Applications of the innovative modelling of urban surface flooding in the UK case studies

S. Boonya-aroonnet[1]*

[1] *Urban Water Research Group, Department of Civil and Environmental Engineering, Imperial College London, London SW7 2AZ, UK.*

**Corresponding author, e-mail* s.boonya@imperial.ac.uk

ABSTRACT
Innovative works on improvement of the modelling of surface flow in urban area has been completed at Imperial College London (ICL) under the AUDACIOUS (2006), WaND (2007) and FRMRC (2007) projects. Detailed concepts of methodology are reported in Boonya-aroonnet et al. (2007). It presented concept and modelling system, a tool containing several GIS-based routines that automatically analyses, quantifies and generates surface flow network inputs for urban drainage models. The tool analyses several GIS layers such as high resolution and accuracy LiDAR DEM, land use (buildings, streets, green areas etc.) This paper demonstrated applications (implementing) of the above breakthrough modelling methodology of surface flow under pluvial flooding conditions in urban areas. The developed tool has been tested in several UK urban catchments. Analysis, results and discussions on the implementation of the tool in the selected case studies are reported.

KEYWORDS
GIS; LiDAR; pathway analysis; surface flooding; urban flood modelling

INTRODUCTION
Urban flooding happens when capacity of drainage system is overloaded. The surcharged flows travel overland along the preferential flood pathways to the downstream depressions or return to downstream gulleys if the drainage capacity is available. Besides in case of heavy storm local depressions (acting as temporary ponds) could be filled up and the water starts overflowing further downstream. To realistically model urban flooding processes, it is crucial to understand and represent dynamics of overland flow and subsurface flow i.e. interactions between surface flow network and the buried storm or combined drainage network systems.

During the past decades attempts were made to develop a better representation of the surface flow processes while modelling of pipe flow was already well described. One of the approaches was to use a “virtual reservoir” to store surcharged water when system is overloaded and the stored water returns to the drainage system after storm. The comments on this approach were documented in Maksimović and Prodanović (2001). A later approach was to route the surcharged water by integrating surface flow network of street defined by 1D open channels (Tomicic et al, 1999; Apirumanekul, 2001; Carr et al, 2001; Boonya-aroonnet et al, 2002). This approach allows surface flood volume migrates overland, but water is kept within the street channels. Recently, an integrated approach of various models (Schmitt et al, 2004; Mark and Parkinson, 2005) is commonly employed and the use of sophisticated hydraulic models as diagnostic, design and decision-support tools has become standard practice in water industry. There has also been significant progress in wrapping urban drainage models in the sophisticated interfaces, linking them with GIS (Geographical Information Systems) and adding elaborate optimization techniques (Lhomme et al, 2004). In addition, results presented recently by Ball and Alexander (2006) and Vojinović et al (2006) contribute to general understanding of some aspects of flooding process.

However, these approaches still could not represent essential elements of urban flooding processes such as formulation of ponds, preferential flood pathways across the urban catchment (not inside the streets) or complete picture of the surface flow network. A very recent and sophisticated approach was to model surface flow two dimensionally (Chen et al, 2005; Carr and Smith, 2006; Dey and Kamioka, 2006). This approach could represent the movements of surface flow and illustrate the dynamic of flood inundation in a reliable way. However it demands lots of data, efforts and computer resources to perform the analysis. It is clear now that the way of modelling surface flow is to integrate pipe flow with either 1D or 2D surface flow model. Both approaches had benefits and limitations and could complement each other. However there is still a huge gap between them for example accuracy, data needed and computational demands. Fortunately, the emerging technology of the high-resolution DTM (Digital Terrain Model) and DEM (Digital Elevation Model) for example LiDAR (Light Detection And Ranging) makes a detailed analysis of overland flow achievable, although further work is still needed in developing this technological advance in the context of urban flood management. This in fact opens a new possibility to enhance 1D model's capability for the next generation of urban flood modelling beyond the limitations reported by Mark et al (2004).

This paper presents the results of testing a recently completed modelling system of overland flow in urban environment caused by pluvial flooding, originally initiated by Prodanović (1999) and Djordjević (2001). The concept is based on GIS-centred analysis of the DTM/DEM so that the features of the catchment crucial for identification of flood vulnerable areas (mainly ponds) are derived and the geometric characteristics of the preferential paths computed. Realistic modelling of overland flow coupled with subsurface network is then enabled by applying physically based surface runoff modelling concept developed by Maksimović and Radojković (1986). A set of GIS modules defining various phases of overland flow and its interactions with time dependent water bodies created in ponds and computational (and physical) inlets to sewer network has been developed and tested. In addition to describing the concept and modelling process the paper provides the results of the trial applications of the system in the selected UK case studies.

Based on analysis of high-resolution LiDAR dataset, author believes that the approach presented here is bridging the gap between 1D and 2D approaches by significantly enhance the accuracy of 1D approach in a way that key 2D movement of surface flooding is represented by the 1D flow network consisting of the ponds (nodes with temporary storage of runoff water) and features (shape and slope) of their connectivity (links).

MODELLING CONCEPTS

In physically-based modelling approach water movement over the surface (as well as in sewer pipes) is modelled by solving the appropriate approximation of mass and momentum conservation equations. With such models it is feasible to simulate the features of urban areas more realistically. For example, after subtracting interception in surface depression (see figure

1) and infiltration it is possible to include the dynamics of the processes in temporary surface retentions (ponds - large depressions) as a basis for the analysis of the effective rainfall intensity and flow across the urban catchment along preferential pathways. Addressing these processes is an essential requirement for overland process in urban flood modelling.

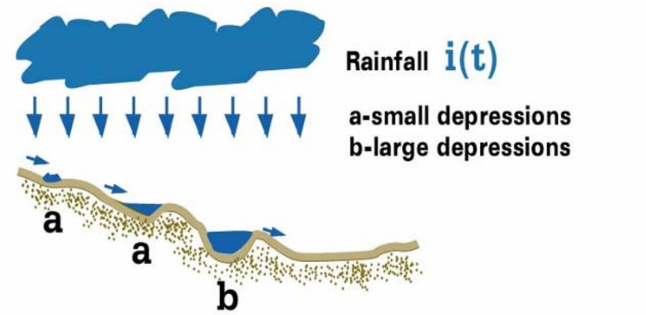

Figure 1. Surface retention of schematised surface flow in urban areas as a basis for assessment of effective rainfall intensity.

To prepare the input data for improved overland flow modelling the activities identified in the Maksimović et al (2008) were carried out. The surface runoff has to be routed by the application of the full dynamic St.Venant equations simultaneously with the underground sewer network (dual-drainage system). The advantage of this approach is that once the model has been calibrated, changes in land use and the physical characteristics of the catchment can be introduced by changing the relevant input files (representing cathcment's physical characteristics without compromising modelling integrity).

Uncertainty of LiDAR data

Performance and reliability of surface overland flow model is highly dependent on quality and resolution of DTM. Physical processes such as surface flow, surface retention, and surface conveyance along preferential pathways are essential elements in modelling of urban flooding. These require high quality of terrain data e.g. DTM/DEM with horizontal resolution finer than 5m (in order for the urban features such as streets to be properly described) and preferably 5cm vertical accuracy. At present LiDAR data resolution (1x1m and becoming finer) make the detailed analysis possible. Additionally, land-use maps are essential to locate streets and building and other features which influence routes and directions of surface runoff. Obviously, the quality of terrain and land use data is essential. Imperfection could lead to unfavourable results of surface flow network. The acquired LiDAR data may contain noise which will create severe problems in pathway delineation because the delineation is only based on ground slopes and they could trigger a fault flow direction. Some efforts to analyse and improve the DTM quality for urban flood modelling were reported in Leitão et al (2006) and Leitão et al (2008). The presented tool has several techniques developed to make the pathway delineation robust without modification or averaging the DTM/DEM. A detailed discussion of this problem is reported in Maksimović et al (2008).

Identification of ponds and flood vulnerable areas

In most cases, flood events occur during extreme rainfall when surface runoff is combined with water from the surcharged ground drainage system. These two volumes of water, which would normally blend and flow, are routed along the preferential surface pathways (including streets) and subsequently they fill in local depressions (temporary ponds).

Ponds have their own characteristics and flow dynamics determined by the local terrain and built environment. They can be isolated or mutually connected, and the flow pattern into and out of a pond may change quickly in time. In order to highlight flood-vulnerable areas within urban fabric, it is needed to identify and characterise ponds. To do this LiDAR DEM is used.

Interaction between ponds and sewer network

The surface and sub-surface networks are physically linked at manholes, gullies or inlets as shown in figure 2. The connection type has to be identified and its potential interaction quantified (Leandro et al, 2007). Flow out from or into the gully or manhole and flow rate is a function of the difference in piezometric level in the sewer and of the water sheet (or pond) above the manhole. If the manhole is within the pond's boundary, the surcharged flow starts filling the pond. When the pond is full, the excess flow leaves (overflows from) the pond and flows over the catchment surface along the preferential paths. After or during the storm, most of the flood water, if it stayed in the pond, returns to the drainage system through the same manholes. The rest of the water flows downstream. The model has been developed such that the identified interactions and mutual movements of flood water between the two systems can be represented realistically with its full dynamics.

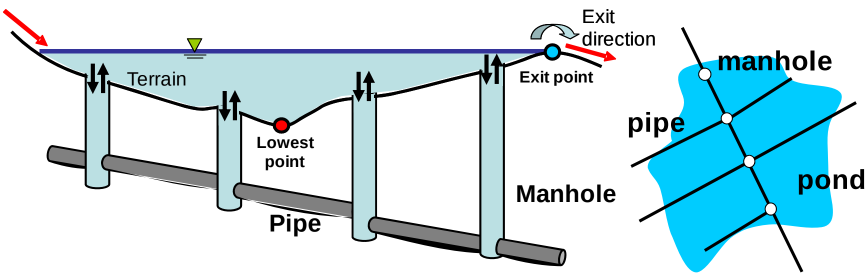

Figure 2. The interaction between manholes and surface pond.

Connectivity analysis

Urban surface is a complex array of different types of permeable and impermeable surfaces which include roadways and footpaths that are generally lower than the surrounding areas. Such pathways can transfer flow over significant distances so that flooding can occur at locations that are remote from the source of the flood water. Overland flow accumulates in depressions, and once the top level of the depression, is reached, it will overtop and create a surface flow. This flow will either overflow directly into an adjacent depression or will flow along a connecting pathway until it enters another depression or enters into the sewer network via a gulley inlet or manhole. It can also leave the sub-catchment and this volume of water has to be subtracted from the water balance of the catchment.

The "rolling ball" technique is used to trace the water path and delineate all processes. Starting at the natural exit points of the identified ponds or surcharged manholes, the analysis determines pathways by preferential flow directions based on terrain slope, taking into account the presence of buildings and other features which are included within the DEM. Thus the ponds and pathways are representatives of the major flooding related features of the urban surface. The following types of surface pathways in urban area can be summarised as:

(1) from pond to downstream pond via pond link;
(2) from pond to downstream manhole or gully;
(3) from pond out of the catchment;
(4) spillway between two mutually connected ponds;
(5) from surcharged manhole to downstream manhole;
(6) from manhole to downstream pond, and
(7) from surcharged manhole to the outlet of the catchment.

Estimation of pathway geometry

Surface pathways are approximated by open channels. To model flow in pathways, the following information are required: the geometry of the open-channel, upstream/downstream elevations, roughness and the actual length between two ponds or surface nodes. The process of the approximation is presented in figure 3(a-d). The algorithm uses the previously extracted pathways (a) and draws equi-distant cross-sections along each pathway length (b). It then uses the surrounding DEM to estimate the areas of each cross-section (c). Finally, the algorithm allows users to select the shape of the channel cross- section which can be either an arbitrary (user-defined) set of points or pre-defined (trapezoidal) cross-sections (d).

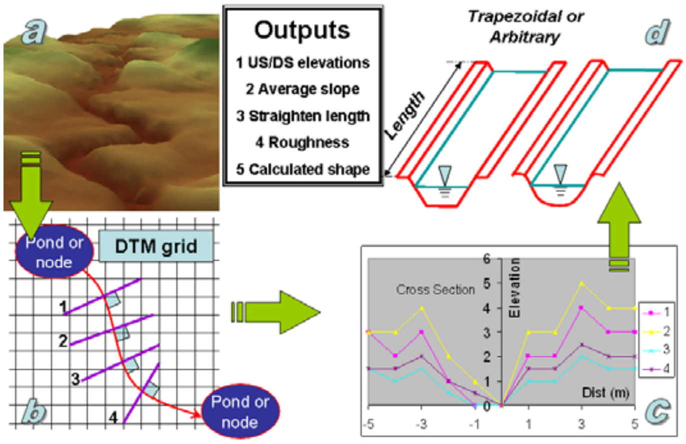

Figure 3. Estimation of pathways geometry: a) 3D DTM showing identified flow path, b) a number of cross-section lines drawn perpendicularly to the path, c) the arbitrary shapes of cross sections plotted as found from the DTM, and d) averaged output with two choices – trapezoidal or arbitrary shapes

THE TOOLS DEVELOPED

Overland flow sub-systems modelling is organised in a series of modules including DTM/DEM analysis, data preparation, input to hydrodynamic models, post-processing and graphical (GIS based) presentation of results (figure 4). All modules are wrapped together within one GIS tool for automatic generation of the surface pathway network across urban area.

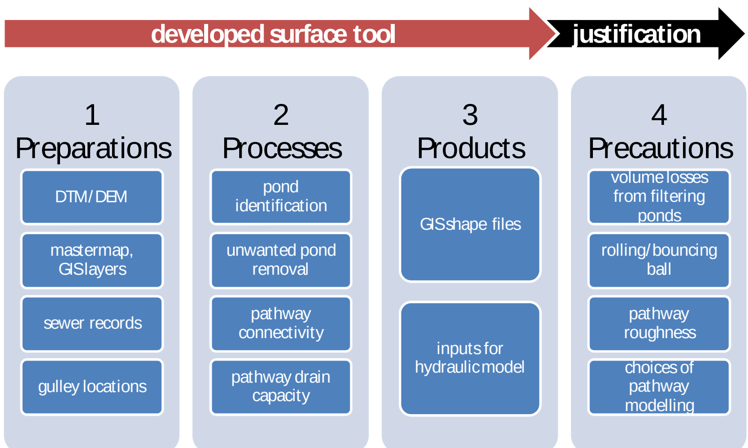

Figure 4. Methodology for analysing DTM/DEM and creation of surface flow network for simulation of urban pluvial flooding and user interface of the developed tool.

The tool usage can be divided into five main steps: (1) sub-catchment delineation, (2) pond delineation, (3) pathway delineation, (4) pathway geometry extraction, and (5) generation of output files. Currently the results are exported as a plain ASCII text file. It contains all the information needed by the hydraulic model for running 1D-1D flood simulation.

THE RESULTS AND DISCUSSION

The development of the tool for analysing surface flow network was carried out within the AUDACIOUS (2006) and FRMRC (2007) projects. Currently the tool is being applied at several UK case studies. The most interesting results obtained in the cases of Keighley and Town A (a coastal town in southern England) are discussed here, the results for other cases will be presented elsewhere.

Keighley

The tool was applied to the Keighley catchment of 1.6 km^2. The hybrid filtered LiDAR DEM 1x1m used has building elevations without vegetations. This type of LiDAR data is preferable to the urban flood modelling. The result from pond delineation is shown in figure 5. When analysing a high resolution DEM (e.g. 1x1m) it is very likely that a large number of small ponds will be generated. They result either from existing pit cells or errors (noise) in the DEM. Statistical analysis of small pond removal is needed in order to reduce computational burden (figure 6). The removal has to be kept under control, otherwise large amounts of storage will be ignored in the simulation. The conventional method for pit cells removal in GIS is to fill all little ponds (sinks) in the DEM with a threshold depth. However, filling DEM will create flat areas which are unfavourable for determination of flow direction. This tool employed a combination of threshold volume and depth of delineated storages. Ponds smaller and shallower than the thresholds are taken out and the DEM remains untouched to keep slope features required for the pathway delineation procedure. Result of the pond removal is shown in figure 5.

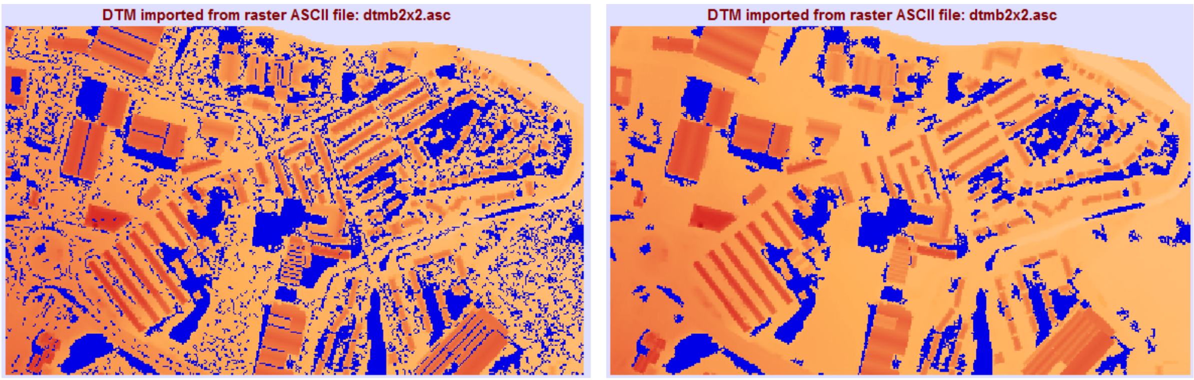

Figure 5. (Left) Delineated ponds found in the Keighley area totally 15,437 ponds. (Right) 2,304 ponds remain after the removal with depth 20cm and volume 3m^3 thresholds.

Analysis of total number of removed ponds and total volume loss from the removal with various combinations of thresholds is shown in the figure 6. It can be observed here that half of total ponds (7,700) are smaller than 0.5m^3. If they are removed, the total storage ignored will be only 2% of the original total storage.

Pathways delineated of the Keighley area were compared with simulation of 2D model of surface flow. All pathways coincide with flood route from the 2D model. It verified that the 2D movement of surface flood can be well represented by the delineated pathways (figure 7).

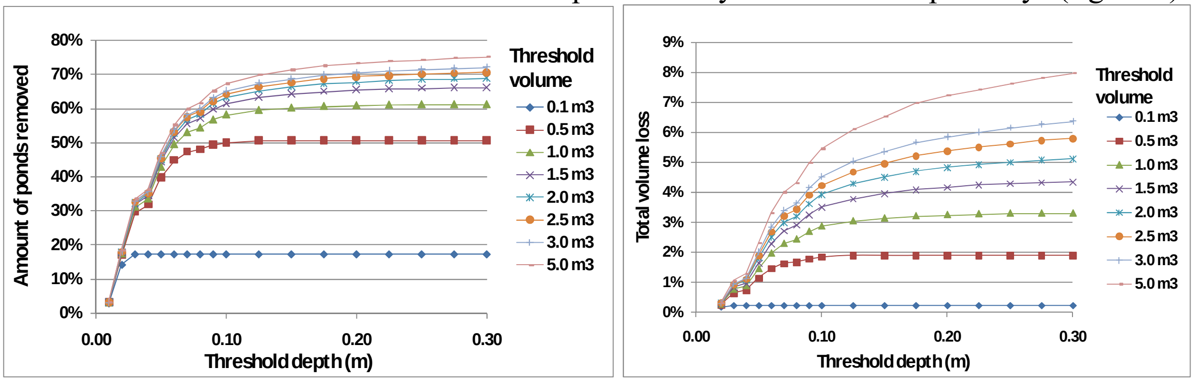

Figure 6. Total number of removed ponds with various filtering thresholds (left) and total volume loss by pond removal (right).

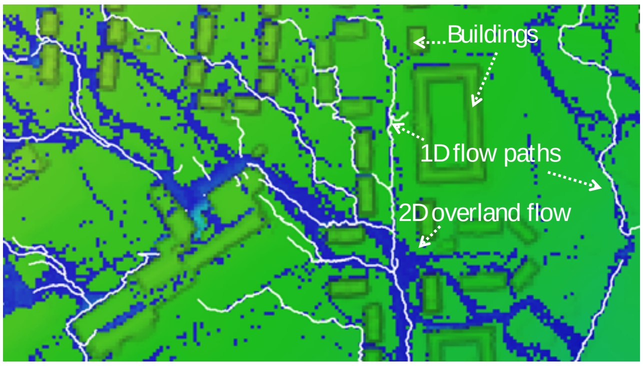

Figure 7. The comparison of the delineated pathways with the results from 2D model.

Town A

A similar procedure was applied to the dataset from the Town A's catchment. The hybrid filtered LiDAR DEM 1x1m with building elevations without vegetation was used. Local depressions were delineated and presented in figure 8. Total number of 4649 ponds was found.

To reduce computational burdens, a suitable volume and depth thresholds is necessary to filter out those small depressions. Figure 9a shows the results of the analysis of volume loss with various depth and volume thresholds. High resolution DEM (e.g. 1x1m) is fine enough to represent houses or buildings. When delineating ponds it is very likely that local depressions were found inside building boundary. They result from differences in elevations that allow depressions to formulate. Figure 9a shows the analysis of volume loss from the pond removal by building mask. Example where depressions locate inside building is shown in figure 9b.

Pathways (originated from pond's exits and surcharged manholes) identified by the tool complete the surface flow network by linking ponds throughout the area (Figure 10). The created network entirely depends on the LiDAR data resolution and quality. A good example from this case-study on the LiDAR quality is shown in Figure 11. It is reported that flood water in one street which is flooded frequently is known to escape through alleyway between houses, while the tool gives the pathway at different location. The reason is that LiDAR DEM cannot pick up the alley detail (about 1m wide). The manual modification of DEM or re-location of the pond exit point is necessary according to local resident's experience.

Figure 8. Boundary of the studied area and the pond delineated from LiDAR DEM.

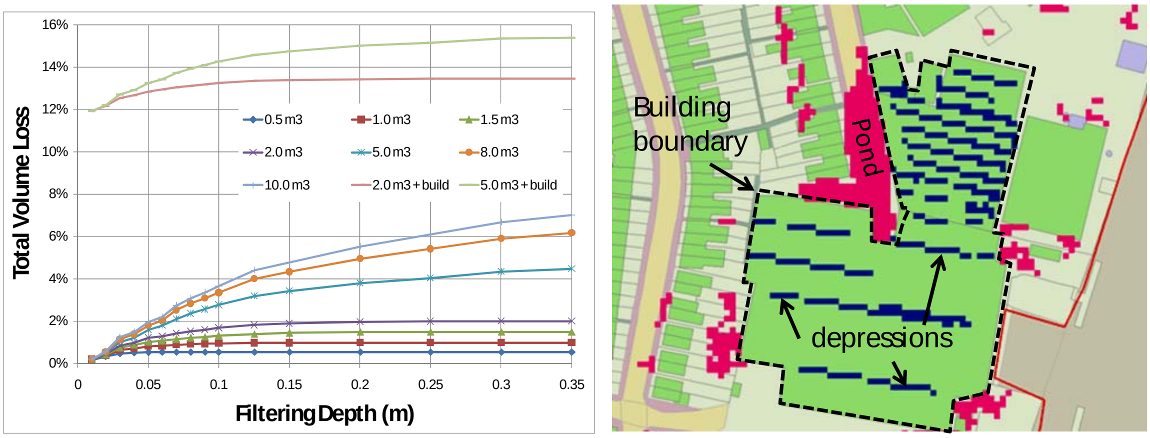

Figure 9. (a) The test on various combination of pond removal thresholds. (b) Illustration of depressions found within building boundary.

Figure 10. A complete surface network example from part of the area in Town A.

Figure 11. Original pond's exit (upper arrow) was corrected based on the flood reported that flood water escaped at the alleyway between houses (lower arrow).

Another interesting point is that existing walls or fences are not represented by the DEM. These walls may block pathways and result in different routes. In this area few pathways divert from streets and pathways through gardens of houses may occur, but different results can be expected with the presence of walls in the DEM.

CONCLUSIONS

The results of testing an innovative method for analysis of overland flow component during pluvial flooding in urban areas has been presented. The concept is based on the use of detailed high resolution DEM which enables creation of the surface runoff pathways network. The surface network of ponds and preferential paths (along the streets originated from surcharged manholes or across the urban catchment from other remote areas) are created by automatic catchment delineation. The information required for flood simulation such as pond storage and pathway geometries are prepared for hydraulic model. The mutual interactions between surface and underground sewer networks are established through inlets or manholes located on the bottom of ponds and through predefined surface pathways that can carry water to the sewer network at downstream inlets. Detailed description of tool's applications was shown using study cases in the Keighley and Town A catchment, UK. The work presented here enables a fully integrated urban pluvial flood to be modelled by the 1D-1D approach. However, it should be noted that full success in implementing this concept depends on the quality of the DEM. Local resident's experience is also essential and can be used to fine tune the model. Detailed analysis is required to improve DEM quality in complex urban area for purposes of modelling of urban flooding.

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