A Modelling Approach to Support the Management of Flood and Pollution Risks for Extreme Events in Urban Stormwater Drainage Systems

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Abstract
The complexity and interactions of flooding and associated pollution resulting from exceedance surface water flows during extreme storm events presents a major threat for future sustainable urban drainage management. Innovative coupled 1D/2D modelling approaches are described for the detailed delineation and analysis of surface flowpaths, flood depths and velocities during such extreme events. The modelling structure and potential outputs are illustrated by reference to the Birmingham Eastside SWITCH demonstration area.

Keywords: urban stormwater, drainage complexity, exceedance flows, GIS-based 1D/2D modelling

1 Introduction

The principal objective of Work Package (WP) 2.1 "*Technological Options for Stormwater Control Under Conditions of Uncertainty*" within the SWITCH project is to utilise the control and treatment of impermeable surface runoff to support sustainable urban stormwater management and provide an enhanced level of service and quality of life to the urban community. Both current and future threats and uncertainties to such holistic, sustainable stormwater management were identified in consultation with the Birmingham and Belo Horizonte Learning Alliances (LAs) and a guideline risk assessment strategy developed and successfully tested with stakeholders. This work has been fully described in Deliverable 2.1.1b (Ellis *et al.*, 2008a), with the methodological application further illustrated in a paper presented at the 2nd SWITCH Scientific Meeting in Tel Aviv, Israel (Scholes *et al.*, 2007).

The primary threat for future urban stormwater control identified by both SWITCH demonstration cities was that of increasing flood risk occurring from inadequate drainage capacity (of both carrier sewers and receiving water channels), increasingly exacerbated by urban creep and climate change. A risk assessment matrix for flooding and associated pollution risks, developed in conjunction with the LAs for both contemporary and future conditions, was outlined in a paper presented at the 3rd SWITCH Scientific Meeting convened in Belo Horizonte, Brazil (Ellis *et al*., 2008b). One major issue and source of uncertainty highlighted in this risk analysis work is that of accurately defining and targeting appropriate mitigating measures for the relief of extreme event flood and pollution "hotspots" within urban development areas. This challenge comprises the central focus of Task 2.1.3 within SWITCH WP 2.1 in terms of quantifying the potential of different stormwater control options through the application of a GIS-based modelling approach.

GIS systems are most commonly used to collate and manage spatial data required as essential input for stormwater models such as SWMM, MIKE Urban CS, InfoWorks SD or STORM whose comparative attributes and strengths have been reviewed in Deliverable 2.1.2, Part A (Scholes and Revitt, 2008). In the context of a typical urban development scenario involving multiple stakeholders having a wide variety of interests and concerns, there is clear potential for the use of a central data integration and communication tool to act as a precursor to analytical modelling. In addition, the availability of such a forecasting/screening tool is regarded as being a priority warning system for future pluvial flood management in the UK (Falconer *et al*., 2009) given the change in national perspectives on flood risk management following the extreme storm events of 2007. The development of this type of specific GIS tool, which facilitates stakeholder involvement and interaction in the decision-making process of BMP selection and location, is an identifed objective of SWITCH WP 2.3 (Task 2.1) and the development of this GIS tool has been reported elsewhere (Viavattene *et al*., 2008).

The application of such a GIS-based tool in combination with a stormwater modelling tool to provide a novel, coupled 1D/2D approach to the analysis and quantification of complex inter-urban extreme event flooding and pollution represents a further novel contribution within SWITCH and has been briefly introduced in Ellis *et al*., (2008b). The development of an extreme event management approach to map potentially vulnerable urban areas in order to prioritise mitigation measures and maximize lead times for emergency flood preparation, as well as underpinning Stormwater Management Plans (SWMPs), is regarded as constituting an urgent priority need in the UK (Pitt, 2008). Such risk mapping of potentially vulnerable urban areas is also a prime requirement of the EU Floods Directive. In addition, it would also provide a service tool of value to drainage practitioners and local authorities responsible for urban surface water management. This current paper develops this theme further and outlines the challenges posed by drainage system complexity and describes both the structure of the 1D/2D modelling approach and how it might be applied to sites and sub-catchments of the SWITCH demonstration cities.

2 Complexity and interactions in urban surface drainage

It is now generally acknowledged that urban flooding and pollution are frequently the result of multiple urban land use sources associated with a combination of overland flow, sewer surcharging and receiving watercourse overloading. Figure 1 provides detail on the sources, pathways, receptors and return flows for the urban drainage system and emphasises the complexity of interactions between the various above and below ground sources. The intra-urban response to flooding operates through various process mechanisms and acts on differing spatial scales, combining above and below ground systems, storage facilities and flow routes. Four individual but interlinked drainage systems can be identified from Figure 1:

- a foul (combined) sewerage system with combined sewer overflows (CSOs) discharging to the receiving water,

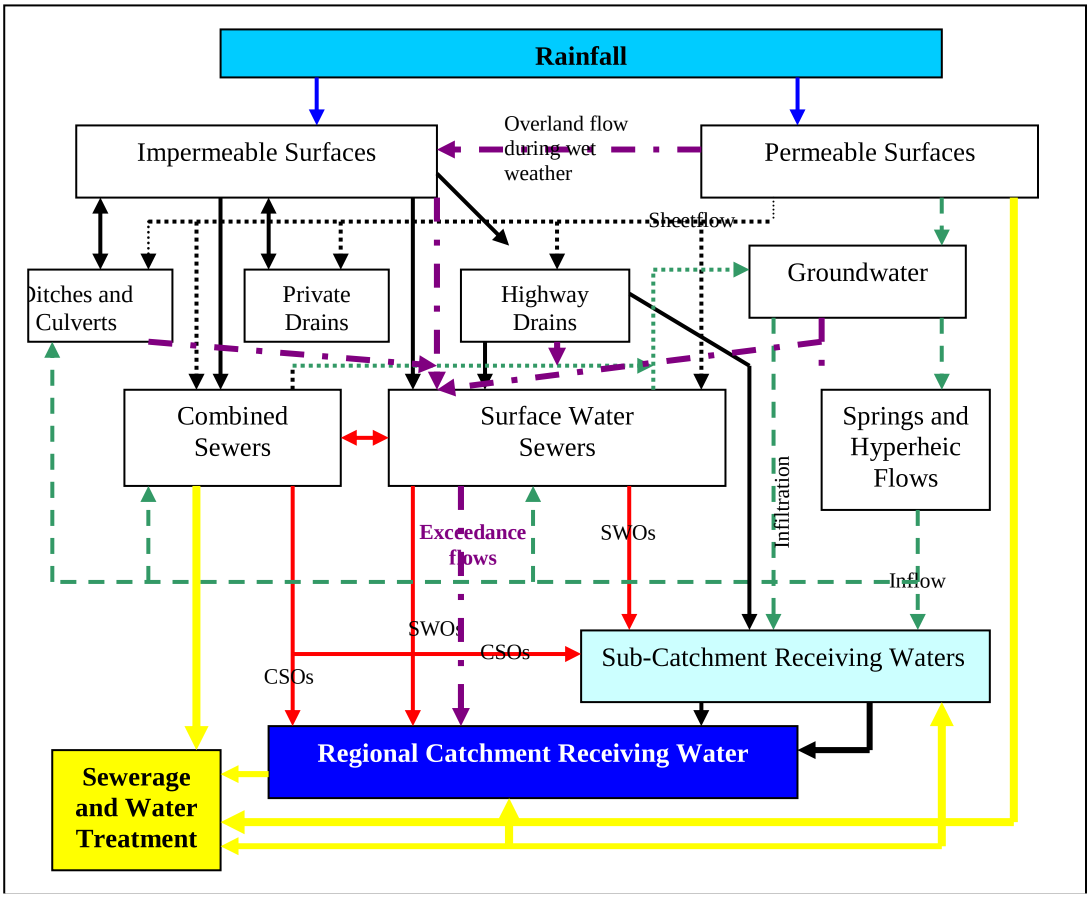


Figure 1. Interactions Between Urban Drainage Sources, Pathways and Receptors.

- a separate surface water sewer system with surface water outfalls (SWOs) discharging to the receiving water,
- the receiving water (normally "heavily modified"),
- and exceedance surface flows during extreme wet weather conditions.

Interconnections, including system cross- (or mis-) connections, infiltration and inflow pathways as well as system abstractions further complicate the process interactions. A theoretical distinction can be made between pluvial flooding caused by rainfall-runoff over impermeable surfaces and exceedance flooding caused by a combination of surcharging, overland flow and sheetflow from sewers, impermeable and saturated permeable surfaces, as well as over-top flooding from ditches and culverts during extreme wet weather conditions. These distinct source contributions are identified in Figure 1 although it is practically impossible to separately identify them under actual field conditions. During extremely intense rain storms, pluvial flooding may occur on the urban surface even when the sewer network is only subject to free surface (non-surcharging) conditions i.e under non-exceedance conditions as the roadside gullies cannot pass the surface runoff fast enough into the below-ground sewer system. However, the interactive nature of urban drainage systems demands a fully integrated, GIS-based modelling approach to simulate a replication of the real flooding and pollution situation during extreme events (>1:30 RI). Potential responses to the flood and associated pollution driver mechanisms must take into consideration this complexity of sources and scales of operation. Control and management approaches should therefore consider the level of the individual building (and curtilage), through the plot, site and sub-catchment levels with initial data input to the modelling process giving indications of flood mechanisms and interactions, the areal distribution and frequency of flooding as well as damage consequences. A crucial data component is that relating to road gully and manhole location, spacing and surcharging contributions to surface overland flow during storm events.

Figure 2 illustrates the complex hydraulic interactions between major (overland) and minor (sewer) drainage systems that can occur under exceedance flow conditions during a storm event and which can lead to "coincident" flooding. The varying storm design standards shown for the differing parts of the sewer system further illustrate how the hydraulic capacity of the minor system is readily overcome during extreme events with roadside gully chambers, normally designed to a 1:1 - 1:2 RI capacity, being rapidly drowned out and contributing to exceedance flows in the highway cross-section.

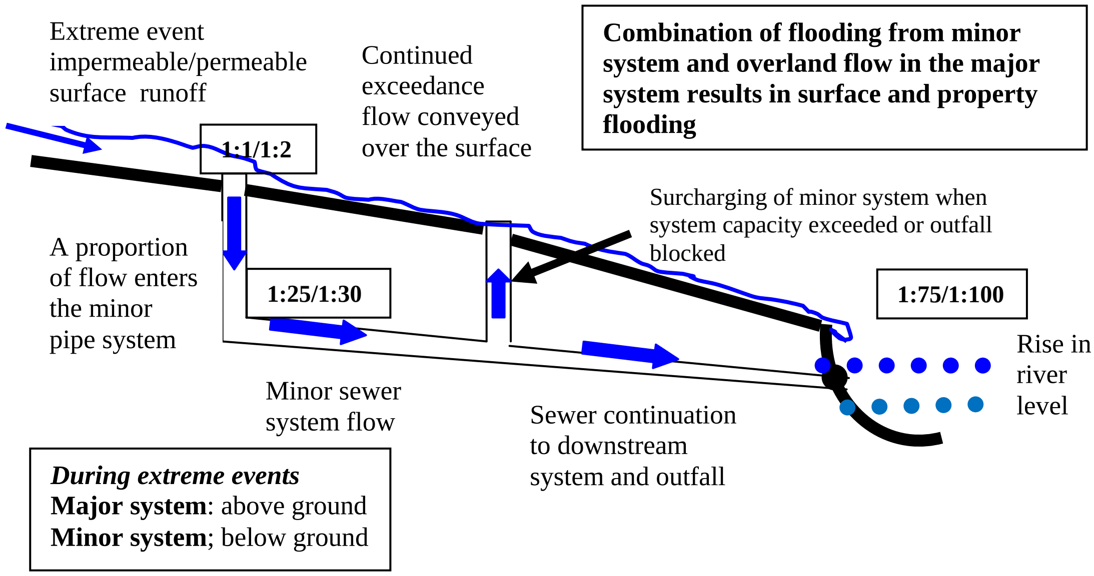


Figure 2. Urban Drainage System Extreme Event Interactions
(Based on Digman *et al*., 2006)

The key control interaction for management action is the ability to discharge excess flows generated within the development site to appropriate temporary storage and/or infiltration facilities in order to reduce surface flooding and to improve the final discharge quality. In addition, above-ground flood routes and temporary storage for extreme event exceedance flows need to be delineated rather than seeking to expand or enlarge traditional below-ground conveyance systems given the prohibitive costs of system rehabilitation and enlargement. The complexity of urban drainage systems can be further illustrated by reference to the July 2002 floods in Glasgow, Scotland where post-flood modelling studies attributed the discrete catchment flood volumes to the four specific sources mentioned above (Adshead, 2007). Pluvial overland runoff from impervious surfaces was considered to contribute over one-third (34%) of the total flood volume with sewer surcharging accounting for 23% and watercourse (fluvial) overspill some 43%. The preliminary Pitt review of the summer 2007 UK floods attributed some two thirds of the flooding to inadequacies in the current hydraulic capacity of surface water drainage systems (Pitt, 2007) and the final report (Pitt, 2008) drew attention to the need for appropriate modelling tools. Considerable effort is now being placed on developing integrated, interactive surface and sub-surface flood models for exceedance conditions in urban areas and a number of commercial modelling approaches such as TELEMAC (www.telemacsystem.com), TUFLOW (www.tuflow.com), FLO-2D (www.flo-2d) and FloodArea (www.savannah-simulations.com) have all recently appeared which attempt to conceptualise surface drainage complexity and interactions.

3 Integrated modelling approaches for extreme events

A number of recent reviews within the UK have now reported on the challenges presented by complex flooding and diffuse pollution sources and mechanisms (Balmforth *et al.*, 2008; Dignam *et al*., 2006; Pitt, 2008). The UK government Foresight report (Evans *et al.*, 2004) estimated that the number of urban properties at risk of pluvial flooding could be up to 0.5 million by the 2080s. It is estimated that two-thirds of the 57,000 flooded homes during the recent summer 2007 extreme events were inundated by surface water drainage with damage estimated at about £3 billion (Crichton, 2008), In principle these findings provide a considerable stimulus to facilitate the availability of robust and accurate modelling techniques for assessing the real-time risk of such complex exceedance flow conditions. The availability and implementation of fully integrated coupled models for urban drainage will enable decision-makers to identify the likely severity of flood and pollution impacts as well as to select and locate compensatory storage and/or infiltration controls (Diaz-Niets *et al*., 2008). High-level screening for exceedance urban flooding would also serve to inform preliminary flood risk assessment (FRA) as required under the EU Floods Directive.

The majority of modelling approaches for surface water flooding have been based on 1D overland routing of an assumed uniformly distributed design rainfall event (or "blanket" approach) although there is increasing interest in dynamic time series rainfall. A decoupled 1D sewer model with 2D overland routing such as SIPSON (Djordjevic *et a*l., 2005), produces a much better estimate of the spatial extent of flooding as 2D solutions are not forced to follow pre-defined flowpaths. However, 1D/2D modelling of overland surface flows is still in its infancy. Such 1D/2D approaches utilizing GIS and high-resolution digital terrain (or elevation) modelling (DTM or DEM) obtained with LiDAR or by photogrammetry, can handle large data sets and provide a very powerful tool for detailed urban surface water management. DTM/DEM dictates the scale to which the modelling can be undertaken and the accuracy of the output; for detailed extreme flow (Type III) risk assessment, fine scale (±50 – 150 mm) topographic resolution is necessary. Only such 2D modelling can deliver accurate strategic planning information on the detailed temporal distribution of flood depth, duration and velocities during an extreme event.

An example of 1D/2D modelling output for identifying surface flow paths and depths during an extreme event was illustrated in the paper presented at the 3rd SWITCH Scientific Meeting (Ellis *et al*., 2008b). The surface exceedance flows and flowpaths are mapped by a 2D "rolling-ball" routing algorithm which tracks overland flow paths down the steepest gradient from flooded gullies and manholes along preferred highway "channels", and replicates the actual physical process of surface flooding (Hankin *et al*., 2008), based on ground topography of the road and containing kerbs, walls etc. Where overland flows are constrained by such kerb lines, walls etc., it may be entirely adequate to model the flow paths in 1D. However, such a 1D approach confines the overland flow to linear "channels" defined by the street lines and does not account for varying water depths or the filling of low points (sinks or ponds) which can lead to changes in flow route direction. The 1D approach has been now largely superseded by 2D overland flow modelling which allows for multiple and multi-directional flow paths with uncertainties reduced by the small cell sizes which can be used in the modelling analysis. The topography, slope and surface characteristics (such as roughness) are used to calculate how water will flow and spread across the surface. This approach can overestimate the actual flood ponding as it actually occurs on the ground as it does not allow for surface flows to return back into the below-ground system as may often occur, particularly as the storm event subsides. However, a coupled sewer modelling approach provides for a more realistic interchange of flows between the various types of drainage system as well as being able to take into account receiving water (fluvial) flood effects. The modelled output can then allow a determination of the routes of least impact (or damage), so that overland flows can be safely diverted for attenuation, infiltration and/or treatment. It is important to note however, that the individual contributing flow sources to the final flood outcomes are not distinguished in the modelling simulations.

Such integrated modelling, being based on the inter-connectivity of the different sources of urban drainage and their effect on intra-urban flooding and pollution, provides a much firmer strategic foundation for risk management. The dynamic surface and sub-surface hydraulic modelling techniques allow the flow complexity to be spatially and temporally analysed and provides a much better understanding of the extreme event problem and the management of potential solutions including the location of sacrificial flood storage areas (Bamford *et al*. 2008) based on source contributions. However, such modelling requires detailed data on the geo-located flooding and the generating rainfall event, which is not always available or requires considerable effort and cost as well as rigorous "ground truthing" (Gill, 2008). One particular problem relates to the accuracy of the digital elevation model (DEM) used in the modelling algorithms as walls, fences, alleyways, driveways (and sometimes bridges, flyovers etc.) are not always represented in the DEM. Unless they are filtered from, or taken into account in the data set, such common urban features can lead to apparent shortcutting and/or blocking of surface flow routes within the model results (Boonya-aroonnet *et al*., 2007). However, recent work on automated "barrier" detection to surface flow path analysis has suggested that utilising LiDAR data representation based on recognition of elevated map features (such as bridges, crossings etc.), can provide the possibility of much more effective flowpath mapping (Evans, 2008).

Nevertheless, fully dynamic risk mapping is only likely to be cost-effective for flood "hotspots" of high vulnerability and/or damage costs and will require careful "ground truthing" (Falconer *et al*., 2009). The hydraulic modelling also requires a supporting tool to identify appropriate locations for, and types of, BMP/SUDS that might be retrofitted and dimensioned for flow and quality control. Such a tool is being developed concurrently within the SWITCH programme and its structure and performance capabilities have been outlined elsewhere (Viavattene *et al*., 2008; Ellis *et al*., 2008a). There are additional pressures on the spatial and process complexity of exceedance flooding associated with climate change, future urban development and urban creep. Climate change is predicted to increase winter rainfall by 10 – 30% in the UK by the 2080s with rainfall intensities increasing by up to 20%. Up to 3 million new dwellings are scheduled to be built in England alone by 2016 and "urban creep" from paving of previously pervious areas will collectively increase significantly the surface water flood risk. It is therefore appropriate in the context of SWITCH demonstration cities to consider user-focussed support tools to identify the threats and hazards posed by future urban exceedance flows and to provide a basis for the optimum choice and location of mitigating and emergency measures.

4 The structure of 1D/2D modelling approaches

Recent linkages between modelling tools and platforms have significantly improved and now allow user-specific linkages to be created between very different and independent modelling approaches (a process called Open Modelling Interface or OpenMI). 2D approaches which resolve the continuity and momentum equations for shallow water free surface flow are now readily available and which can additionally incorporate the full functionality of 1D hydrodynamic network analysis (such as STORM, SWMM etc.) for sewered and surface channel flows. Figure 3 shows the nodes and links of the Birmingham Eastside development area surface water sewers as modelled by STORM and which

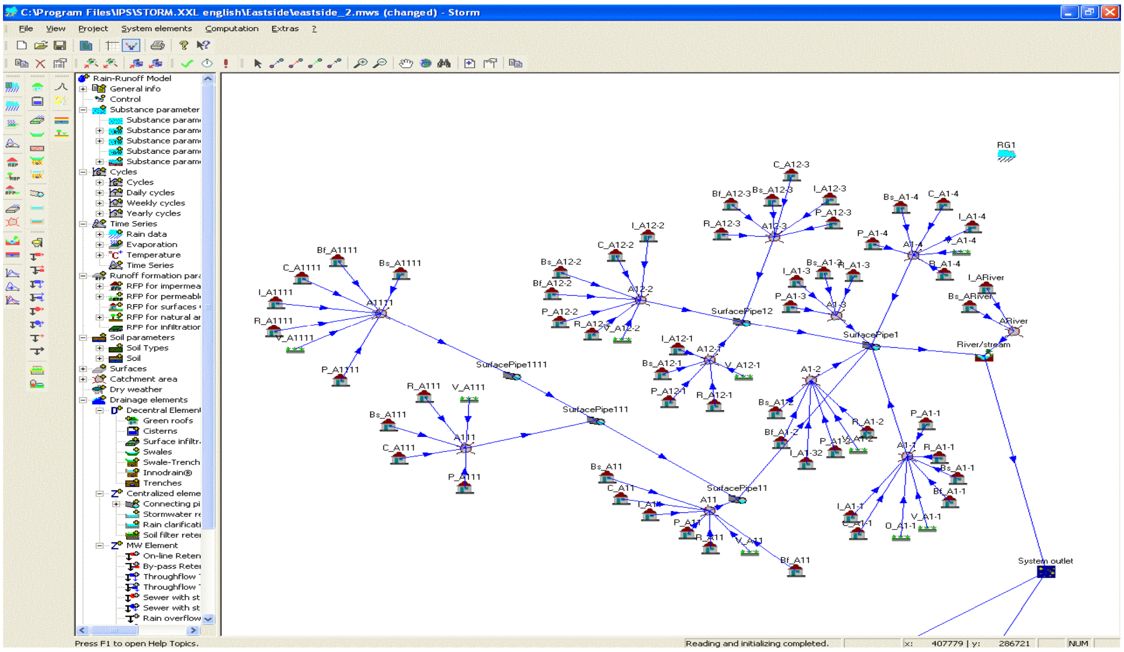
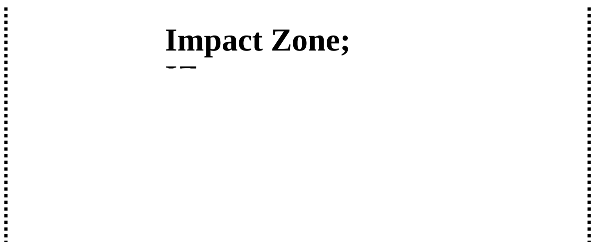


Figure 3. STORM modelling ouput for Birmingham Eastside

provides a basis for the 1D hydrodynamic input to such a coupled approach. 1D domains include the surface water sewer network and nodes, open-channel ditches and culverts with overland 2D domains extending over the surface from gully and manhole surcharge locations. Stormwater sewer data and urban land use types areprovided via a GIS layer and 2D domains derived from DEM/DTM (±0.05 m) in unfiltered or filtered form i.e buildings, vegetation, bridges etc, being removed from the data. The OS Mastermap street network is ”stamped” onto unfiltered DEM/DTM, thus forcing the road network to act as a part of the surface drainage system. In this way, even very minor features such as 100 mm kerbs become significant controlling features affecting flood pathways and storage points. Each land use type (or material) is assigned a roughness coefficient which can vary to allow for frictional losses due to bridge piers, walls, surface composition etc., which can be obtained from conventional “look-up” tables for Manning “n” values.

The clearest identification of flood risk domains (or impact zones; IZs) within a development site can be obtained through applying a contour polyline screening (CPS) technique based on the raster DEM/DTM grid mesh. Each pixel in the IZ grid is treated as an individual storage or impact cell (IC) which is assigned an elevation from the raster DEM and closed contours are constructed using automatic ArcMap functions (Figure 4). CPS uses filtered topographic data to create polygons representing closed contours within the IZ using standard GIS functions. These unfiltered closed contours form a sequence of “rings” or depth contours around sinks (depressions or ponds) as seen in Figure 4. The identified IZ depressions (or ponds) can then be filtered with minor shallow-depth hollows (<0.05 m) not likely to pose any serious flooding problem, being removed if it is felt necessary. This reduces mapping “clutter” and more clearly defines those impact cells (ICs) within the IZ which pose the highest flood risks. The CPS technique can be displayed at differing IZ contour spacings varying between 0.01 m – 1.5 m, with a minimum 0.05 m vertical resolution being essential for accuracy. Figure 5 shows an example of 50 cm contoured LiDAR data for the Birmingham Eastside area based on a fairly coarse 5 m grid cell which indicates large potential depression areas to the east and south east parts of the development area lying between 101.5 m to 102 5 m. The storage



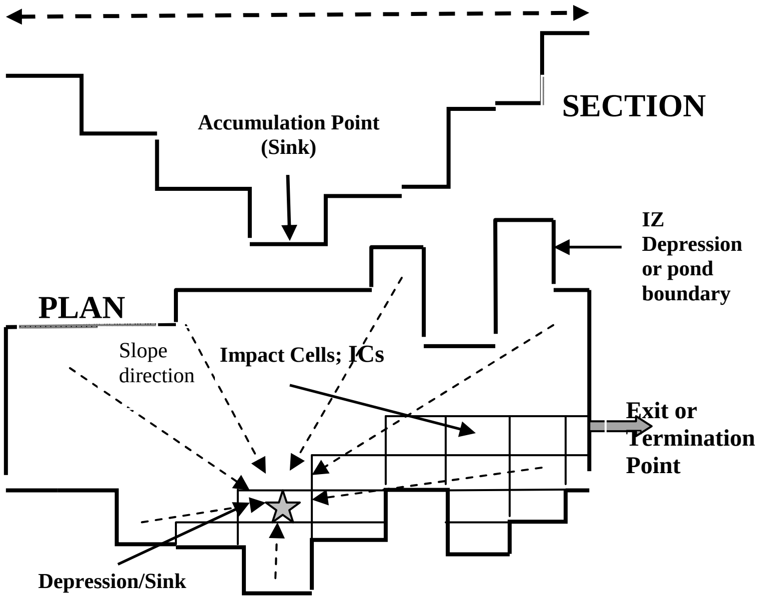


Figure 4. Link-based flood impact zones and cells.

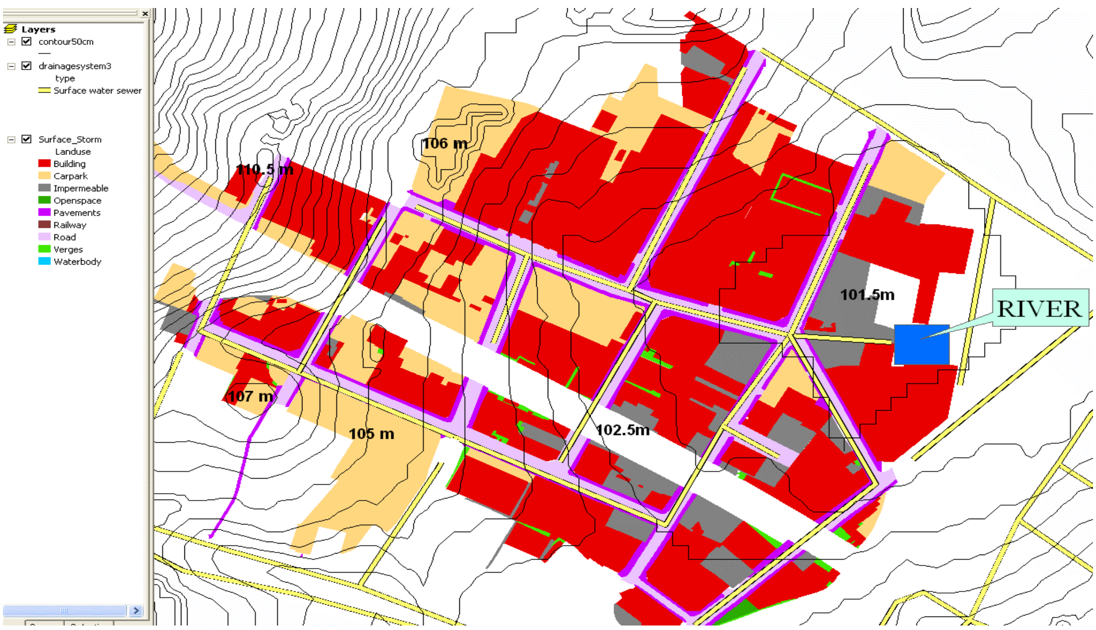


Figure 5. LiDAR image for Birmingham Eastside.

volume, overtopping and connectivity of cells will clearly change dynamically over time during a storm event as a function of the overland rainfall- runoff volume. However, raster routing methods (i.e flow between ICs) are known to suffer from scale dependency and so different cell/grid sizes can influence the results.

The CPS technique can then be coupled with the "rolling ball" method to define steepest slopes and thus identify surface water flowpaths over the impermeable surface based on standard ArcHydro tools. The "spillway" exit between IZ ponds (see Figure 4) must also take into account building lines, street furniture and other features of the urban fabric. Post-processing can be undertaken to indicate the severity of flowpaths in terms of slope and flow depths e.g many flowpaths will be confined by the road camber and limiting kerb face to one side of the highway. Site inspection comprises an important element to "groundtruthing" the spatial mapping technique. Doorway threshold levels relative to highway levels and side alleys for example, may be critical to flood vulnerability and can only be accurately assessed from field inspection. Such site inspection provides both modelling verification and a means of understanding the physical processes and factors influencing macro- and meso- surface flooding, and further serves to validate the overall screening approach.

The 2D FloodArea model coupled with STORM will be adopted in SWITCH WP 2.1 to delineate the dynamic temporal surface water flooding during extreme events for the Eastside development area in the demonstration city of Birmingham, UK. FloodArea is an ArcGIS extension which is completely integrated in the graphical user interface (GUI) of ArcGIS desktop utilizing Spatial Analyst and ArcMap functionality. Discharge volumes to neighbouring cells in the individual IZs are calculated using the Manning-Strickland formula. The quality of simulation is therefore not only a function of the selected cell size but also depends very much on the choice of roughness values for each land use type since flow velocity is linearly related to roughness. The flow depth during an iteration interval is derived from the difference between water level and maximum terrain elevation along the flow path. The modelling procedure maintains a permanent optimisation between the calculated discharge rates and the available storage volumes. The overall discharge volume during the extreme event is defined by either an input hydrograph or by a discretised rain storm distributed uniformly across the IZs.

5 Concluding remarks

The 1D/2D approach provides a realistic analysis of extreme event overland surface flows, especially where the flowpaths are not confined to preferred street sections. The outputs allow the testing of different flood planning scenarios and the generation of risk/hazard maps as well as enabling flood vulnerability analysis. However, the modelling methodology is very sensitive to the DTM/SEM data and allocation of roughness values and requires small scale time steps and is also computationally demanding. As such it is probably inappropriate for real time flood representation and rapid forecasting, being much better suited as a planning and management screening tool for identification and quantification of flood areas, depths and flow paths. This makes it ideally suitable for selecting locations for mitigating measures and deciding on emergency/hazard planning procedures as well as a basis for analyzing detailed depth-damage costings.

Extreme event flood analysis together with associated receiving water pollution and degradation comprise substantial challenges for the city-of-the-future and comprise major components in the EU Strategic Research Agenda. Without consideration of such complex drainage interactions, integrated urban stormwater management strategies cannot be adequately addressed. EU RTD projects such as SWITCH need to connect with national policy objectives and be able to translate scientific principles and approaches to support both strategic policy and stakeholder involvement as well as reinforcing local structures of knowledge to enable sustainable development based on local capacities. This is the only effective way to ensure RTD ownership but does require a fundamental effort to communicate the methods, tools and outcomes more effectively with the stakeholder community. This presents a major challenge to the demonstration city LAs for the final stages of the SWITCH project.

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