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Improving models of river flood inundation using remote sensing

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ABSTRACT: Flooding remains a substantial natural hazard despite recent advances in the understanding of the scientific mechanisms causing it and increased expenditure on flood defences. There is a need to improve river flood inundation extent maps by developing better flood models. Two dimensional hydraulic models are currently at the forefront of research into river flood inundation prediction. The two dimensional nature of these models requires spatially distributed 2-D data for their parameterisation and validation. Remote sensors carried on satellites and aircraft are now proving to be a rich source of such data. We have been using satellite and airborne Synthetic Aperture Radar (SAR) and airborne scanning laser altimetry (LiDAR) data to improve flood models. The flood inundation extents observed in satellite and airborne SAR imagery have been used to validate the modelled flood extents. LiDAR data have been used to improve model parameterisation, providing the model with a dense and accurate DTM of the floodplain, and parameterising friction in the model by providing information for assessing vegetation resistance to flood flow. Methods developed for rural flood extent prediction are now being extended to the urban environment.

1 INTRODUCTION

Globally, flooding causes about one half of all fatalities and one third of all economic losses due to natural hazards. It is also on the increase, due partly to the effects of global warming and partly to increased building on floodplains. The UK Hadley Centre estimates that in the UK river floods that were previously 1 in 100 year events will become 1 in 10 year events over the next century. In the UK, it is standard practice to employ a flood risk map to identify the risk at a particular location. There are two main end-users for such maps. One is the UK Environment Agency (EA), which provides web-based flood risk maps for the general public and maintains the existing network of river flood defences. Many defence works are in urgent need of maintenance, and it is important that the areas most at risk of flooding are identified in order that the associated flood defence works can be prioritised and completed. The other main end-user is the insurance industry, which uses the maps to set insurance premiums for properties depending on their flood risk. Computerised models of river flood flow are currently used to predict maps of flood inundation extent. These have a number of limitations, and there is a need to improve current maps by developing better flood models.

Two dimensional hydraulic models are currently at the forefront of research into river flood inundation prediction. These models often adopt a 2-D finite element approach, solving the shallow water equations at each node of an irregular mesh covering the channel and floodplain. Each node of the mesh must be assigned a topographic height and a bottom friction factor. During a model run, the time-evolving water depths and flow velocities at each node are calculated, given the input flow rate to the reach and any other boundary conditions.

The two dimensional nature of these models requires spatially distributed 2-D data for their parameterisation and validation. Until recently, development of these models has been hampered by lack of suitable data. As regards data for parameterisation, there has been inadequate floodplain topography data. Inundation depends on topographic features with length scales <~50 m horizontal and <~20 m vertical. UK Ordnance Survey maps provide inadequate coverage, being limited to 5m contours. The specification of flow resistance also remains a significant problem. In lowland floodplains at inundation depths < 1m, flow resistance is probably dominated by vegetation. Typically flow resistance currently has to be left as a free parameter in the model, with a single bottom friction factor being specified for the whole of the floodplain and a different friction factor specified for the channel. As regards data for validation, routinely collected hydraulic data consist solely of bulk flow measures, namely discharge rates and water depths. The spacing of river gauges is quite sparse (10–20 km), so that they usually provide validation data only at the external boundaries of the model. It is easy to calibrate models against such data and therefore they have a limited value in reducing calibration uncertainty.

Remote sensors carried on satellites and aircraft are proving to be a rich source of spatially distributed data for model parameterisation and validation. We have been using satellite and airborne Synthetic Aperture Radar (SAR) and airborne scanning laser altimetry (LiDAR) data to improve flood models.

2 MODEL VALIDATION

We have been using inundation extent measured from SAR imagery to validate the modelled flood extent. SAR has the advantage of being day-night and all-weather, important for the storm conditions that often prevail during flooding, as a visible band satellite cannot see through cloud. Generally flood water will appear darker than adjacent land in a SAR image. An image segmentation algorithm to determine flood extent in a SAR image has been developed, which uses a statistical active contour model or ‘snake’ to distinguish flood water from other classes (Figure 1). We estimate that satellite SAR can predict the true inundated area to an accuracy of 85–90%, the main error being due to unflooded wet vegetation giving similar returns to water (Horritt *et al.*, 2001).

3 MODEL PARAMETERIZATION

We have also been using airborne LiDAR to improve model parameterisation. LiDAR is an important new data source for environmental applications, and can produce maps of

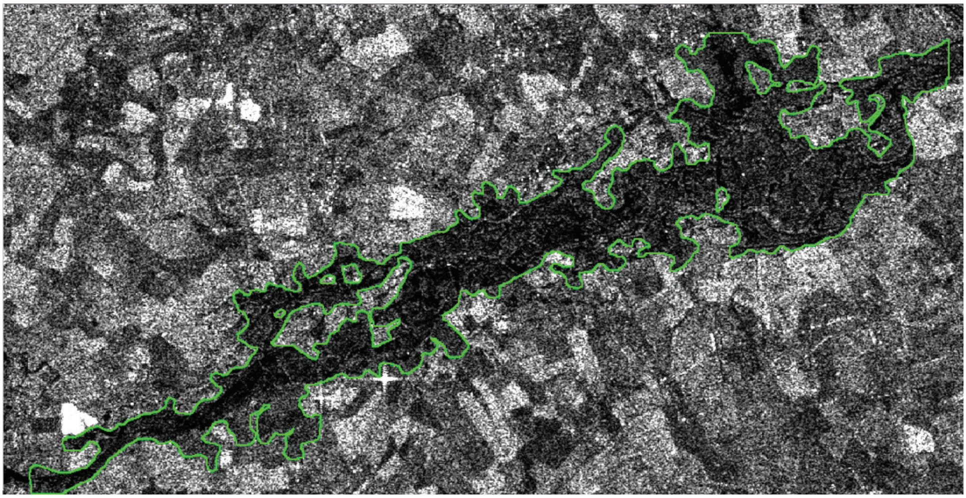

Figure 1. Flood extent from snake superimposed on ERS SAR image (© European Space Agency) (after Horritt *et al*., 2001).

surface height over large areas with a height accuracy of 10–15 cm and a spatial resolution of ~1m. LiDAR is able to provide the model with a dense and accurate DTM of the floodplain, enabling the floodplain topographic surface in 2-D models to be fully parameterized for the first time. It can also provide floodplain vegetation heights, which allows the spatially-distributed parameterisation of friction in the model by providing information for assessing vegetation resistance to flood flows. This means that the model can be made more physically-based, as floodplain friction no longer has to be left as a free parameter in the model (Mason *et al*., 2003).

Figure 2a shows a 6 km × 6 km LiDAR image of a reach on the river Severn, UK, from the EA Optech LiDAR, with brighter values being higher heights. The raw data are shown on the left of the image, with the overlaps between adjacent LiDAR swaths apparent, while on the right the image has been interpolated to make it more sensible to the eye. The basic problem in LiDAR post-processing is how to separate ground hits, which can be used to construct a DTM, from surface object hits on vegetation or buildings. We have developed a LiDAR range image segmentation system to do this. This converts the input height image into two output raster images of surface topography and vegetation height at each point. Many schemes have been developed to perform such filtering. Most of these are concerned with the detection and recognition of buildings in urban areas, or the measurement of tree heights. Our system has been designed specifically for use in flood modelling. A particular characteristic is its use of LiDAR height texture to estimate heights of short vegetation such as grasses or crops. In a rural floodplain the majority of the land surface may be covered with this type of vegetation, which most filtering schemes will simply ignore.

The segmenter first estimates the underlying low frequency trends by interpolating though pixels that are local minima, to produce an initial rough estimate of ground heights over the whole image. The detrended height image is then segmented on the basis of its local height texture. Regions of short vegetation should have low height texture, and regions of tall vegetation larger values. Short vegetation heights are calculated using an empirically-derived relationship between LiDAR standard deviation and measured crop height, while hedge and tree heights are derived by subtracting the ground heights from the canopy returns. Figure 2b shows the resulting vegetation height map. The DTM (Figure 2c) is constructed by subtracting an empirically-determined fraction of the vegetation height from the original data in short vegetation regions, and by interpolating between ground hits elsewhere.

The vegetation height map can be used to estimate a friction factor at each of the model's finite element nodes. The values of the friction factor depend on the vegetation

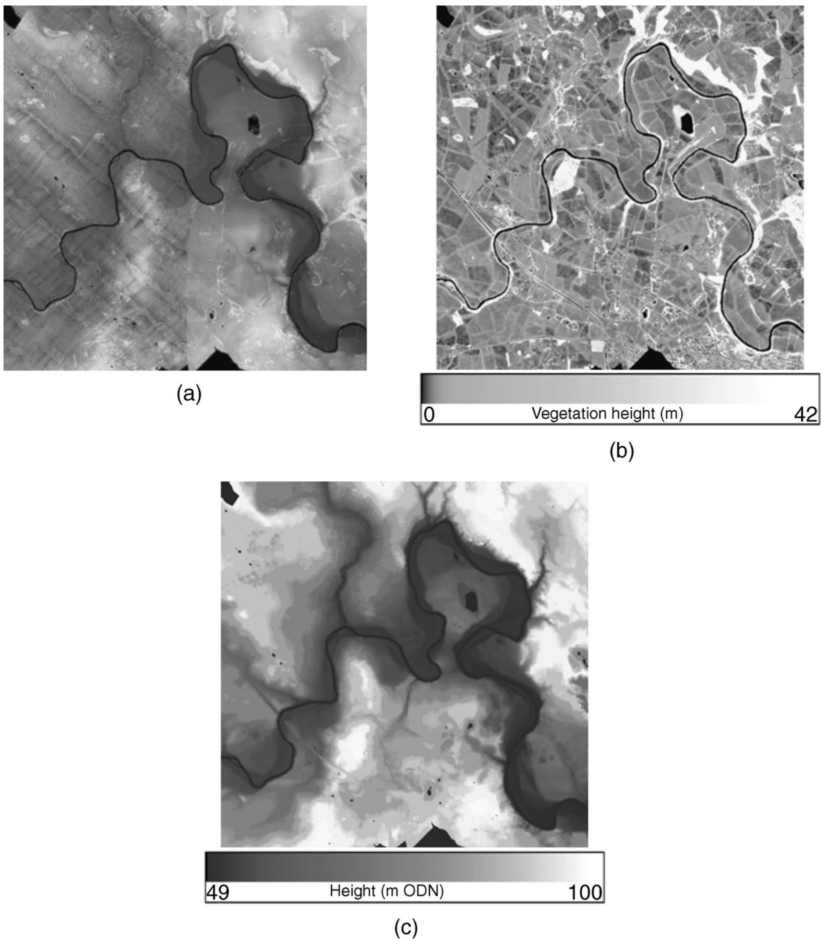

Figure 2. (a) LiDAR data of a 6 × 6 km area in the Severn basin (raw data on left-hand side, interpolated on right-hand side), (b) vegetation height map, (c) DTM (after Mason *et al*., 2003).

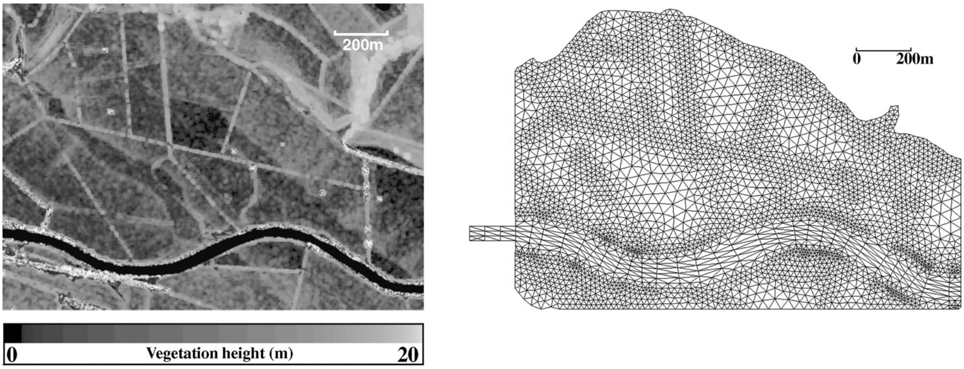

Figure 3. Mesh refinement using the LiDAR segmentation. Refined mesh shows finer detail around taller vegetation features (after Cobby *et al*., 2003).

heights and the water depth and velocity in the vicinity of the node, and are calculated at each model time step. It turns out that the only vegetation attribute required to measure the friction factors for vegetation is vegetation height, measurable from the LiDAR.

A difficulty we found was that important surface features such as hedges often occupied only a small part of the mesh element they were in. However, the friction at a hedge may be significantly higher than that in the fields adjacent to it. Ideally what is required is smaller elements where the friction surface changes rapidly (e.g. along hedges). So we developed a mesh generator that identifies taller vegetation features such as hedges and trees in the vegetation height map, and decomposes the mesh to match the feature width (Figure 3) (Cobby *et al*., 2003).

These techniques were used for model parameterisation and validation for the example of a 1 in 50-year flood on the Severn in October 1998. The observed flood extent was estimated from a RADARSAT SAR image using the snake algorithm, and this was compared to the flood extent predicted by the model. Figure 4 shows the model (black) and SAR (red) flood extents superimposed on the floodplain topography. The modelled flood extent was found to agree with the observed flood extent almost everywhere. This gives us some confidence in the variable friction model using LiDAR-derived vegetation heights, at least for this particular flood, though further experiments on other reaches and floods are required.

4 URBAN FLOOD MODEL PARAMETERISATION

The above work has been concerned mainly with modelling floods in rural areas. We have recently become involved in the UK's Flood Risk Management Research Consortium project, which is being carried out by a large consortium and will be central to all research on flooding being carried out in the UK over the next few years. In the FRMRC project we are concerned with urban flood modelling, as it is in urban areas that most of the risk lies.

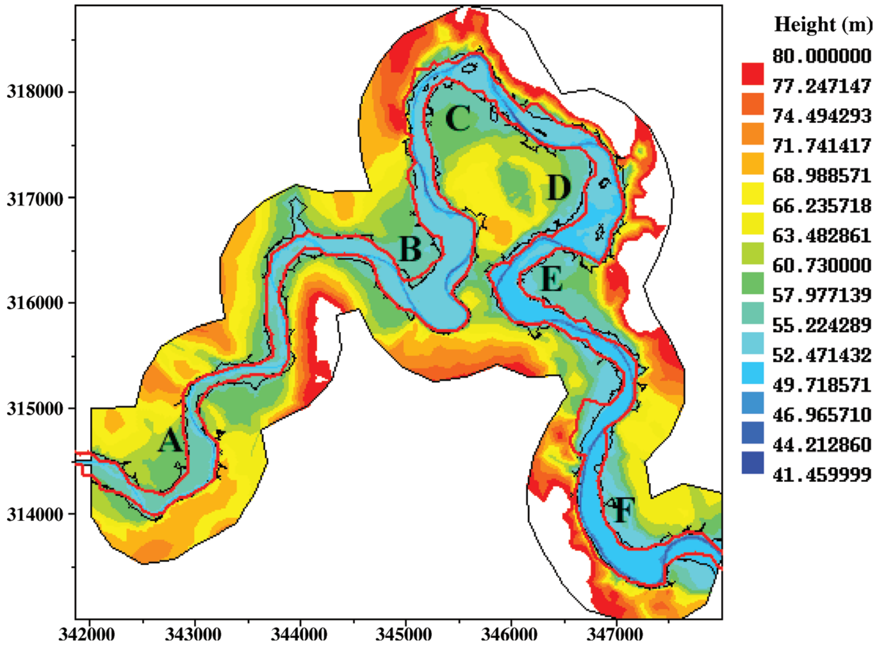

Figure 4. Model (black) and SAR (red) flood extents superimposed on bottom topography (after Mason *et al*., 2003).

In the UK, over 2 million properties are located in floodplains, with an estimated 200,000 of these being classified as at risk because they do not have protection against a 1-in-75 year flood event. The majority of these properties are in urban areas. Urban flood modelling is still at an early stage, and is more complicated than in rural areas. While some processes such as channel-floodplain interactions are common to both environments, in urban areas flows interacting with the built environment must also be modelled. Surface flows will be affected not only by the ground topography and vegetation, but also by buildings and other man-made features such as walls, roads, embankments, ditches, kerbs and parked vehicles.

We originally developed the segmenter to analyse rural scenes, so that it worked only with LiDAR heights, and as a result could not distinguish tall vegetation from buildings, and grass from tarmac roads. It was necessary to modify the segmenter because this caused a number of problems in urban areas. The outputs required from an urban segmenter are a DTM and a friction parameter map (a superset of the vegetation height map). We require that objects in the DTM should be solid and not allow through-flow. So, assuming that we regard buildings as impermeable, the DTM surface should rise up over buildings. The friction parameter map contains information that can be used to estimate local bottom friction, including information on objects that allow both through-flow (short vegetation, hedges, trees) and over-flow (roads, man-made surfaces). For vegetated surfaces, this information includes vegetation type and height, which can be converted to friction factors as previously. For surfaces allowing over-flow, the surface type can be stored, and can be converted to a friction factor using lookup tables.

Several authors have devised methods of distinguishing tall vegetation from buildings, and grass from tarmac roads, using computer vision techniques applied to combined LiDAR height and intensity images or combined LiDAR/multispectral images. This is certainly one possible approach. The simpler approach we have adopted is to use digital map data in conjunction with the LiDAR height data to detect buildings and roads (Mason *et al.*, in press). Pattern recognition techniques are also used to cope in cases where the map may not be up-to-date, or where small buildings are missing from the map. Objects in the map with high spatial height frequencies such as buildings are masked out in the process of interpolating through the local minima, thus ensuring that such objects are unable to influence the interpolation process. However, roads, man-made surfaces and railways are not masked out, as they are vegetation-free regions that can be used to tie down the DTM heights in their locality. At the completion of the segmentation process, the building heights may be re-introduced directly into the DTM in the areas masked out if this is what is required. Also, the vegetation heights of buildings, roads, railways and man-made surfaces are set to zero in the friction parameter map. Figure 5 shows the LiDAR and map data being combined to form a DTM and friction parameter map (the bright region in the NE of the LiDAR image is a river).

The method of decomposing the mesh in the neighbourhood of taller vegetation features has also been extended to cope with urban areas containing vegetation. The mesh

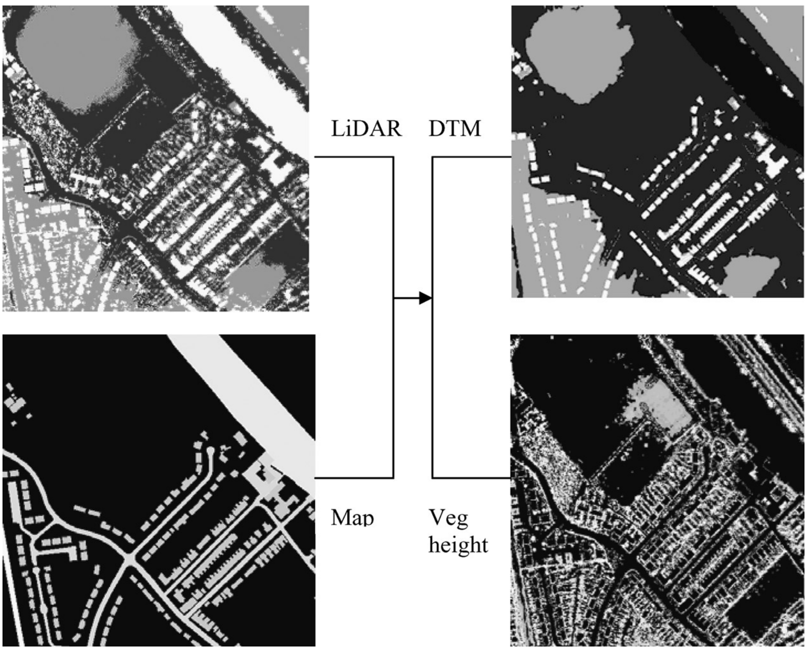

Figure 5. LiDAR and map data combined to form an urban DTM and vegetation height map.

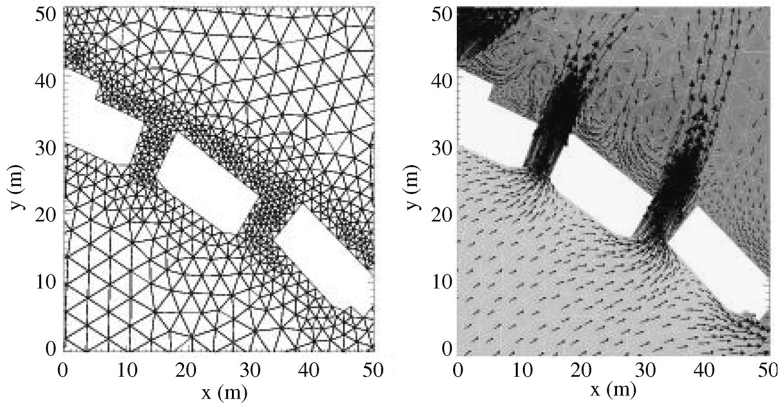

Figure 6. Modelling studies. (a) high resolution mesh, (b) water elevations and velocities (darker values = lower elevations) (after Mason *et al*., submitted).

generator produces smaller elements in the vicinity of buildings as well as vegetation, and larger elements farther away, thus minimizing computation requirements.

The urban segmentation and mesh generation techniques have been tested in a preliminary modelling study of urban flooding. Figure 6a shows a mesh decomposed in the region of buildings, while Figure 6b shows the highly variable flow field produced by the model, with recirculation zones present in the lee of buildings. A full study of urban flood plain hydraulics using validation data is currently underway for a recent UK flood.

5 CONCLUSIONS

These results demonstrate the utility of flood extents derived from SAR data for validating 2D hydraulic model flood extents in rural areas, and of LiDAR and digital map data for parameterising such models in rural and urban environments.

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