A RAPID FLOOD INUNDATION MODEL

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ABSTRACT

Government flooding policy across Europe, and elsewhere, has switched from flood defence to flood risk management. This move to risk based analysis requires adopting a systems approach to the management of flood assets. Such an approach requires the evaluation of the consequences of all possible asset failures, e.g. breaching, overtopping or surcharging. For a typical flood system this necessitates the simulation of thousands of inundation permutations. As a consequence speed of simulation is a significant factor in the practical implementation of this approach. The paper reports progress on the on-going development of a rapid flood inundation prediction model designed to satisfy this requirement. The model makes use of high resolution remotely sensed digital elevation models. These are analysed to create a system of flood cells. The results of this precalculation are then used by the rapid inundation algorithm to compute water exchanges between flood cells and the maximum water level and depth over each pixel.

The application of the method is demonstrated through the simulation of inundation on an urban floodplain. Ability to accurately predict the maximum inundation extent while maintaining a very short model run-time has been tested.

Keywords: flood modelling, raster, DEM, storage cell

1 INTRODUCTION

In the UK it has long been recognised that risk-based analysis of flood defence schemes can be employed to improve flood asset management decision-making (Sayers *et al*, 2002a, Defra, 2006). In this approach, each element of a flood defence system is analysed in terms of its contribution to the overall flood risk, enabling weak points to be identified and the benefits of possible improvements assessed. The approach evaluates the probability and consequences of all possible breach and overtopping scenarios and takes account of a range of sources of flood water, defence system responses and the impacts of flooding (Sayers *et al*, 2002b, HR Wallingford, 2004).

1.1 FLOOD RISK

Climate change plus economics mean it is not possible to eliminate flood risk completely. It is now widely accepted that the most efficient approach is to understand the risks and manage them by the construction and maintenance of defences, delivering well designed flood warning schemes, or restricting development in areas that are prone to regular or severe flooding.

Risk generally has two components - the chance (probability) of an event occurring and the impact (consequence) associated with that event (HR Wallingford, 2002).

$$risk = probability \times consequence \quad \text{(Eq. 1)}$$

Consequence refers to the undesirable outcome or harm that would arise if a risk is realised. To assess the probability and consequence of each flooding scenario the flood system can be simplified into three elements (Figure 1):

Sources of risk - meteorological factors such as rainfall, runoff, waves and storm surge.

Pathways - catchment and floodplain topography, and flood management assets (including their condition). Note that flood risk management measures can change the behaviour of pathways.

Receptors of risk - exposure and vulnerability of the people, property and environmental features that may be harmed by flooding.

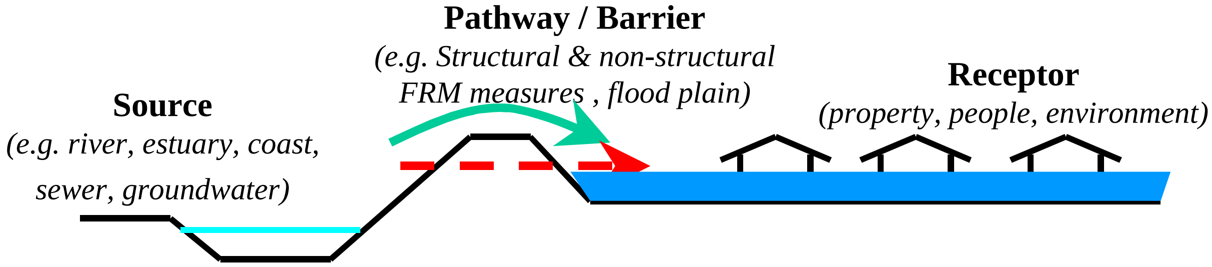

Figure 1: Simplified illustration of Source-Pathways-Receptors Concept (HR Wallingford, 2002)

A quantified approach to assessing flood risk seeks to quantify each element of flood risk system (Figure 2). The source of flooding (load) can be described by the return period, indicating how frequently a particular load will be exceeded. The performance of flood defences is described by a reliability curve that depends on the structure, material, failure mechanisms and current condition of the assets. When a flood defence is breached the flood extent and flood characteristics (inundation depth, flow velocity) are a function of breach size, effectiveness of flood risk management measures and floodplain topography. The probability of exceeding certain water depth or flow velocity values in certain locations can also be quantified in the form of probability relationships.

To obtain such data, flood extent has to be calculated for given initial and boundary conditions. The consequence of flooding (Eq.1) is described as the damage or harm related to depth or flow velocity. The expected risk is evaluated from the probability that particular damage values are exceeded, using damage curves. As a result of this step-by-step calculation the risk of flooding of the floodplain under certain flood defence breach or overtopping scenarios can be estimated.

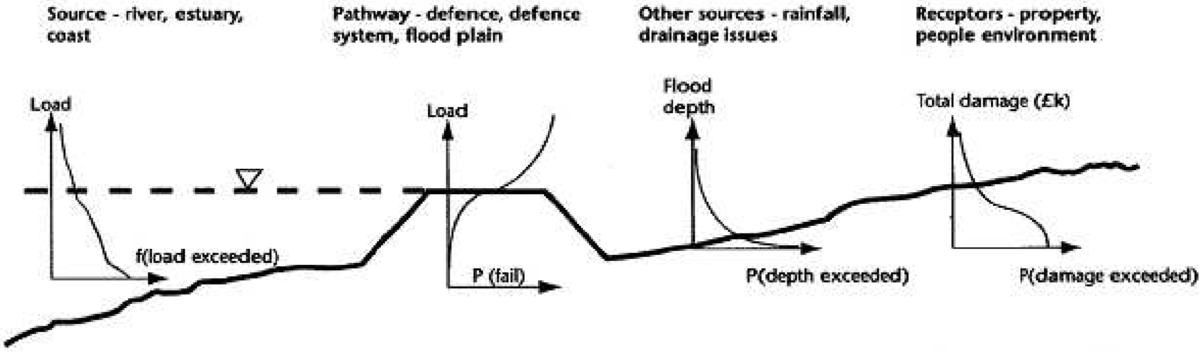

Figure 2: Generic risk characteristic curves used in the first generation RASP methods (Sayers *et al*, 2002)

The key question for those managing flood risk is - what combination of risk management measures provide the best value? To answer this question many possible flood inundation scenarios have to be assessed. The number of flood inundation model runs is dependent on two issues – the number of defences and the number of loading conditions. Each flood defence is considered to have two systems states - failed or not failed. This means that the theoretical number of possible system states is 2^n, where n is the number of defences within the defence system (HR Wallingford, 2004). Based on this, the number of simulations that need to be carried out for a typical urban floodplain can vary between hundreds and thousands (Figure 3). The second variable – the number of loading conditions is dependent on the complexity of the flood defence scheme and the severity of the flood event and can increase the number of required simulations still further.

Number of flood defences	Number of scenarios
10	55
20	210
30	465
40	820
50	1275
60	1830
70	2485

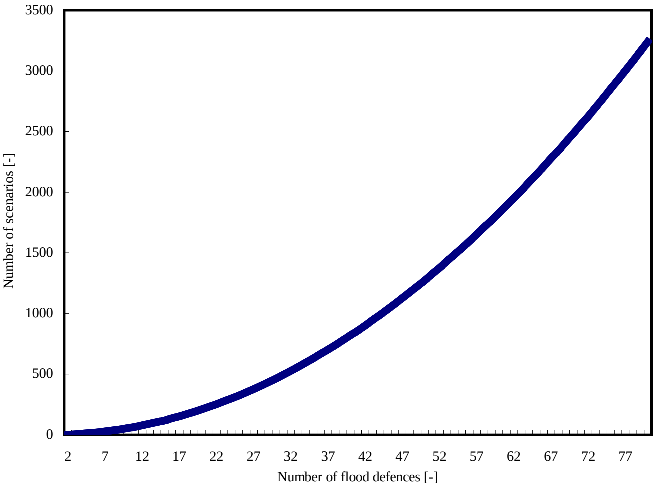

Figure 3: Number of possible breach scenarios for each return period storm in case of maximum of 2 breached flood defences.

The number of simulations can be reduced by taking account of only those important defence failures - i.e those contributing to risk (Gouldby *et al*, 2007).

2 HYDRAULIC MODELS

Floodplain inundation has been the subject of intensive research in previous decades. Historically, the 1D and Quasi – 2D approaches described below have been used to simulate floodplain inundation:

With 1D modelling the floodplain is treated as an extended river cross-section representation of the 1D St Venant equations, with conveyance estimated using a uniform flow law. The continuity and momentum equations are usually discretized using a finite difference method. The main disadvantage is that the 2D nature of flooding may not be well represented by cross sections that are separated by hundreds of meters. A 1D model, such as HEC-RAS, can be expected to deliver reasonable results when floodplain storage doesn’t play a significant role.

For Quasi-2D the floodplain is split into a system of interconnected flood cells (compartments). The splitting has to be done by an experienced modeller, requires time to set-up and is to some extent subjective. Flow between flood cells is calculated by a weir equation and hence is a function of water level in the cells. The advantage of this method is that basic information on the speed of the spreading of the water is obtained, however, this has its limitations because local velocity information for the whole domain is not available. Additionally the evolution of floodplain inundation may not be well represented because the flood cells may not be correctly set-up. Recently the increased availability of remotely sensed digital elevation models have resulted in an increased popularity of raster routing and full 2D routing.

Raster routing is similar to Quasi-2D approach, however, in this case flood cell size is much smaller and may be as small as the DEM grid size (~1m). LISFLOOD-FP is probably the most well known raster routing model (Bates & De Roo 2000, Horritt & Bates 2001a, 2002). The scale dependency that the approach suffers from can be overcome by the implementation of an adaptive time step (Hunter *et al*, 2005). Although LISFLOOD-FP contains simplified physics, the requirement of using a short time step limits the use of this model in multi-scenario flood risk analysis.

Full 2D models calculate floodplain inundation spreading by solving the full two-dimensional shallow water equations, conserving both mass and momentum. Examples of this approach are the finite element model TELEMAC and the finite difference model TUFLOW.

All of the above techniques attempt to simulate how floodplain inundation develops through time. This is necessary if one is interested in modelling the dynamic movement of the flood water through the flood system. It is however often unnecessarily complicated and too computationally demanding to provide the high number of model realisations necessary to support the risk based analysis described above. Therefore new rapid methods have recently been advanced and tested within the context of the Thames Estuary 2100 project (see for example the Rapid Flood Spreading Model developed by HR Wallingford, 2005, 2006). These new methods are consistent with the needs of a risk based analysis and provide a promising new approach. The performance of these new methods is yet to be fully understood and remain an area of active research.

3 MODEL AND TEST SITE

The rapid inundation model presented in this paper is flood storage cell algorithm. The approach is similar to the technique used in many one-dimensional river modelling codes and has also been applied by HR Wallingford to flood inundation problems (HR Wallingford, 2005, 2006). It takes advantage of extensive digital elevation model datasets (Marks and Bates, 2000). The calculation domain is restricted only to the floodplain. The flow entering the floodplain is specified simply as a total volume, and no dynamic interaction between the river and the floodplain is considered. The approach is similar to the flood storage cell approach used in Quasi 2D models but without time stepping. It is based on continuity and is therefore mass conservation and provides an estimate of the final extent of inundation.

In order to minimise the run-time, the algorithm is divided into two parts - **precalculation**, in which extensive DEM analysis is performed and a system of flood cells is constructed. The result of the precalculation is then used as input to the **inundation routine** in which the flood volume is spread over the flood cells from the location of a flood defence breach or overtopping incident. To support risk analysis it is the computational efficiency of the inundation routine that must be optimised.

3.1 PRECALCULATION

Precalculation is a key part of the rapid inundation model and is performed only once for the whole floodplain (irrespective of the breach or overtopping scenarios). All flooding scenarios then use the result of the precalculation. In existing major software packages that use a flood cell inundation approach (Infoworks-RS, ISIS, Mike-II, HEC-RAS), the flood cells have to be defined by the modeller and hence the distribution of flood cells is subjective. To avoid these problems, the floodplain sub-division process in the model described here is automated.

Initially the lowest points of the DEM data are found following the rule that each of the lowest pixels is surrounded by 8 pixels with higher elevation. These locations are then as a source for an imaginary horizontal water surface. This is raised in increments and the intersection of the water surface with the DEM captured as flood cell boundaries. As the water level rises all surrounding pixels that are flooded are attached to the same flood cell as their already flooded neighbours. The computed flood cells have a physical meaning, being directly related to small watersheds, in which any water dropped on to a pixel would flow downhill and end up in the lowest point of the flood cell. As a result, the floodplain is initially covered by hundreds of small flood cells. As the imaginary water level rises incrementally the flood cells grow and combine until the full floodplain is covered by viable flood cells. Viability is controlled using rules on the minimum plan area and depth of flood cells. The choice of minimum values can be set by the user and can, to some extent, ensure realistic predictions by comparing results with those from an observed flood or predictions by a more sophisticated model.

Figure 4: An example of a flood cell distribution at Greenwich embayment

When all the flood cells satisfy the viability conditions (Figure 4) of minimum surface area and depth the flood cell distribution is saved and the elevations of the links between all cells calculated. Additionally, volume vs. elevation curves of all the flood cells are calculated.

3.2 INUNDATION ROUTINE

The inundation routine distributes the total flood volume over the system of flood cells. The calculation is a loop of cell-by-cell flooding. Each flood cell having one of three states: dry, flooded active or flooded inactive. As the water is transferred from the breach or overtopping location the status of the flooded cells change. A flow diagram of the calculation is given in Fig. 5.

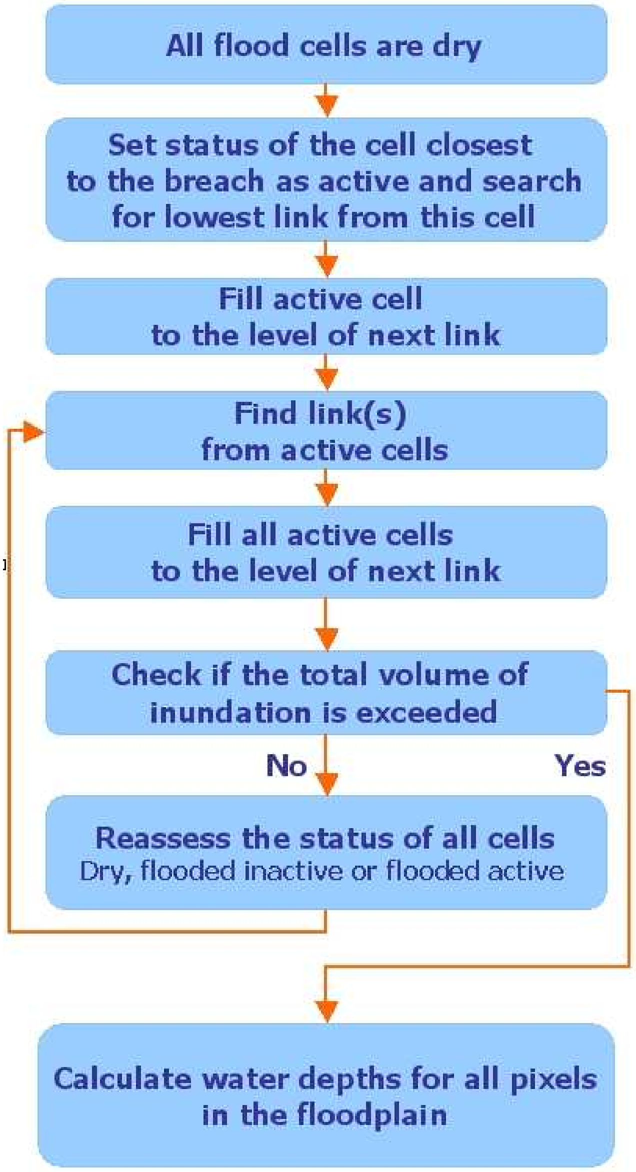

Figure 5: Flow diagram of inundation routine

Each inundation calculation starts by filling the flood cell located at the source of the breach or overtopping incident. When a link to a neighbouring cell is reached the cell becomes inactive and stops filling. The linked cell then becomes active and the water level in this cell is raised to the level of its next link (see Figure 6). This calculation continues until the total volume of inundation is reached,

$$\sum_{i=1}^{n} V_i = V_{Total} \quad \text{(Eq. 2)}$$

where n is the number of flooded cells, V_i is the volume stored in cell *i* and *V* is the total volume entering floodplain. This mass conserving calculation simulates intuitively the natural process of floodplain inundation. It is part of the simulation process that has to be as fast to generate inundation extents for many inflow scenarios.

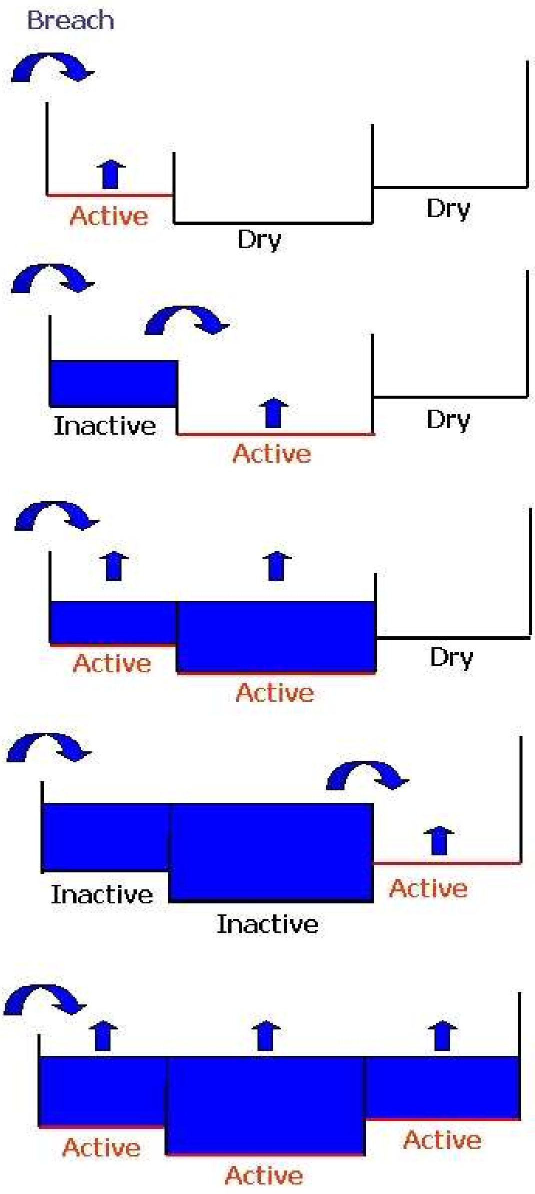

Figure 6: Example of inundation routine

4 APPLICATION

The rapid flood inundation model was tested on the Greenwich embayment on the River Thames in London. This location has been used as a case study location for a number of flood algorithm tests in recent years (Wicks *et al*, 2004, Mulet-Marti and Sayers, 2006). The Greenwich embayment is a flat urbanised area with a network of streets and roads that form a system of flow pathways. There are a few possible breach locations. Most of the previous simulations have predicted inundation from point A on the western side (Figure 7), flooding a large proportion of the embayment. The flood firstly fills the low areas close to the breach and then spreads to the north and east. Predictions for inflow volumes of 5,000 m^3, 50,000 m^3, 200,000 m^3 and 400,000 m^3 are shown in Figure 8a – Figure 8d. According to the model strategy there is no water shown on pathways from the breach as velocities and flow depths are not predicted and only static storage is taken into account. A few separated flooded areas can be seen during the simulation as new flood cells are being flooded. They connect to the main inundated area when the water level in them rises sufficiently.

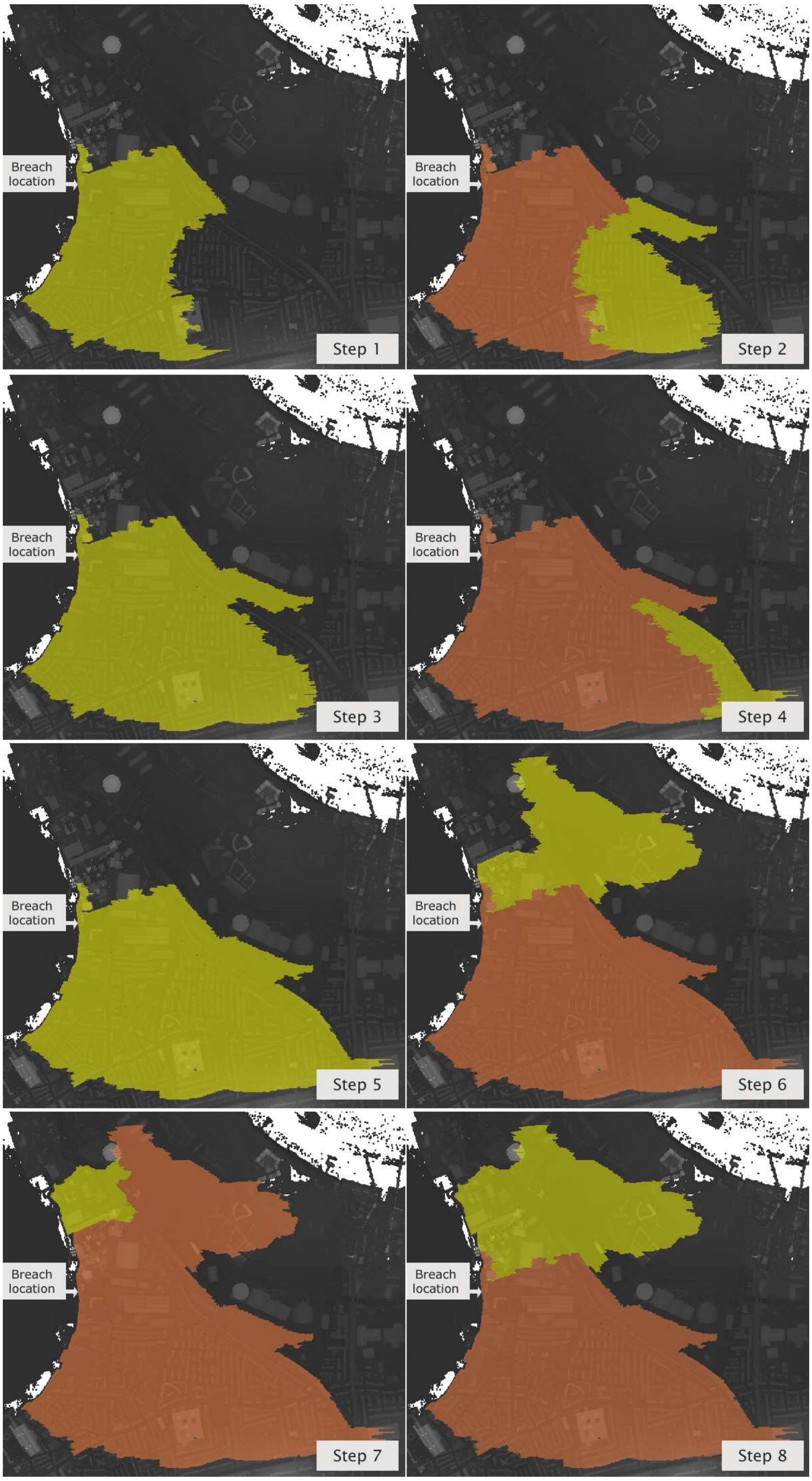

Figure 7: First 8 steps of the Greenwich embayment inundation, cell status is yellow for flooded active cells, brown for flooded but inactive cells. DEM based on LiDAR data provided by UK Environmental Agency.

Comparison of the rapid flood spreading algorithm with results from other models indicate that the proposed algorithm produces a similar flood extent, with the same key areas being predicted as flooded. Importantly, topographic features such as roads, that in reality convey the water from higher locations to lower ones, are correctly recognized.

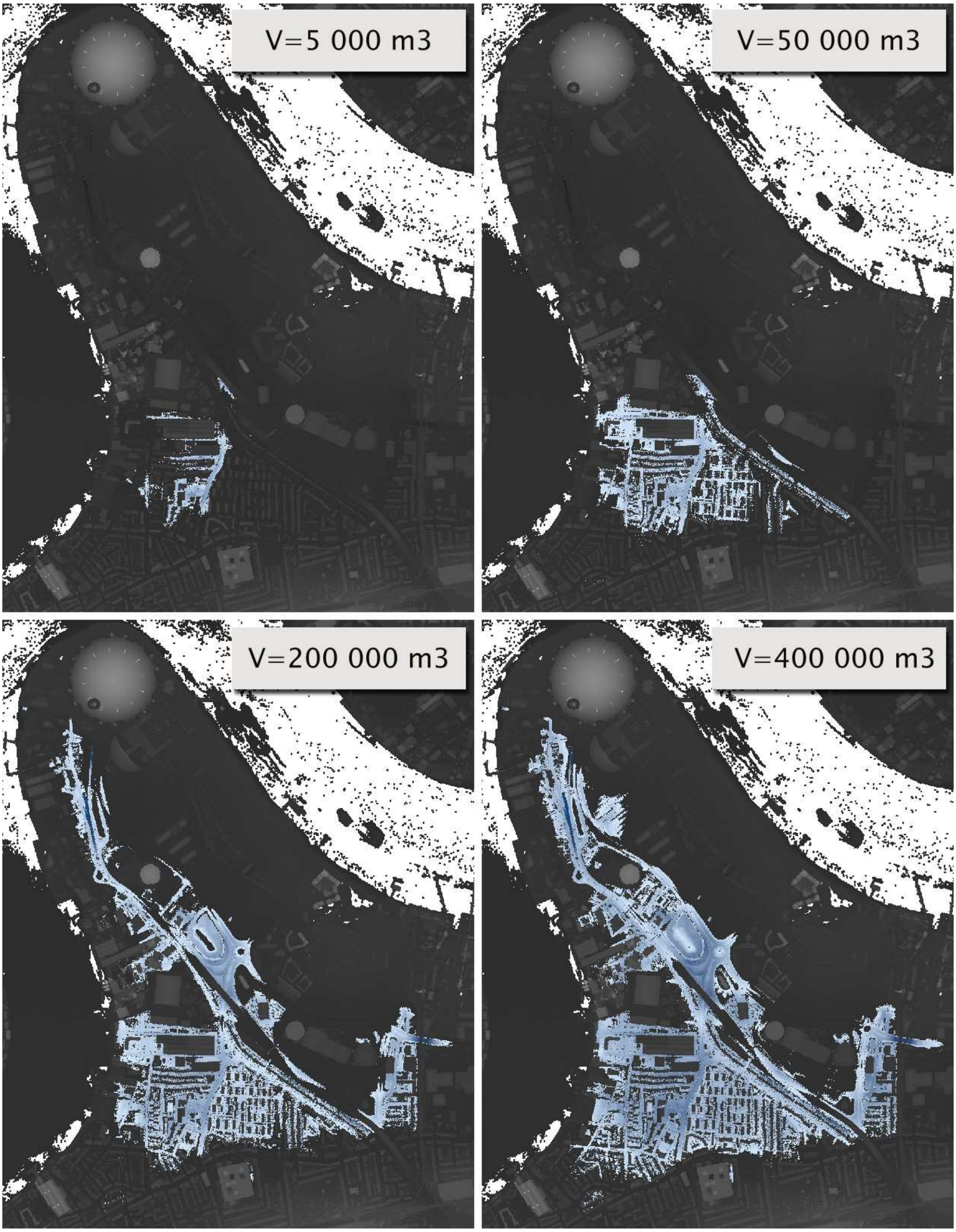

Figure 8: Maximum flood extents at Greenwich embayment. Total volume of inundation, from top left- 5 000 m^3*, 50 000 m*^{3}*, 200 000 m*^{3} *and 400 000 m*^{3}*. DEM based on LiDAR data provided by UK Environmental Agency.*

As mentioned previously, speed of run time is the key factor of the proposed model. The time consuming precalculation routine was executed in an average time of 2 hours depending on the minimum surface area and depth parameters. The larger and deeper the cells are, the more iterations are needed to combine the many small and shallow cells into fewer, larger cells and hence the run-time becomes longer. On the other hand the fewer final flood cells produced, the fewer calculations are necessary in the inundation routine. The balance between run-time and the accuracy of the predicted flood extent is a subject of further research.

Although the precalculation is very time consuming, it is done only once. In contrast the run-time of the inundation routine is very short. In all tests the run-time of the inundation routine was less than 1 second on a desktop PC. Indeed, it was found that most of this time was actually consumed on the final depth calculation for each pixel in the domain.

5 CONCLUSIONS

The ability of a new rapid flood inundation model to predict flood extent has been tested using a real DEM of an urban floodplain. The model proved to be capable of predicting the maximum inundation extent while maintaining a model run-time of less than one second. This suggests the model will be of use for the flood risk assessment planning. Further effort will be focused on calibration and validation of the model by comparing with simulations from more sophisticated models.

Although the maximum flood extent can be predicted by the model it does not at present provide estimates of flood hazard (defined as the product of local depth and velocity). Further development of the rapid inundation model will focus on estimating local velocities on the floodplain and combining them with depths to offer a fast and reliable estimate of flood hazard distribution. As the model does not simulate the dynamic nature of flood spreading velocity will be estimated using knowledge of volumes transferred along flow paths.

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