TWO-DIMENSIONAL MODELLING OF OVERLAND FLOW
Using 2D Dynamic Modelling to Assess Overland Flood Routing and Flood Depths

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ABSTRACT
Two-dimensional hydrodynamic models are widely used in coastal process studies to simulate flowfields and water levels in the nearshore region. Over recent years there has been increasing confidence in the algorithms used to determine wetting and drying of intertidal areas such that supercritical flow is now represented realistically. This, together with the launch of the Government's 'Making Space for Water' consultation exercise and the release of CIRIA's Designing for Exceedance Draft Report No 699, has lead to an exploration of the possibility of using a two-dimensional hydrodynamic model to simulate urban overland flow. This paper outlines a process adopted to simulate overland flow dynamically and identifies the issues, both numerical and physical, to be overcome in adapting the established 'coastal' methodology to account for urban environments. The scenarios examined include a variable water source (rainfall), distinct point sources (sewer overflow) and large volume ingress (flood defence overtopping and breaching). Limitations of the present available numerical tools are also outlined. Finally, results are presented from a number of example applications that show flow routes, flow speeds and water depths in the urban environment.

INTRODUCTION
In July 2004, the Government launched the 'Making Space for Water' consultation exercise which highlights the need to develop a comprehensive, integrated and forward strategy for managing future flood and coastal erosion risks in England. The initiative addresses the messages from the Foresight Future Flooding report published in April 2004 which considered a range of scenarios for flood risk management over the 21st century. 'Making Space for Water' recognises the need to adapt to the reality of climate change particularly in relation to the management of flood risk. It also recognises the need to incorporate urban drainage flooding and overland flow into national flood mapping. In addition, CIRIA's Designing for Exceedence Draft Report No 699 highlights the need for the future hydraulic design and management of urban landform and drainage pathways to reduce the impacts that arise when flows exceed the capacity of drainage systems. Reliable tools are therefore required to facilitate this initiative.

In connection with the above, the ability to accurately model overland flow has a number of applications:

- Integrated flood mapping of rivers, urban drainage and overland flow
- Replicating and understanding existing flood mechanisms and flood routes
- Understanding the consequences of design exceedence
- Designing safe flood routes and detention facilities

Overland flow modelling has therefore become an increasingly significant issue in the design of river and coastal defences and stormwater drainage/sewerage schemes. The modelling and prediction of flooding and overland flows, particularly in urban areas has, until recently, been difficult to achieve and has been limited to a number of one-dimensional and volumetric approaches. The primary difficulties with modelling overland flow are:

- Sufficiently resolved topographic data with which to represent key topographic features and, more importantly, small scale features which convey flow (e.g. roads, paths) and which act as a barrier to flow (e.g. buildings, walls, pavements, embankments etc).
- Accurate descriptions of flood flows, i.e. those overtopping flood defences, river banks or sea walls or those from manholes and sewerage and/or drainage infrastructure.

- Two-dimensional (2D) hydrodynamic models capable of modelling complex, often supercritical and rapidly changing flows while being able to cope with rapid wetting and drying of model cells.

Recent advances in topographic surveys (e.g. LiDAR, Kinematic GPS) and improvements in 2D hydrodynamic model numerical schemes have now established the building blocks that allow complex overland flow problems to be accurately modelled as true two-dimensional dynamic systems.

The overland flow modelling method discussed here is based around the use of a two-dimensional hydrodynamic model, MIKE21, developed by the Danish Hydraulics Institute. MIKE21 has traditionally been used for, and limited to, river, lake, estuarine and coastal studies where flows are sub-critical and the associated velocities and Froude Numbers low. However, recent innovations have led to significant improvements in the numerical scheme of the model which allow the accurate simulation of critical and super-critical flows, thus permitting the use of the model for a far larger range of fluid flow problems. In recent years, MIKE21 has been used extensively to assess floodplain flows, dam breaks, runoff associated with high return period rainfall and more recently urban overland flows.

As the model is a true 2D hydrodynamic model it can provide an accurate representation of fluid flow under a range of circumstances and conditions. The MIKE21 system offers:

- True 2D hydrodynamic modelling of fluid flows at high resolution.
- Advanced facilities to import, manipulate and modify topographic data to produce model topographies from Digital Elevation Models (DEMs).
- The ability to modify the model DEM to introduce design options or “what if” scenarios.
- The ability to add a variety of sink and source terms to represent flows into and out of the area under consideration.
- The ability to explicitly add rainfall to the model to assess the overland routing of runoff.
- Advanced output and export routines. Model output can be provided as flow velocity plots, inundation maps or combined plots. Output can also be written to time stamped animation files in a variety of formats as both 2D and 3D representations. The results can also be overlaid on digital maps and plotted to a preferred scale.

METHODOLOGY

Figure 1 shows the methodology adopted to simulate overland flows from a variety of sources.

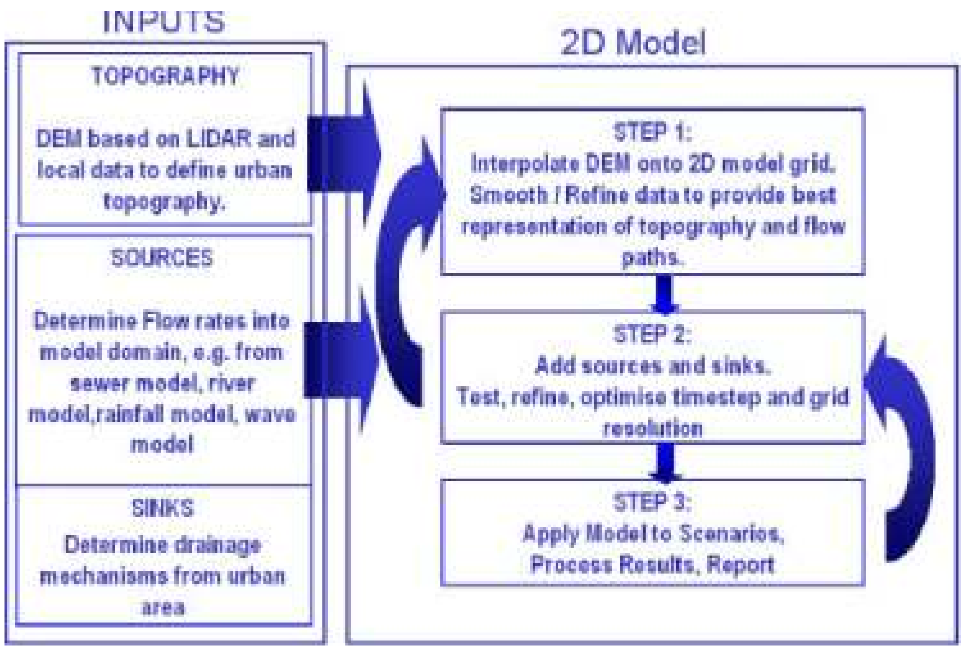


Figure 1 Overland Flow Modelling Methodology

The method has three parts and includes input data in the form of topographical data and flow inputs.

Step 1 – Create and filter topography

Light Detection and Ranging (LiDAR) is a method of obtaining ground elevation data for a large area with a relatively high resolution. The data is recorded using a laser operated from aircraft to allow truly vertical readings of elevations. The horizontal resolution of LiDAR data is usually in the order of 1-2m and the vertical resolution is in the order of centimetres. LiDAR data is used to create a model topography (DEM) for the area where overland flow is to be simulated (see Figure 2) which includes roads, buildings and other man-made structures overlaid on the local topography.

The LiDAR data is recorded on a grid, usually at 1m resolution. As such, small scale, but key features, such as curbs and walls may not be fully resolved. LiDAR data is used directly as the model topography, i.e. the model grid is set to the same resolution and origin as the LiDAR data in order to avoid interpolation errors which can cause the loss of some pertinent features.

Filtering of the model topography is sometimes required as LiDAR tends to record the highest point and therefore only 'sees' the top of objects which may be largely hollow underneath. Without filtering these objects would appear in the model as a solid object and therefore a barrier to flow. Areas of the model topography which require filtering (such as trees, bridges and overpasses) are identified and removed. The ground level is then re-calculated by interpolation from surrounding ground levels or manually where specific survey data is available.

For a particularly complex environment, ground truthing may be required to enable the correct representation of the local ground elevation (for example, a brick wall obscured in the LiDAR data by a tree). Where necessary, the model DEM can also be modified to better represent key features (curbs, walls, etc.), although this may be restricted by the model grid resolution.

Step 2 – Sources, sinks and boundary conditions

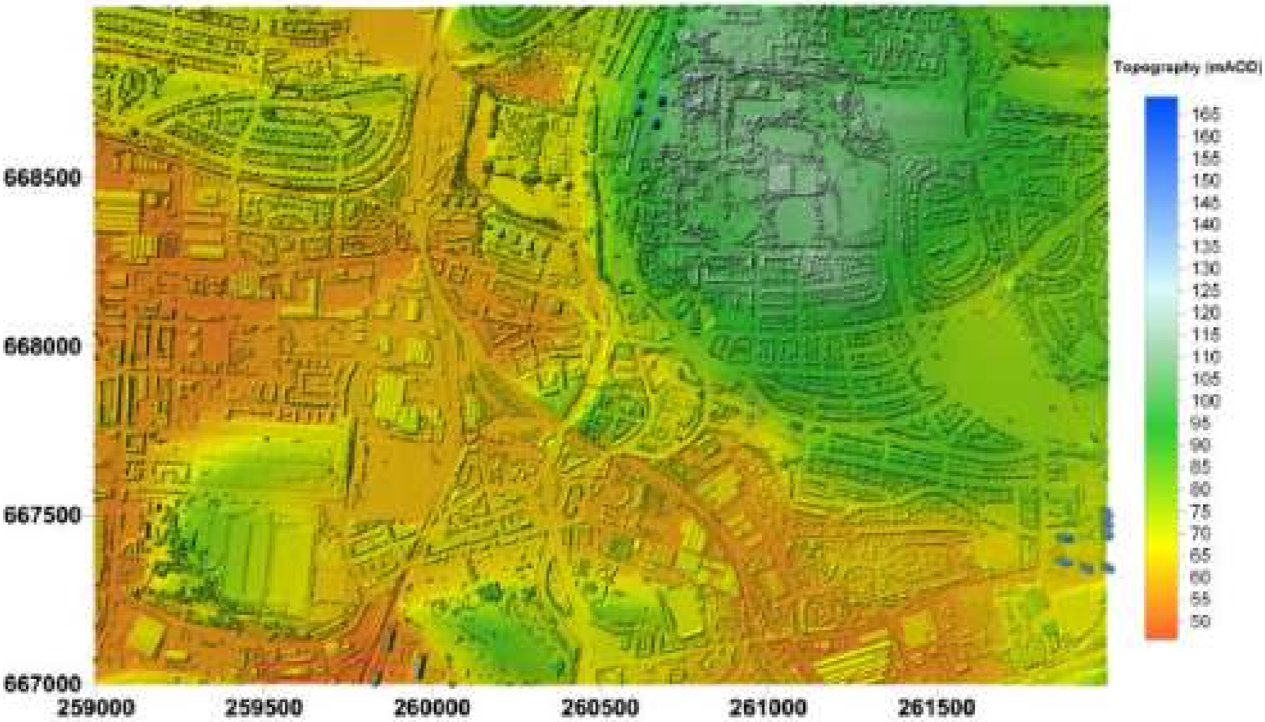
Once the model topography has been derived, sources of flow in the system must be identified and quantified. Some sources can be represented by point sources within the model area (see Figure 3a). These sources include flow from sewers and drains and overtopping due to waves (which can be calculated using empirical formulae). Other sources can be considered to be model boundary conditions (see Figure 3b) in that a water level is defined on a model boundary and allowed to increase until overland flow occurs (for example, inundation of a coastal area due to local storm surge effects or overtopping of a river embankment under high flow conditions).

When rainfall runoff is to be simulated, rainfall rates can be specified for the whole model area as either spatially and/or temporally varying or constant.

Point sinks can be included in the model to represent the removal of water from the model area by stormwater drainage systems or local drainage channels. Some assessment of capacity within drainage systems is required to determine sink rates, which in many cases may need to be estimated from available data and information.

The boundaries of the model area must be carefully located as flow leaving the model area is lost from the calculations and could produce errors in the final simulated water depths. Usually flow is not allowed out of the model area so the area to be modelled is carefully chosen to be horizontally concave (i.e. a depression which has higher ground at all sides). This gives rise to natural barriers to flow at the edges of the model therefore restricting flow from the model area. Road and railway embankments are useful restrictions to flow that can be employed as model boundaries.

a)



b)

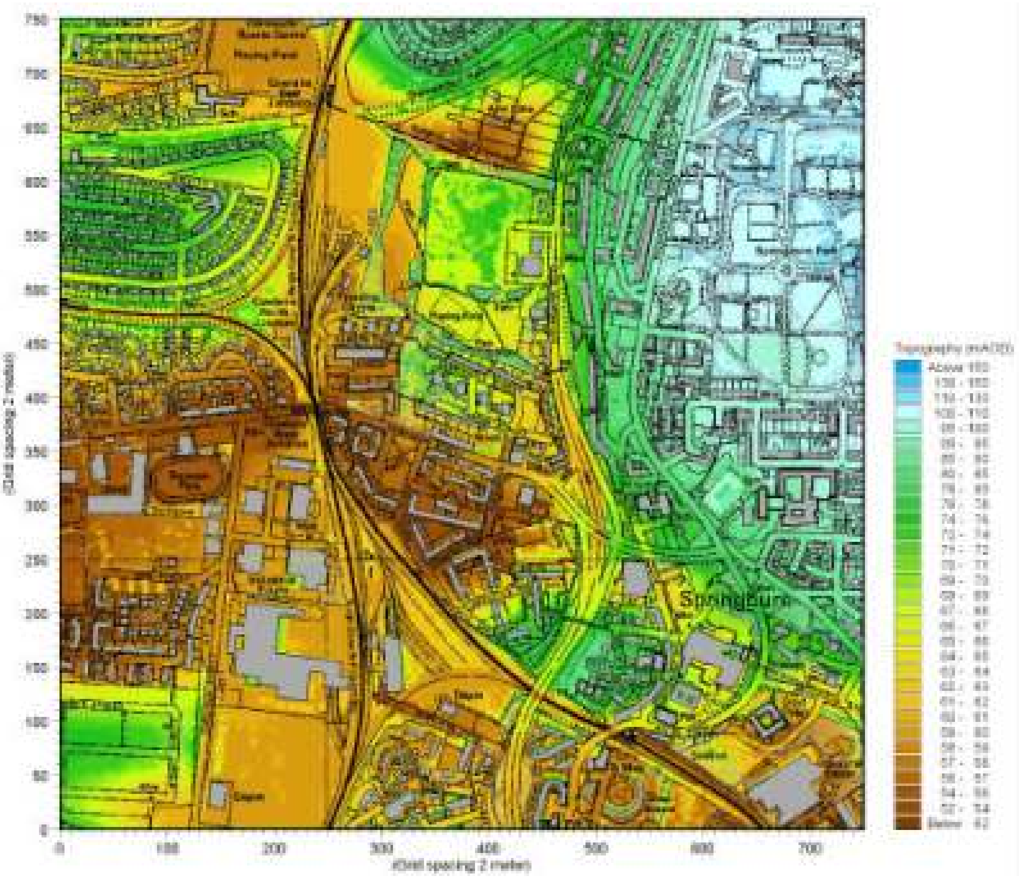
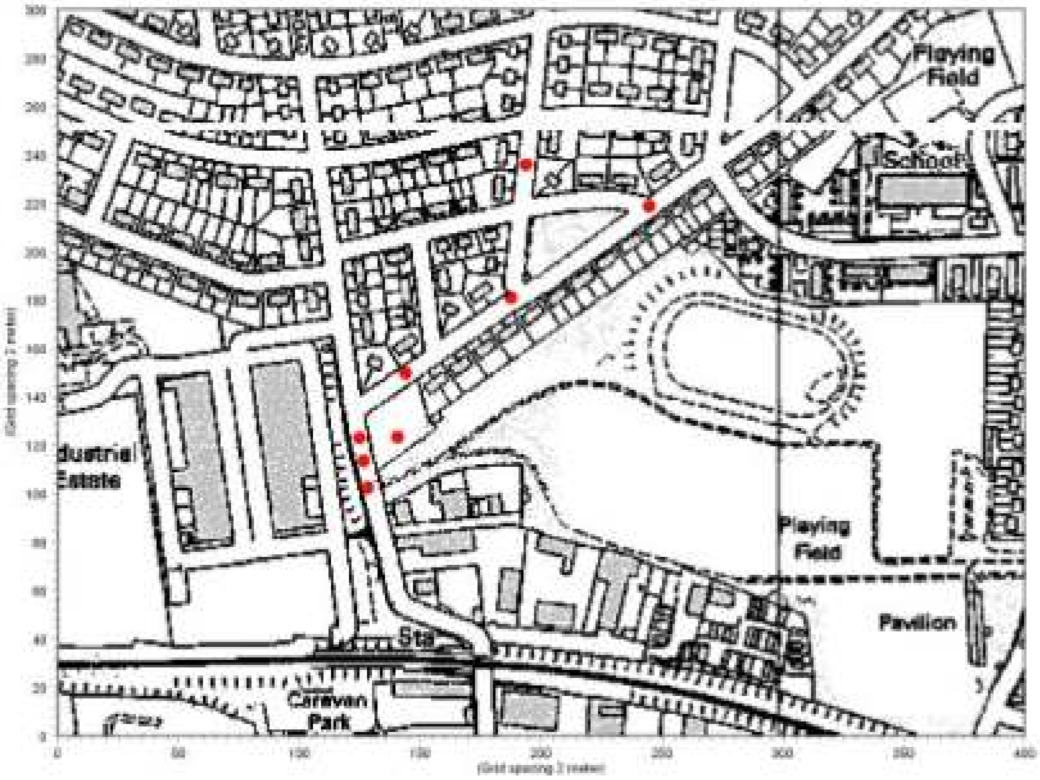


Figure 2 **Generation of Model Topography a) LiDAR Data and b) Corresponding Model Topography (Street Map Overlaid for Clarity)**

a)



b)

Figure 3 Flow Sources for Overland Flow a) Point Sources and b) Boundary Conditions

Step 3 – Apply model

Once the topography, sources and sinks have all been defined, model applications can be undertaken. It is important to understand the properties of the flow input data to ensure double accounting does not occur. For example, a sewerage/drainage model such as INFOWORKS may be used to provide flow from sewers to the overland flow model. However, if rainfall runoff is also to be simulated to assess overland flow pathways, then double accounting of the rainfall will occur. INFOWORKS routes runoff within a specified area to the associated local node. Runoff will enter the node even if it then immediately flows back out due to incapacity (see Figure 4). By also attempting to model pluvial (surface) runoff within the overland flow model rainfall runoff is effectively included twice. Furthermore the water held in the node by INFOWORKS will eventually enter the drain when the system has sufficient capacity, however, the overland flow model may show this water ponding or being routed away from the node once the system is full. One way of overcoming this issue is to modify the rainfall in order to account for varying runoff and the component that has drained to sewer. This is however a complex process that cannot yet be fully represented.

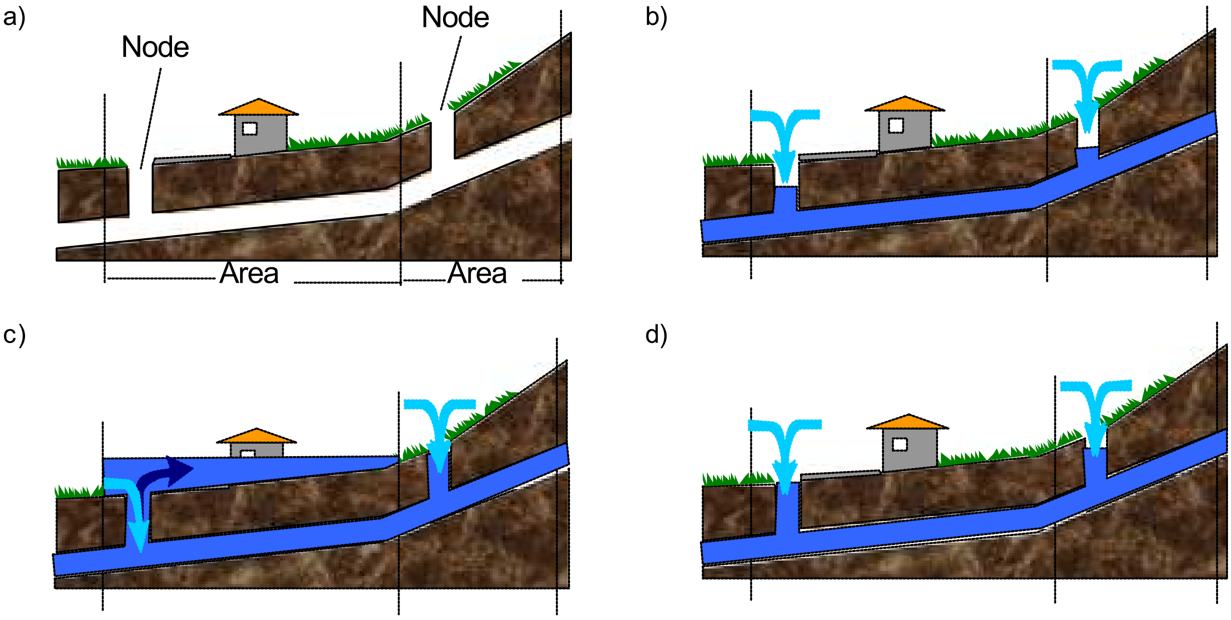


Figure 4 **Diagram of the INFOWORKS Drainage Model Methodology**
a) Model representation of nodes and drainage areas
b) Runoff enters model nodes
c) Excess runoff or sewer flooding is stored at the node
d) Stored water drains as sewer capacity becomes available

EXAMPLE APPLICATIONS

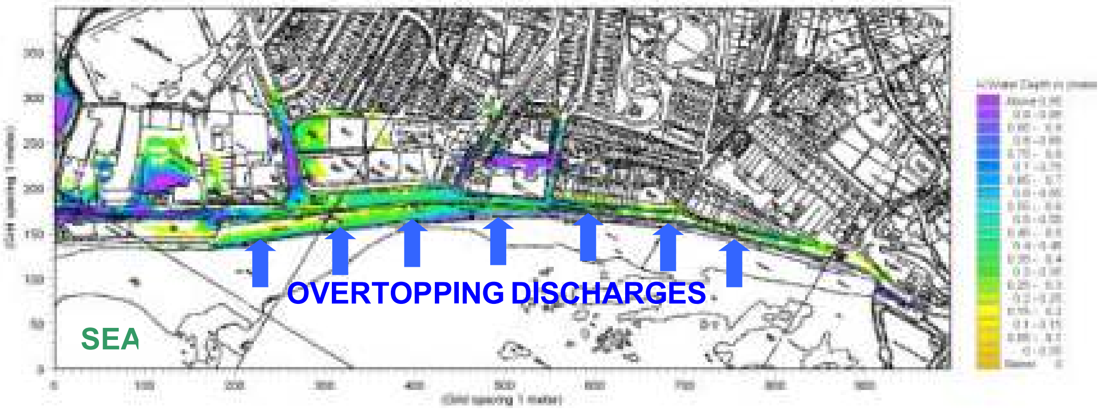
A number of applications have been undertaken using the previously described methodology. Examples include:

- Overtopping of a seawall onto a promenade due to waves and high sea levels (storm surge)
- Inundation of coastal land due to extreme storm surge levels and flood defence failure
- Urban flooding due to sewer and watercourse flooding
- Urban flooding due to rainfall runoff

Example output is presented over the following pages.

Overtopping

a)



b)

Figure 5 **Example of Results from Overland Flow Due to Overtopping Simulation a) Two-Dimensional Representation and b) Three-Dimensional Representation Showing Depths (Blue) and Velocity Vectors (Red)**

Inundation

a) b)

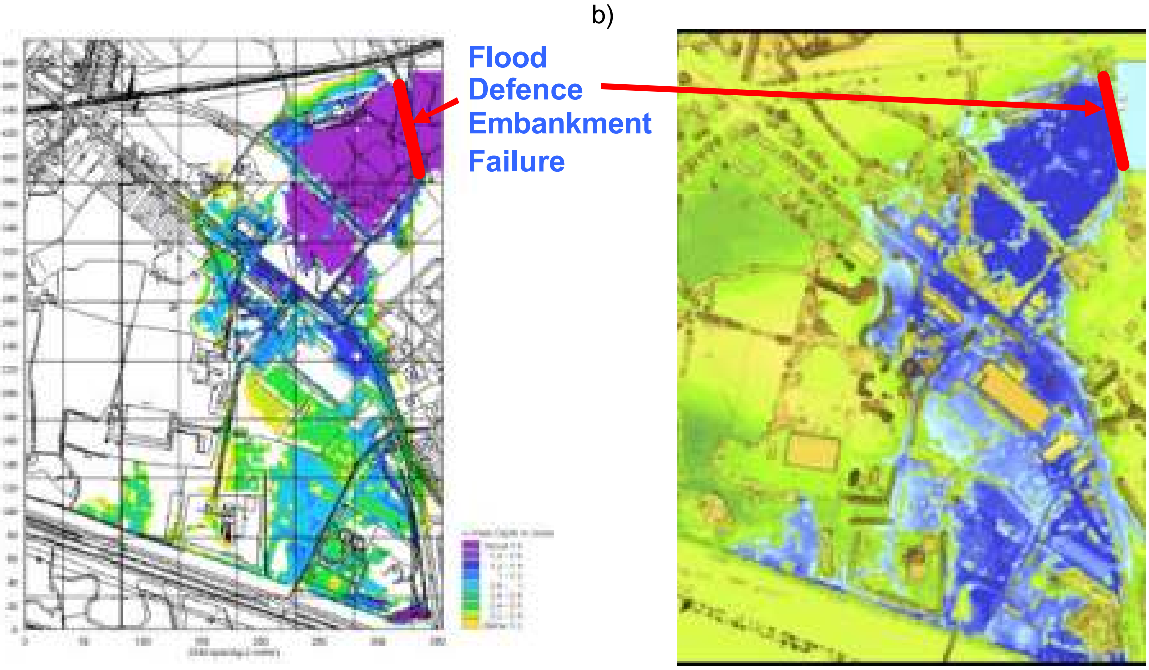
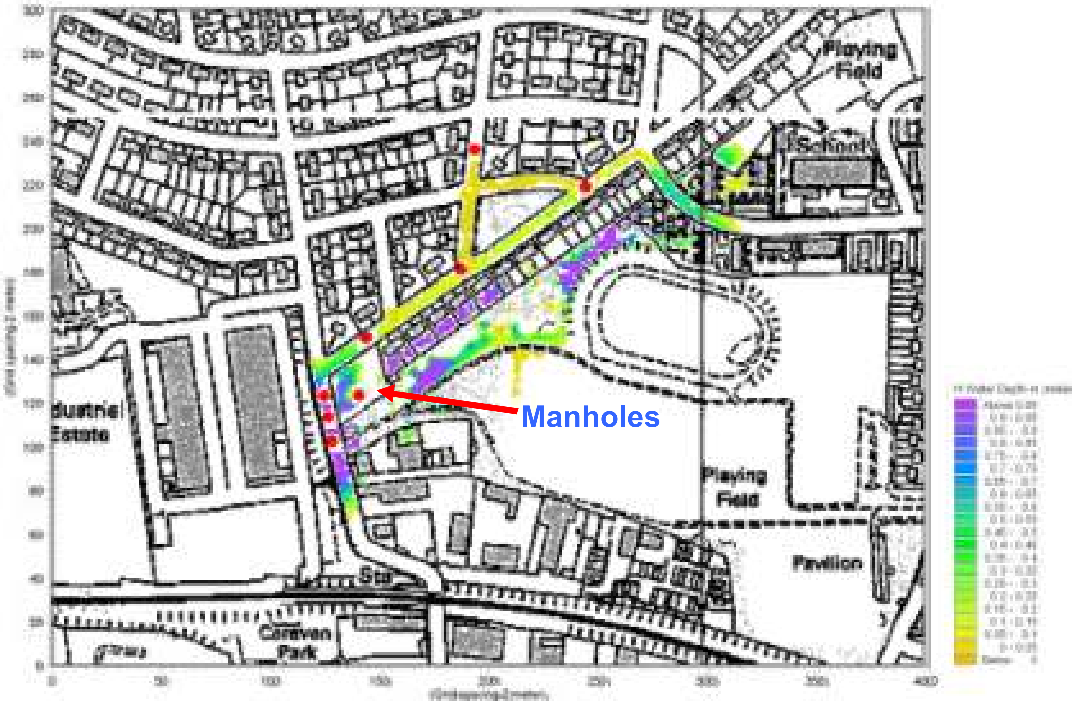


Figure 6 **Example of Results from Overland Flow Due to Inundation Simulation a) Two-Dimensional Representation and b) Three-Dimensional Representation**

Sewer Overflow

a)

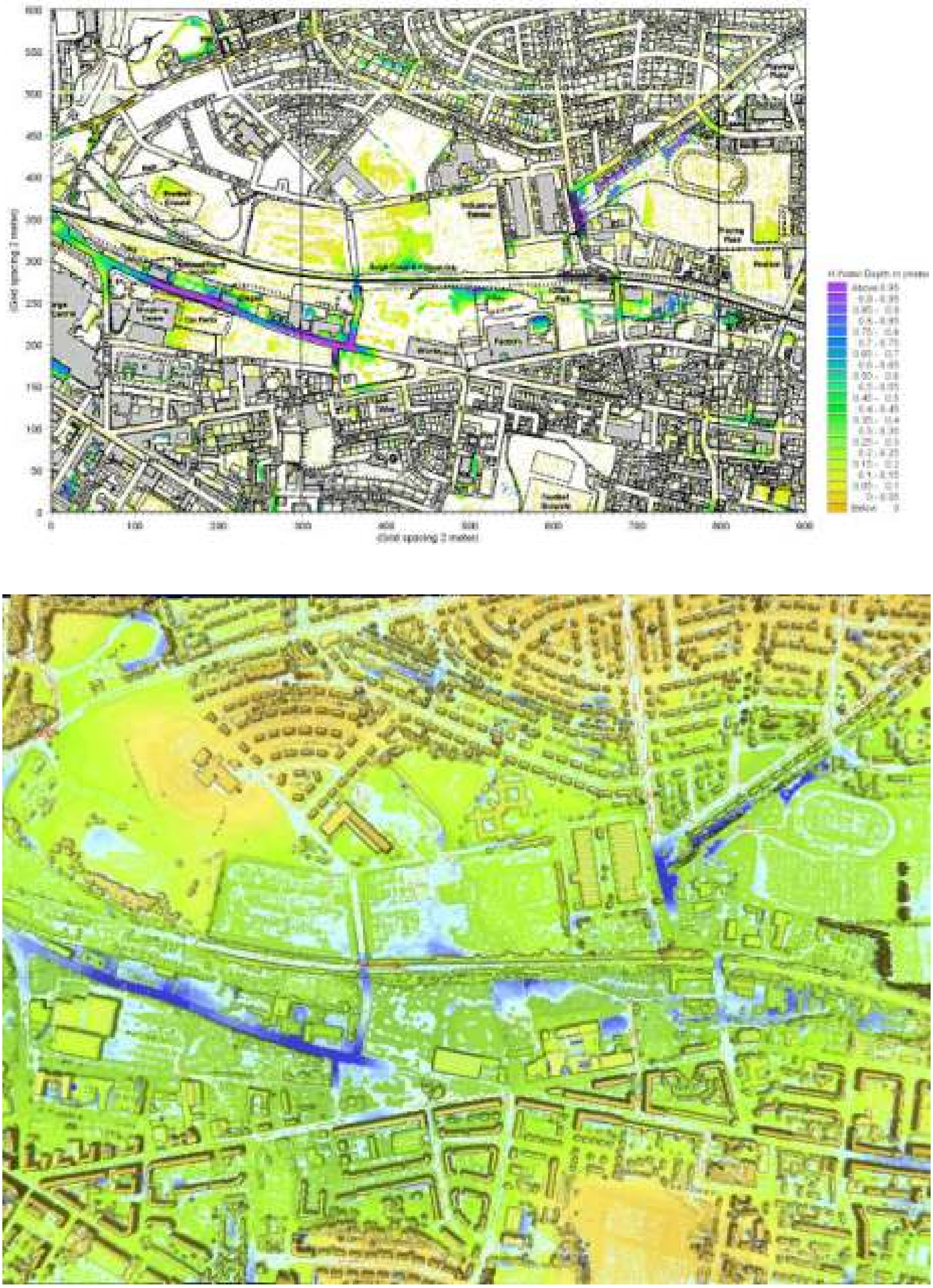


b)

Figure 7 **Example of Results from Overland Flow Due to Sewer Overflow Simulation a) Two-Dimensional Representation and b) Three-Dimensional Representation**

Rainfall Runoff

a)



b)

Figure 8 Example of Results from Overland Flow Due to Rainfall Runoff Simulation a) Two-Dimensional Representation and b) Three-Dimensional Representation

DISCUSSION AND CONCLUSIONS

Two-dimensional hydrodynamic models have been use to determine overland flood routes, flood velocities and inundation depths for a range of flood scenarios. This form of modelling represents a valuable tool for assessing the impacts of development, stormwater management planning and designing for exceedence on overland flood routes and urban flooding.

Models are based on LiDAR data, with appropriate filtering applied, and can be driven using a variety of source and sink terms. While the LiDAR may not fully resolve all features that affect flood routing, it provides the most comprehensive data set currently available and can be improved by local ground truthing. To resolve features at less than the LiDAR resolution does, however, require a finer model grid with associated issues of run time and file size. At present, the 1m resolution available from most LiDAR is considered to provide an acceptable compromise.

The models can be used to assess flood routes, flood risk and inundation depths. Models can be modified to assess design options. In the case of sewer and watercourse flooding, source and sink terms can be modified to include hard engineering solutions such as increased conveyance or storage. The models can also be used to assess alternative solutions, such as above ground retention/detention ponds, and overland flow diversion schemes, such as virtual flood routes, by modifying the model DEM to reflect excavation of ponds, ditches, or similar.

The ability of the model to route rainfall provides a further capability. However, work is required to convert rainfall data to runoff in each grid cell in order to account for permeability and antecedent conditions. Work is currently ongoing to develop a methodology to use DEM data to modify the input rainfall file to account for relevant runoff characteristics over the model grid and to time vary these parameters to account for changing runoff characteristics.

At present the technique relies on explicitly defining source and sink terms as flow hydrographs. These terms may interact with the overland flooding, e.g. flow from one manhole may route overland to the nearest drain, however, under the present methodology, such interactions must be largely ignored. Integration of MIKE21 with a sewer model is therefore required to allow the physical interaction of runoff, sewer flooding and overland flow to be dynamically linked such that the hydraulic relationships between sewer and overland flow are better accounted for. This is currently possible using MIKE21 and MikeUrban and it is hoped that this can be tested in the near future.

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