Tracing and visualisation of contributing water sources in a model of flood inundation

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Abstract

We describe the formulation of a simple method of water source tracing for computational models of flood inundation and demonstrate its implementation within CAESAR-Lisflood. Water source tracing can provide additional insight into flood dynamics by accounting for flow pathways. The method developed is independent of the hydraulic formulation used, allowing it to be implemented in other model codes. In addition, we developed a method which allows up to three water sources to be visualised in RGB colour-space, while continuing to allow depth to be resolved. We show the application of the methods developed for the 2005 flood event at Carlisle, United Kingdom.

Keywords: Flood inundation, water source tracing, flood visualisation, reduced complexity modelling, Carlisle.

1 Introduction

Flood inundation models relate upstream river inflow and other dynamic boundary conditions (e.g. downstream stage) to inundation extent, depth and velocity; and they have become invaluable tools for the assessment and understanding of flood dynamics and risk. Recently a series of fast and effective two dimensional hydrodynamic models have been developed (e.g. Bates et al., 2010) that have enabled flood modelling to be applied at high resolutions and even at continental scales (e.g. Wing et al., 2017). Understanding the contribution of different water sources to flooding and river flows is important when managing river basins, for example determining the relative contribution of tributaries or where water borne contamination is an issue. However, this ability is presently missing from previously described 2D flood models and normally only reserved for more complex 2/3D commercial codes. We developed a simple and efficient method to track the contribution of multiple water sources to flood depths, and demonstrate it for the CAESAR-Lisflood model (Coulthard et al., 2013) for a multi-river flood event. A key advantage of the formulation developed is that the number of water sources which may be traced is limited only by computational considerations. In addition, the method is independent of the hydraulic formulation, meaning that it is relatively straightforward to add to existing codes.

CAESAR-Lisflood[1] is a development of the CAESAR model (Coulthard et al., 2002; Van De Wiel et al.,

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[1]Available from https://sourceforge.net/projects/caesar-lisflood/

2007) and the LISFLOOD-FP 2D hydrodynamic model (Bates et al., 2010) that simulates landscape evolution by coupling a hydrological model, a surface water flow model, fluvial erosion and deposition and slope processes. Here, we focus only on surface water, and additionally develop a method for the visualisation of water sources.

2 Methods

2.1 Flow formulation

CAESAR-Lisflood implements the LISFLOOD-FP inertial formulation (Bates et al., 2010) to estimate depths across the domain. This is a reduced physical complexity mass-conservative hydraulic model structured on a Cartesian grid, in which the updated water depth h, at time t, for cell i, j is determined using (Bates and De Roo, 2000):

$$h^t_{i,j} = h^{t-\Delta t}_{i,j} + \Delta t \frac{Q^t_{x,i-1,j} - Q^t_{x,i,j} + Q^t_{y,i,j-1} - Q^t_{y,i,j}}{\Delta x^2} \tag{1}$$

where $h^{t-\Delta t}_{i,j}$ is the cell depth at the end of the previous timestep (Δt), Q represents the flows into or out of the cell in the x or y directions, and Δx is the cell size. Flows are decoupled in each direction; flow in the x direction is determined using (Bates et al., 2010):

$$Q^t_x = \frac{q^{t-\Delta t}_x - g h^t_{[\text{flow}]} \Delta t \frac{\Delta(h^t + z)}{\Delta x}}{(1 + g h^t_{[\text{flow}]} \Delta t n^2 |q^{t-\Delta t}_x| / (h^t_{[\text{flow}]})^{10/3})} \Delta y \tag{2}$$

with flow in the y direction obtained analogously. In Eqn. 2, $q^{t-\Delta t}_x$ represents the flux between the cells from the previous timestep ($Q^{t-\Delta t}_x / \Delta y$), g is acceleration from gravity, $h_{[\text{flow}]}$ is the maximum depth of flow between two cells, n is Manning's roughness and z is the cell bed elevation. Neal et al. (2012) benchmarked LISFLOOD-FP against other formulations and industry standard codes and showed that, in appropriate flow conditions (i.e. gradually varied flow, Froude number < 1), the model performed favourably and with high efficiency.

2.2 Water source tracing

Given that the sum of depths in a cell from each source, w, make up its total flood depth, h:

$$\sum_{w=1}^{N} h_w = h, \tag{3}$$

the volume fraction of each source, ϕ_w, may be obtained from:

$$\phi_w = \frac{h_w}{h}, \tag{4}$$

ensuring:

$$\sum_{w=1}^{N} \phi_w = 1. \tag{5}$$

Thus, the fraction of each water source in each cell is defined as the depth of water from that source in the cell, divided by the total cell depth.

Following this, once flows between cells are calculated and depths updated, water tracing proceeds as follows: (1) for each cell, the remaining depth following removal of water from any outflows is found; (2) the amount of the depth belonging to each water source is obtained by scaling the depths according to water source fractions from the previous timestep; (3) contributing inflow depths from each source for all neighbours is added to each source depth; and (4) updated water source fractions are calculated as per Eqn. 4 by dividing the fractions from each source by the updated total cell depth. More formally, for each cell, for each water source, w, at time, t, the volume fraction ϕ is:

$$\phi_w^t = \frac{h^t_{Q_{\text{[out]}}} \phi_w^{t-\Delta t} + \sum_D (Q^{t,D}_{\text{[in]}} \phi_w^{t-\Delta t, D}) \frac{\Delta t}{\Delta x^2}}{h^t} \tag{6}$$

where $h^t_{Q_{\text{[out]}}}$ represents the depth remaining in the cell after the removal of outflows at the current time, $Q^t_{\text{[out]}}$ (and before the addition of any inflows), which is scaled according to the fraction from this source from the previous timestep, $\phi_w^{t-\Delta t}$. To this depth is added the total amount of water from this source which is contributed from neighbouring cells, given by $\sum_D (Q^{t,D}_{\text{[in]}} \phi_w^{t-\Delta t,D})$, where $Q^{t,D}_{\text{[in]}}$ is the inflow from a particular direction, D, and $\phi_w^{t-\Delta t,D}$ is the fraction of flow for source from that direction. The updated source volume fraction is obtained by dividing by the updated cell depth, h_t. Finally, $h^t_{Q_{\text{[out]}}}$ is given by:

$$h^t_{Q_{\text{[out]}}} = h^{t-\Delta t} - \sum_D Q^{t,D}_{\text{[out]}} \frac{\Delta t}{\Delta x^2} \tag{7}$$

where $Q^{t,D}_{\text{[out]}}$ are the outflows in each direction.

It should be noted that, for simplicity, this method treats cell water volumes as fully mixed. Consequently, it may be possible for small fractions to propagate quickly in a downstream direction, since fluxes into a cell would be included in the fractions assigned as inflow to a downstream neighbouring cell in the next timestep, via $\phi_w^{t-\Delta t,D}$. As a result, caution should be given in the interpretation of very small water source fractions.

Boundary condition inputs are added prior to the routing of surface water. Adjusting the water volume fractions for the cells in which water is added is straightforward. The boundary modified water volume fractions, ϕ'_w, are obtained using:

$$\phi'_w = \frac{h\phi_w + q_w \frac{\Delta t}{\Delta x^2}}{h + \sum_w q_w \frac{\Delta t}{\Delta x^2}} \tag{8}$$

for input sources, or:

$$\phi'_w = \frac{h\phi_w}{h + \sum_w q_w \frac{\Delta t}{\Delta x^2}} \tag{9}$$

for other sources, where q_w is the inflow added to the cell from source w at the start of timestep. Thus, fractions from sources where water is added to the cell are adjusted upwards, while fractions for non-source volumes are adjusted downwards.

2.3 Water source visualisation

Visualisations of flood model outputs are often produced for depths in the form of animated maps. Here, we derived a simple colour scaling which permitted up to three water sources to be visualised in RGB colourspace, while continuing to allow depth to be resolved through the use of darker hues for deeper water. For each cell, the RGB colour index in the range 0 - 256 is obtained for the desired water source, w, using:

$$RGB_{i,j} = ((1 - h_{i,j}/h_{\text{[range]}}) \cdot 128) + (128 \cdot (\phi_{i,j,w})^{\beta}) \tag{10}$$

where $h_{\text{[range]}}$ is the range of depths. The power term, β, enables visual enhancement of lower water fractions, in the range ~0.1 to 1.0, where 1 would represent no enhancement.

3 Application

We demonstrate water source tracing and visualisation for a major flood event in 2005 at Carlisle, United Kingdom. With the benefit of an extensive set of observational data obtained from field collection, the event has been used extensively as a test case for hydraulic model development (e.g. Neal et al., 2009; Horritt et al., 2010). Here, the site is of particular interest as it is at the confluence of three separate rivers: the main River Eden, which runs from east to west through the city, is joined by the Rivers Petteril and Caldew which flow into the city from the south (Figure 1). A simulation was run using a model grid of 5 m, topography from LiDAR and inflows from gauging station records. The simulation began on 08 January 2005, 00:00 AM, for 120 hrs (5 days).

Visualisations of the model output are shown in Figure 2. Here, flood water mixing is shown in RGB colourspace, as per Eqn. 10: i.e. the mixing of red and blue gives pink; green and blue gives cyan; red and green give yellow; and shades towards white would indicate mixing of all three sources. Darker shades indicate deeper water.

Time-series plots in Figure 2 illustrate locations where water is mixed from multiple sources. The larger volume of water from the River Eden dominates, but at point A, a railway embankment prevents flooding from the Eden but the area is flooded by the Caldew. Points B and D are initially flooded by the Caldew and Petteril, respectively, until flooding from the Eden arrives. This is likely due to the timing of the flood peaks (~11.5 hours earlier on the Petteril than the Eden; ~17 hours earlier on the Caldew).

4 Summary

We developed a simple method for tracing water sources through a flood inundation model. The key advantage of the approach lies in its independence from the hydraulic methodology used, meaning that it is relatively straightforward to add to existing code. The method enables effective and informative visualisation of flood inundation, providing additional insight into flood dynamics.

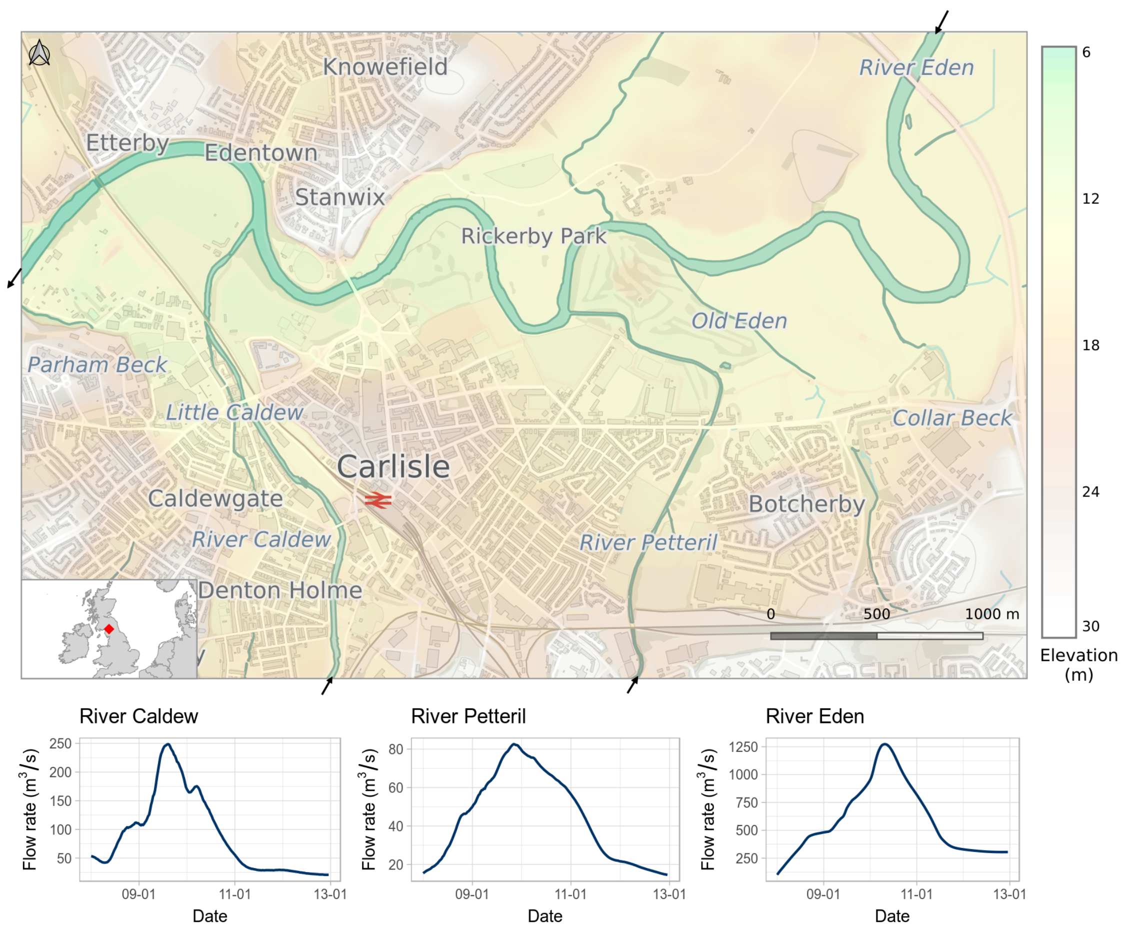

Figure 1: Study site at Carlisle, UK, at the confluence of the Rivers Caldew, Petteril and Eden. Hydrographs of the January 2005 flood event simulated are shown. Contains OS data © Crown copyright and database right (2019).

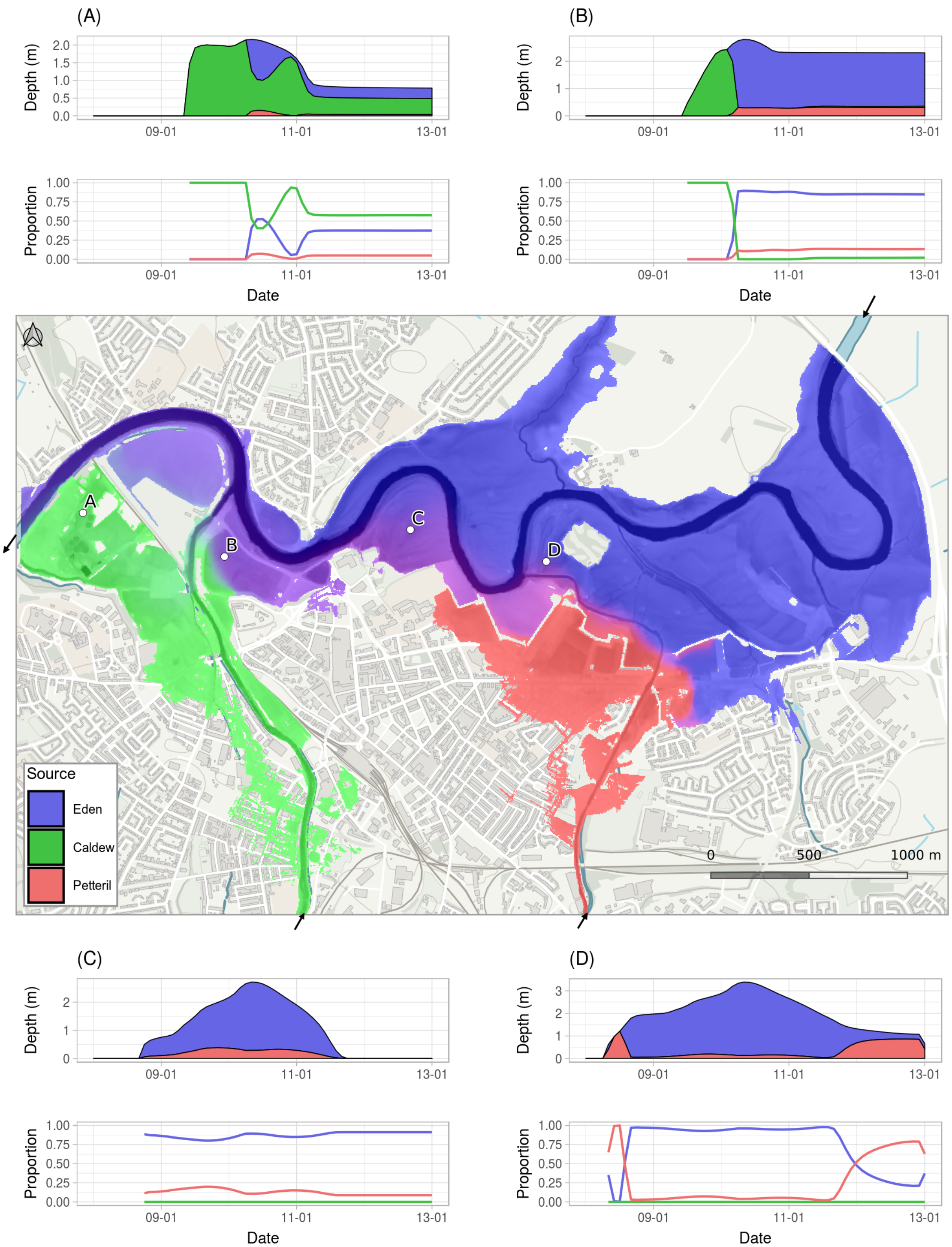

Figure 2: Flood extent, 10 January 2005, 06:00 AM, close to flood peak. Map colours indicate mixing of water, with $\beta = 0.2$ to emphasise lower water fractions from the Caldew and Petteril Rivers. Depths and proportions for four selected locations, marked A-D, are shown. For an animated version see: `https://youtu.be/xOtOi06cXvA`.

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