 10cm terrestrial LiDAR DEM is lost when degrading  
17 to 1m. The steepness of the kerbs is reduced gradually and road surface camber is smoothed  
18 progressively as the resolutions drops to 1m. Representing these types of small scale features  
19 (i.e. walls, kerbs, steps, road camber) in the DEM can have significant impact especially on  
20 surface flooding in urban areas (Djokic & Maidment, 1991; Hunter et al. 2008; Fewtrell et al.  
21 2011; Sampson et al. 2012). By contrast, Sampson et al. (2012) show that micro scale terrain  
22 features such as kerbs are not typically captured in airborne LiDAR data.

23 [Fig. 3 about here]

24 In previous studies on this test case (Fewtrell et al. 2011; Sampson et al. 2012), a single fixed  
25 composite friction coefficient was used ( $n=0.035$ ) for the whole area due to large oscillations  
26 in the solution which arose at more realistic friction values when using the Bates et al. (2010)  
27 numerical solution for equation (2). This value ( $n=0.035$ ) is likely to be too high to properly  
28 represent urban skin friction conditions. In this study, we applied to the models two types of  
29 friction coefficient, namely distributed Manning's n and a single composite friction coefficient

1 for the entire domain (Fig 4). Distributed Manning's n data were derived using UK Ordnance  
2 Survey (OS) MasterMap® vector data. The derived data were then checked by reference to  
3 Google® satellite images and Google® street view, and any misclassified areas (such as grass  
4 classified as pavement in the MasterMap® data) were manually corrected. Manning's n values  
5 taken from the standard Chow table (1959) were assigned to every type of land use and then  
6 converted to 10cm, 50cm and 1m raster data using the cell centred method. As shown in Fig. 4,  
7 Manning's n values of 0.013, 0.015, 0.025 and 0.035 were assigned to asphalt road, brick,  
8 gravel and short grass surfaces respectively. During the data-processing stage buildings and  
9 other high features are marked as 'no-data' pixels that function as impermeable boundaries,  
10 ensuring that such features are excluded from the DEM. The second type of friction  
11 parameterization is a uniform composite, assigned to the whole domain, for which the value of  
12  $n=0.013$  was chosen because it represents the smooth and impervious road surfaces that  
13 typically underlie flow paths taken by surface flood water in urban areas.

14 [Fig. 4 about here]

15 In order to evaluate the different resolution terrestrial LiDAR DEM and roughness conditions,  
16 we used the new inertial formulation of LISFLOOD-FP (de Almeida et al. 2012, eq. 4) to  
17 simulate the urban inundation test case in Alcester, UK. The improvement introduced by this  
18 new scheme is particularly relevant in situations involving low friction surfaces, where the  
19 previous scheme (Bates et al. 2010) exhibited problems of numerical stability which can  
20 introduce additional problems of mass balance to the model. In particular, in shallow parts of  
21 the computational domain these unphysical oscillations can lead to negative values of the water  
22 depth. The current implementation of the model handles this situation by resetting the negative  
23 values to zero so that the model can proceed to the next time step. This artificially adds water  
24 into the domain, causing mass balance errors to grow. The comparison of the mass balance  
25 error (difference between the net inflow through the boundaries and the change in the water  
26 volume within the domain) in different simulations can actually be used as a first indicator of  
27 numerical stability. The previous inertial formulation developed by Bates et al. (2010) was  
28 initially compared to that by de Almeida et al (2012) on the 50cm LYNX DEM and one single  
29 composite low friction ( $n=0.013$ ) conditions. The results obtained with the former showed non-  
30 negligible numerical oscillations (see figure 5) and high per time step volume error -2.24%.  
31 Using the same parameters, the new improved inertial scheme (with  $\theta = 0.8$ ) was applied to the  
32 test site. This new formulation produced an oscillation free solution with much reduced per

1 time step volume error (-0.03%). All the simulations for the paper were run using  $\alpha$  of 0.7 for  
2 the time step limiter (i.e. eq. 7), for 2 hours of simulated time (30 minutes of inflow event  
3 followed by 90 minutes for the water in the domain to come to steady state).

4 [Fig. 5 about here]

5 Even though this study uses values of Manning's coefficient that are relatively low, only  
6 subcritical flow conditions are observed in all simulations as a consequence of the relatively  
7 flat topography. The results of the simulations have shown that the Froude number  $Fr =$   
8  $u/\sqrt{gh}$  (where  $u$  is the magnitude of the velocity vector) is smaller than 0.6 over most of the  
9 domain during all stages of the flood propagation, which ensures that the model's assumptions  
10 introduce minimum errors (de Almeida and Bates, in press).

### 11 **3 Results and discussion**

#### 12 **3.1 Overview of simulations**

13 Initially, two configurations (fixed and distributed Manning's  $n$ ) of the new inertial model were  
14 built for each DEM grid scale ( $\Delta x = 10\text{cm}, 50\text{cm}$  and  $1\text{m}$ ) to establish the variability associated  
15 with changing resolution and different surface friction conditions. Model prediction of water  
16 depths, flood extent and flow velocity were evaluated against the relevant benchmark high-  
17 resolution (10cm terrestrial LiDAR DEM) simulations using root mean square differences  
18 (RMSD) and fit ( $F^2$ ) statistic (Werner et al. 2005). Fig. 6 shows the propagation of the flood  
19 wave over the 10cm, 50cm and 1m terrestrial LiDAR DEMs for different roughness conditions  
20 at four times (9, 24, 36, 120 min) using the new inertial formulation. In all simulations, the  
21 domain is initially dry and water enters at the simulated blocked drain in the north east corner  
22 and flows down the main north-south aligned street. During the early stages of the simulations  
23 ( $t = 9$  min), water passes the first side street, which is perpendicular the main road, without  
24 flowing down it, continuing instead in a south-easterly direction. The wave front initially  
25 propagates alongside kerbs due to the representation of the road camber in the DEM, with water  
26 only spreading across the entire width of the road as water depths increase. The kerbs also serve  
27 to prevent water from spilling off the road and towards adjacent properties until the water depth  
28 is sufficient to exceed the kerb heights. This simulated behaviour is due to the retention of the  
29 road camber within the DEM, demonstrating the importance and representation capability of  
30 very high resolution DEMs in surface water flood modelling (Fig. 6 and 7). When the flood  
31 wave reaches the second road junction, the road surface gradient causes some water to spread

1 along the side street which runs in a south-westerly direction, whilst the remainder continues to  
2 flow along the main road which lies in a south-easterly direction (Fig. 6,  $t=24$  min). As the  
3 simulations progress, water depths are seen to increase at the end of second and last southern  
4 perpendicular streets, which are areas of ponding caused by blocking at the boundaries of the  
5 DEM. While some areas of ponding are caused simply by depressions in the DEM, others occur  
6 at the boundaries of the DEM that are specified as being closed in this model. The impact of  
7 road cambers being correctly represented in the terrestrial LiDAR DEM can also be seen clearly  
8 at  $t=36$  and 120 minutes, where water advancing in a south-westerly direction down the second  
9 wetted side street flows along the road edges due to the convex profile of the road surface (fig.  
10 7). Finally, water continues to drain into the ponded areas until a near steady-state ( $t=120$   
11 minutes) is reached.

12 [Fig. 6 about here]

13 [Fig. 7 about here]

### 14 **3.2 Sensitivity to model resolution and surface friction parameterisation**

15 As the flood wave propagates through the street network, differences develop in the simulated  
16 water depths and inundation extent between the distributed and composite friction conditions  
17 and different resolution DEMs. Maximum water depths increase  $\sim 37\%$  when the model  
18 resolution increases from 1m to 10cm and surface water speeds are reduced when using  
19 distributed friction conditions. Surface water inundation is more rapid with a composite friction  
20 ( $n=0.013$ ) and finer resolution models (Fig. 6). This latter result is opposite to the findings of  
21 Yu & Lane (2006a) for urban areas using an airborne LiDAR DEM, and occurs due to rapid  
22 propagation of water along ‘channels’ that form at the road edge as a result of the road camber  
23 and roadside kerbs (Fig. 7). These ‘channels’ are smoothed as resolution decreases, and  
24 consequently water depths and velocities within them are greater on the 10 cm DEM ( $\sim 37\%$   
25 and  $\sim 32\%$  respectively) than the 1 m DEM. A set of idealized tests was performed in order to  
26 confirm that the above differences are a result of the fine scale topography, rather than potential  
27 structural errors introduced by the model. These test cases consist of simulating the flow of a  
28 fixed volume of water, originating from a fixed point, down an idealized road represented by a  
29 long and straight surface of uniform slope, rectangular cross section and Manning’s  $n$  of 0.013.  
30 These tests were run at 10 cm, 50 cm and 1 m resolutions for 60s. The results of these tests  
31 have shown that the distance travelled by the wave front from the fixed point of origin varied

1 by only ~1% between the three resolutions. This provides a strong evidence that the results  
2 obtained on the Alcester DEM above are not an artefact of model structure but rather are the  
3 consequence of the ability of fine resolution DEMs to represent hydraulically relevant surface  
4 features. This is also supported by previous tests performed by Bates et al (2010) and de  
5 Almeida and Bates (in press) at different resolutions. The simulations presented in this paper  
6 are therefore grid independent in what concerns to model structure (also supported by Bates et  
7 al, 2010), so that the main differences between the results at different resolutions can be directly  
8 associated with the representation of topography. The increased speed of wave propagation  
9 across the domain with the fixed Manning's n of 0.013 relative to the distributed friction map  
10 is unsurprising as an increase in surface friction will reduce flow velocities; however it is  
11 interesting to note that later in the simulation the inundation extent is greater in models using  
12 distributed friction as the water is retained for longer (Fig. 8). Therefore, during inflow to the  
13 domain, the inundated area is larger in all models which use a single composite friction due to  
14 higher propagation speeds; after the inflow has ended the inundated area becomes greater in the  
15 models which use distributed friction maps. In terms of maximum inundation extent, when the  
16 model resolution is increased (1m to 10cm), the inundation extent is decreased by ~3% in  
17 composite friction models and ~6% in distributed models in this test case. The area difference  
18 plot in figure 8 clearly demonstrates the effects of both grid resolution and friction  
19 parameterisation on water propagation across the domain. During the inflow period ( $t < 30$   
20 minutes), the inundation area is greater in high resolution models employing the composite  
21 friction map as water propagates across the DEM more quickly under these conditions. After  
22 the inflow period this pattern is reversed, as water drains to depressions in the DEM (thus  
23 reducing inundation area) more quickly in the same high resolution models employing the  
24 composite friction map.

25 [Fig. 8 about here]

26 Figures 9 and 10 show the evolution of water depths and elevations, and the effects of different  
27 roughness, at four control points (see Fig. 1) through the simulation using composite and  
28 distributed friction conditions at grid resolutions of 10cm, 50cm and 1m. Point 1 represents an  
29 area of rapid flow where water runs down a steep section of road, point 2 represents a junction  
30 where water flow splits between two streets, and points 3 and 4 are areas where ponding occurs.  
31 The water depths are higher in models using distributed roughness conditions at points 1  
32 (~23%) and 2 (~13%), but the opposite is observed after approximately 30 minutes at points 3

1 and 4 where the models using composite friction exhibit greater water depths and elevations  
2 with ~15% and ~17% increases respectively. This difference occurs as the wave propagates  
3 faster when the low composite friction value ( $n=0.013$ ) is used, enabling water to reach the  
4 boundary of the DEM and pond earlier. These differences in arrival time between the distributed  
5 and composite friction models can be seen at points 2 to 4 in figure 9 and 10. Time delay in the  
6 distributed roughness models (relative to the composite models) reaches 12 minutes in this test  
7 case, despite the farthest points (3-4) being located only 300 m from the inflow point. For the  
8 distributed and composite friction configurations arrival times increase as resolution decreases,  
9 with a similar increase in time delay between the friction configurations also being observed.  
10 For instance, when using the composite friction model, arrival time to point 4 is 24 minutes at  
11 10 cm resolution, increasing to 30 minutes at 1 m resolution. For the distributed friction model,  
12 surface water reaches point 4 in 36 minutes at 10 cm resolution, increasing to 42 minutes for  
13 the 1 m model. It should also be noted from fig. 8 that, despite representing flows resulting from  
14 a 1-in-200 year rainfall event, simulated water depths in areas of ponding along streets do not  
15 exceed the 0.5 m threshold that represents the minimum depth associated with vehicle damage  
16 (Wallingford, 2006). As such, the flows under discussion in this paper are all shallow in nature,  
17 allowing them to be influenced significantly by detailed surface topography.

18 [Fig. 9 about here]

19 [Fig. 10 about here]

20 Danger to people, vehicles, buildings and some infrastructure are assessed using the concept of  
21 flood hazard, which can be expressed as a combination of not only water depth but also velocity  
22 (Kok et al. 2004; Kelman & Spence, 2004; Jonkman & Kelman, 2005; Wallingford, 2006; Apel  
23 et al. 2009; Xia et al. 2010; Xia et al. 2011). Therefore, in addition to the flood depth, velocity  
24 prediction is a valuable addition to flood studies. Fewtrell et al. (2011) and Neal et al. (2011)  
25 suggested that the simplified models coded in LISFLOOD-FP can be used for velocity  
26 simulation for a wider range of conditions than previously thought due to the inclusion of  
27 stringent stability conditions. Fig. 11 shows the evolution of the velocity at the four points  
28 throughout the simulation at each resolution for both distributed and composite friction  
29 parameters. Velocity is calculated as the square root of the sum of the velocities in the x- and  
30 y- directions squared and hence purely represent the scalar velocity. In the models using the  
31 composite friction condition and the finer resolution DEM, velocities are typically greater  
32 (~15% and ~25%) than models using distributed friction conditions and the coarser resolution

1 DEM. Decrease in arrival time of peak velocity can be seen at point 3 and 4 in each resolution  
2 under distributed friction conditions. These differences can be clearly summarized by  
3 comparing velocities from the 1 m distributed model to the 10 cm composite model in figure  
4 10. In the 1 m distributed model, velocities are low and the timings of peak velocities are clearly  
5 distinct and dependent on the distance of the control point from inflow point. In the 10 cm  
6 composite model, velocities are high and thus separation of peak velocities is greatly reduced,  
7 almost to the point of overlap.

8 [Fig. 11 about here]

### 9 **3.3 Global model performance measures**

10 In order to analyse the global effect of model resolution on simulation results, the root mean  
11 squared difference (RMSD) between coarse models (50cm and 1m) and the benchmark high  
12 resolution (10cm) models for distributed and composite roughness conditions are computed for  
13 depth and velocity (Fig. 12); in addition the fit statistic ( $F^2$ , Werner et al. 2005) is calculated for  
14 inundated area. 50 cm and 1 m composite models are compared to the 10 cm composite  
15 benchmark and 50cm and 1 m distributed models are compared to the 10 cm distributed  
16 benchmark. There is a detectable reduction in model performance at coarse resolution which  
17 was previously noted by Horritt & Bates, 2001; Yu & Lane, 2006a; Fewtrell et al. 2008;  
18 Fewtrell et al. 2011. In this test case, RMSD is typically higher and  $F^2$  is lower in the 1 m  
19 models than in the 50 cm models, both in terms of water depth and velocity over the simulation  
20 period. In terms of distributed and composite roughness conditions, RMSDs of water depth are  
21 lower (by ~12%) in the models using composite friction parameters at a given resolution. The  
22 difference in  $F^2$  between distributed and composite friction parameters is typically greater at 1m  
23 than at 50 cm, especially during the early dynamic stages of the simulation while inflow is  
24 occurring. In the case of the RMSD of velocity, a smooth distribution is not seen as with the  
25 RMSD of water depth. The RMSDs of velocity are typically lower (~32% at 1m and ~8% at  
26 50cm) in the models using distributed roughness parameters during the early stages of the  
27 simulation, a finding that contrasts with the RMSDs of the water depth during this period.

28 [Fig. 12 about here]

29 The above analysis has shown that modelled water depths, inundation areas and velocities all  
30 exhibit sensitivity to friction parameterisation and changes in DEM resolution, even when the  
31 resolution of the coarsest DEM employed here (1 m) exceeds that typically used in urban

1 inundation studies (Mason et al. 2007; Brown et al. 2007; Fewtrell et al. 2008; Hunter et al.  
2 2008; Gallegos et al. 2009; Neal et al; 2009). The results have shown water to propagate most  
3 quickly across the highest resolution DEM as small scale topographical features such as road  
4 camber and street kerbs encourage the formation of small connecting ‘channels’ that rapidly  
5 convey water across the domain. As reducing the resolution from 10 cm to 1 m smoothes these  
6 features and slows down wave propagation, an attempt to recover the 10 cm result on the 1 m  
7 grid will require reduced surface friction to compensate for the loss of connectivity. This  
8 contrasts with previous studies undertaken at coarser grid scales using airborne LiDAR data,  
9 where micro scale topographical features cannot be represented and where decreasing grid  
10 resolution led to faster wave propagation. In these previous studies the terrain smoothing effect  
11 of decreasing DEM resolution (Yu & Lane, 2006a) could potentially be compensated for by  
12 increasing surface friction. To test whether decreasing surface friction could potentially  
13 achieve the same effect here, the 1 m models were re-run with surface friction values of 50%  
14 and 1% of the original distributed and composite values, with the results evaluated in terms of  
15 differences in water depth, arrival time, RMSD and inundated area from the benchmark 10cm  
16 models (Fig. 13). The results show that even when employing the most extreme 1% surface  
17 friction scheme (spatially uniform  $n = 0.00013$ ), the coarse 1 m model was unable to  
18 compensate for the reduced connectivity and recover the water depth, arrival time or inundated  
19 area of the fine 10 cm benchmark model. Furthermore, the RMSD of the 50% and 1% friction  
20 models is increased over the standard model during later stages of the simulation, suggesting  
21 that this approach adversely affects the distribution of final water depths across the domain.  
22 These results suggest that, when modelling shallow water flows such as those associated with  
23 urban surface water flooding, the ability of very high resolution DEMs to represent  
24 hydraulically relevant micro-topographic features (e.g. kerbs, road camber, wall etc.) has a  
25 significant impact on flow propagation that cannot be recovered at coarser grid scales through  
26 surface friction parameterisation alone. Instead, we need to develop optimal ways to include  
27 hydraulically relevant information about micro scale topographic features in coarser DEMs as  
28 for the foreseeable future decimetric resolution hydraulic models of whole city regions may be  
29 computationally prohibitive.

30 [Fig. 13 about here]

### 1 **3.4 Model stability and runtime analysis**

2 With regard to model stability, Bates et al. (2010) highlighted that care should be taken when  
3 using the inertial formulation for large areas where low surface friction dominate due to  
4 increased instabilities, which represented an important obstacle for the application of this  
5 equation set for modeling flow in urban areas. However, the new formulation proposed by de  
6 Almeida et al (2012) considerably reduces spurious oscillations and mass errors on the finer  
7 resolution DEMs (i.e. 50cm and 10cm) and under low friction conditions. In our simulations  
8 this was achieved by adding a relatively small amount of numerical diffusion to the method  
9 (e.g.  $\theta$  between 0.9 and 0.7). The computational cost of running the simulation under distributed  
10 or composite friction conditions was similar. As expected, changing the resolution had a  
11 significant impact on computational time. Runtimes for the 1-in-200 year event at 10cm, 50cm  
12 and 1m scales for 0.1 km<sup>2</sup> area were typically ~90 hours, ~21 minutes and ~5 minutes  
13 respectively using a Quad core Intel Core i7 CPU Q740 1.73 GHz processor. Hence, as  
14 previously noted by Sampson et al. (2012), the current version of LISFLOOD-FP would not be  
15 appropriate for large-scale urban flood modelling using very fine resolution DEMs of 10cm or  
16 below. There is increasing interest in undertaking hydraulic modelling over very large domains  
17 (Pappenberger et al. 2009; Merz et al. 2010), and continued development of efficient hydraulic  
18 code, as well as methods for efficient use of topographic data, will be required to achieve this  
19 aim.

### 20 **4 Conclusions**

21 This paper presents applications and benchmark testing results of a new inertial formulation of  
22 LISFLOOD-FP using distributed and composite friction conditions on high resolution  
23 terrestrial LiDAR DEMs (10cm, 50cm and 1m) in Alcester, UK. This represents the first  
24 attempts at conducting hydraulic modelling using sub-meter scale (10cm, 50cm and 1m)  
25 elevation data derived from terrestrial LiDAR data in conjunction with realistic friction  
26 conditions ( $n < 0.03$ ). The water depth, inundation extent, arrival time and velocity predicted by  
27 the simulations were shown to vary in response to DEM resolution and different friction  
28 conditions. Maximum water depths and velocity are shown to increase by up to ~37% and ~32%  
29 respectively with increasing DEM resolution, whilst inundation extent is shown to decrease by  
30 approximately 6%. A further idealised simulation is used to confirm that the results are grid  
31 independent and due to the ability of terrestrial LiDAR to resolve small scale features missed  
32 by airborne LiDAR due to its use of a sideways looking laser system with ~1-3cm point spacing.

1 During a surface flooding event, the formation of flow ‘channels’ constrained by small scale  
2 features such as road cambers and kerbs is observed in simulations run on the fine scale  
3 terrestrial LiDAR DEMs. These channels improve hydraulic connectivity across the domain,  
4 allowing water to drain rapidly to depressions where ponding occurs.

5 In order to investigate the effects of surface roughness parameterisation, two surface friction  
6 configurations (a uniform composite value and a variable distributed friction map) were applied  
7 to all resolution DEMs of the Alcester test site and the impact on flood depth, flood extent,  
8 flood arrival times and velocity were evaluated. Land use classes for friction conditions were  
9 derived from UK Ordnance Survey (OS) MasterMap® data with some editing using Google®  
10 satellite images and Street View. The results showed flood extent to be less sensitive to surface  
11 friction configuration than water depths and velocities. Flood wave arrival time is particularly  
12 sensitive to the specification of surface friction parameters, a finding that agrees with previous  
13 studies showing flood velocity and wetting-front speeds to be sensitive to resistance parameter  
14 distributions (Mason et al. 2003; Begnudelli & Sanders, 2007). However, recovering the result  
15 of the finest grid resolution simulation on the coarser DEM by changing the surface friction is  
16 shown not to be possible at this site. This is because flow propagation at the finest grid  
17 resolution is not only related to the surface friction values but also to the representation of  
18 hydraulically relevant small scale topographical features in the DEM. Reducing the resolution  
19 of the DEM reduces the capacity to represent these features and leads to a loss in modelling  
20 hydraulic connectivity across the domain, something that cannot here be compensated for by  
21 changing the surface friction parameterisation. We conclude that micro scale terrain features  
22 are therefore relatively more important to flood wave development because they create or block  
23 flow pathways rather than because they generate frictional losses.

24 The new numerical solution for the Bates et al. (2010) equations proposed by de Almeida et al.  
25 (2012) demonstrated increased model stability on high resolution DEMs under low friction  
26 conditions ( $n=0.013$ ) compared to the previous scheme, although it reduced computational  
27 efficiency at 10 cm resolution. The new formulation was also seen to solve the instabilities  
28 caused by low friction conditions on areas with shallow slopes. However, instability can also  
29 originate on high gradient slopes where supercritical flow occurs and this may be outside the  
30 ability of simpler schemes to simulate as these often strictly apply to subcritical flows only  
31 (Neal et al. 2011). Future work should concentrate on increasing the computational  
32 performance of simplified shallow water models on finer resolution DEMs (10cm or below)

1 and improving their ability to simulate supercritical flows for high gradient terrain features  
2 which may be common in urban environments.

3 The paper has shown that fine scale terrain data are required for the simulation of shallow  
4 surface water flows in urban environments. This finding suggests that terrestrial LIDAR would  
5 be beneficial for future urban surface water flood studies where shallow flows occurring across  
6 much of the domain must be modelled accurately to enable the correct identification of areas  
7 where water is likely to accumulate and reach damaging depths. It will also be beneficial for  
8 detailed site-studies where Sustainable Urban Drainage Systems (SUDS) are being considered,  
9 as precise simulation of surface water flow will facilitate the planning and implementation of  
10 SUDS techniques such as source control, permeable conveyance systems and temporary storm  
11 water storage solutions (DEFRA, 2004). A complete SUDS design analysis for a site could not  
12 be completed without coupling the model to a sewer model able to represent the typically  
13 employed overflow pipe system. An uncoupled model would still be of value at the planning  
14 stage to identify areas most at risk from surface water flooding, as well as when considering  
15 remedial flood drainage for when the system capacity is exceeded. Unfortunately, simulation  
16 at decimetric scales remains computationally expensive even when using efficient state-of-the-  
17 art hydraulic models, so it is suggested that future research should focus on further increasing  
18 the efficiency of such models as well as developing techniques that enable the representation  
19 of key hydraulically relevant small scale features at coarser resolutions.

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4

1 **Figure 1.** MasterMap® data of study area in Alcester with over plotted 10 cm LYNX data of  
2 the model domain. The locations of the assumed sewer surcharge inflow point and the control  
3 points are highlighted.

4

5 **Figure 2.** Inflow boundary conditions.

6

7 **Figure 3.** Google street view and street cross-sections showing the variation in kerb and road  
8 surface camber representation on the 10cm and derived 50cm and 1m terrestrial DEMs.

9

10 **Figure 4.** Land use classification and Manning's n value distribution (a) Google® satellite  
11 image (b) distributed Manning n value (c) single composite friction value.

12

13 **Figure 5.** (a) Simulation result at t=1080s using inertial formulation Bates et al. (2010) (b)  
14 Simulation result at t=1080s using inertial formulation de Almeida et al. (2012) (c) water  
15 surface profiles with original 50cm terrestrial LIDAR DEM surface.

16

17 **Figure 6.** Progression of surface flooding predicted by different resolution and roughness  
18 conditions using the new inertial formulation.

19

20 **Figure 7.** South junction road surface and maximum water depth transects for simulation of 1-  
21 in-200 year event on 10 cm and 1 m terrestrial LIDAR DEM.

22

23 **Figure 8.** Predictions of inundated area and differences based on 10 cm models through time  
24 with different resolutions and roughness conditions.

25

26 **Figure 9.** Profiles of simulated water depth through time at the four control points at  $\Delta x = 10\text{cm}$ ,  
27 50cm and 1m using Composite (C) and Distributed (D) roughness conditions.

28

1 **Figure 10.** Profiles of simulated water elevation through time at the four control points at  $\Delta x =$   
2 10cm, 50cm and 1m using Composite (C) and Distributed roughness conditions.

3

4 **Figure 11.** Simulated velocity over time at the four control points across the different  
5 resolutions using distributed and composite frictions and difference plots (distributed minus  
6 composite).

7

8 **Figure 12.** Evolution of the root mean squared difference (RMSD) and  $F^2$  between the  
9 benchmark  $\Delta x = 10$  cm models with distributed and composite roughness and the coarser 50cm  
10 and 1m models throughout the simulation for the water depth and velocity.

11

12 **Figure 13.** (a) Comparison of simulated water depth through time at the four control points  
13 between 10cm models using distributed (D) and composite (C) friction and 1m models using  
14 50% and 1% of distributed and composite friction values. (b) Comparison of RMSD through  
15 time between the benchmark 10cm models with distributed (D) and composite (C) friction and  
16 the 1m models using 100%, 50% and 1 % of distributed and composite values (c) comparison  
17 of inundated area between benchmark 10cm models using distributed and composite friction  
18 and 1m models using 50% and 1% of friction values.