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Risk Assessment and Control Approaches for Stormwater Flood and Pollution Management

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Abstract
Integrated urban stormwater management (IUSM) must address pluvial flooding and diffuse pollution at varying temporal and spatial scales of operation in order to identify appropriate mitigating and management options. A risk assessment procedure is outlined which enables multi-stakeholders involved in the decision-making process on urban drainage infrastructure, to identify contemporary and future threats and uncertainties. Of particular concern to the Eastside development area (the SWITCH demonstration site in Birmingham, UK), are those risks associated with extreme exceedance flows and overland flow routes, as well as diffuse pollution and receiving water ecology, in addition to planning and source control issues. The principal barriers to IUSM are discussed and the particular technical difficulties associated with delineating extreme pluvial exceedance flooding are examined. A GIS decision-support methodology is outlined which is intended to provide an integrated, holistic approach for addressing the needs of multi-level, multi-stakeholder engagement aimed at resolving long term urban flood and pollution risks.

Keywords: pluvial flooding; urban diffuse pollution; risk assessment; IUSM; GIS modelling

1 Introduction

Set against a scenario of climate change and uncertain economic and socio-political futures, it is inevitable that there will be a variety of both risks and opportunities which will arise in the implementation and management of urban surface water drainage infrastructure. The priority objectives must be to avoid or minimize increased flooding and pollution risks whilst increasing performance efficiency and enhancing local environmental quality-of-life. Clearly the identification of priority action strategies and the evaluation of mitigating options will be prime components in future adaptive sustainable urban stormwater management. A key element in any future innovative organisational framework must be the recognition of the differing regimes and impacts of storm events (Davies and McManus, 2004). Figure 1 demonstrates that sustainable integrated urban stormwater

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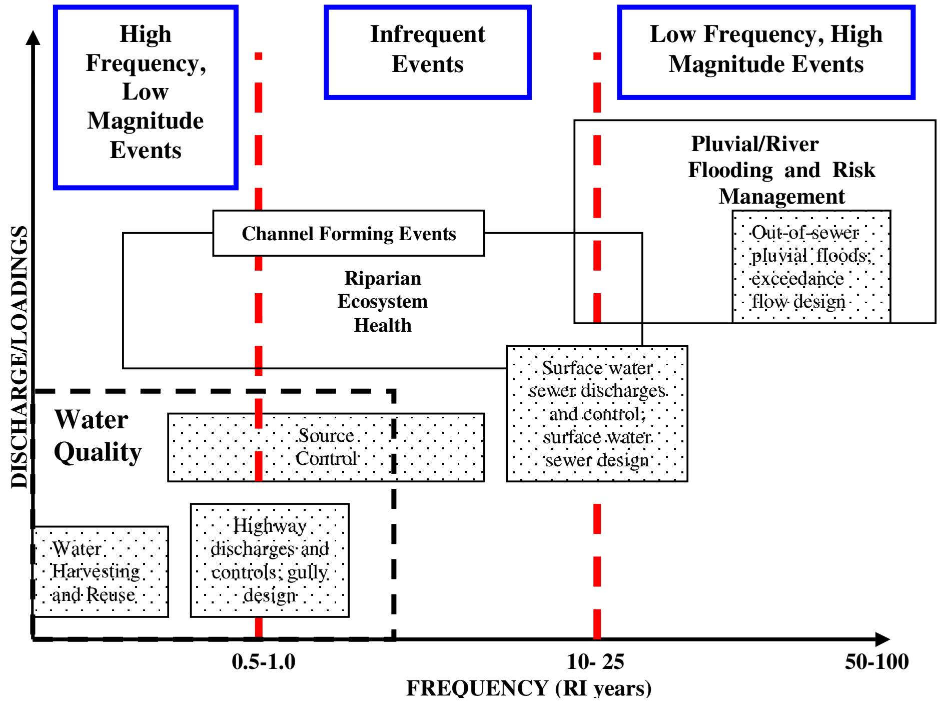

Figure 1. Stormwater Management Planning Scales and Issues.

management (IUSM) will need to plan for three major categories of storm events within the hydrologic spectrum, each of which will have different impacts on the biophysical, social and economic environment. Diffuse non-point pollution, water re-use and source control are essentially related to high frequency, low magnitude flow events (<1:1 RI), with pluvial surface flooding associated with extreme events (>1:30 RI). Receiving water ecology is sensitive to both these return event scales in terms of acute and chronic impacts; long term ecological integrity and channel morphology both being dominantly shaped by the intermediate infrequent time scales. This tri-level storm event consideration of urban surface water management represents a significant shift from the conventional drainage infrastructure planning process which tended to focus exclusively on the design and management of extreme flow events operating at or near the limit of the drainage design.

However, current management frameworks intended to address major flood risk must consider not only receiving water health and ecosystem functioning but also issues of land use capacity and potential, social/community values and expectations as well as cost viability. In addition, proposed controls and management approaches must also be compatible with legislation and planning objectives set at municipal, regional and catchment levels. Specific objectives, targets and performance-based criteria will therefore need to be set, monitored and evaluated for a variety of biophysical, ecological, social and economic environmental parameters (Evans *et al*., 2004). The interfaces between the science of urban catchment health, ecosystem functioning, urban land planning and strategic policy decision-making will thus present major challenges for future organisational structures intended for IUSM.

This functionality and effectiveness must be related to specific flow regime levels and to water quality effects on both short (acute) and long term (chronic) time spans. An evaluation of environmental values and controlling regime factors will assist in the determination of the principal waterbody stressors in order to aid the prioritisation of "hotspots" and to effectively target scarce resources.

There is also a need to relate drainage decisions to practical planning solutions and thus to local, regional/state and national policy as well as catchment-based intervention strategies. Increasingly the preferred sustainable approach to urban water management will be an integrated multi-disciplinary and multi-stakeholder decision process founded on an understanding of ecosystem health and urban hydrology. This paper discusses the principal threats, uncertainties and risks for surface water management identified by the SWITCH Birmingham Learning Alliance (LA) in relation to the Eastside development area of the UK demonstration city. An integrated GIS-based modelling approach is being developed to address the complexities associated with the evolution of strategies for the mitigation of urban flooding and water quality, which have been identified as prime threats to future development.

2 Threats, Uncertainties and Risks

2.1 Risk Assessment

Each demonstration city involved with the SWITCH Workpackage 2 having an interest in urban stormwater management was invited to undertake a detailed survey of their LA representatives to identify and quantify the principal threats and uncertainties associated with the achievement of integrated urban stormwater management (IUSM). These risks were identified within the context of both contemporary environmental, institutional, legal, and socio-political conditions as well as for the extrapolated city-of-the-future in 20 to 30 years time. This database survey then provided the basis for a risk assessment analysis and the development of a risk rating procedure to support LAs in evaluating the relative strengths and vulnerabilities of differing stormwater control systems and management approaches under the varying identified scenarios. A risk assessment template, essentially based on the well-recognised "traffic light model" was developed, which will enable LAs to differentiate between three levels of risk ranging from "acceptable" to "tolerable" and "non-acceptable". The generic basis and structure of this risk assessment approach has been presented at a previous SWITCH Scientific meeting (Scholes *et al.*, 2007) and the results of this risk analysis for both the Birmingham, UK and Belo Horizonte, Brazil demonstration cities are presented in detail within the SWITCH Deliverable Task 2.1.1b (Ellis *et al.*, 2008) available on the SWITCH website (www.switchurbanwater.eu).

Figure 2 provides a risk assessment matrix for the identified threats and uncertainties associated with urban surface water management within the Birmingham Eastside area in relation to flooding and water quality parameters. Other parameters considered in the matrix but not shown here, include receiving water ecology, surface water management, urban landuse planning and BMP/SUDS control implementation. The matrix parameters and scores shown in Figure 2 were developed based on available data and on stakeholder interviews. The rating scores (developed on a scale of 1 – 5), are given for both prevailing conditions anticipated over the next five years as well as extrapolated for the city-of-the-future in 25 – 30 years time. The shadings allocated to the final summed scores equate with "acceptable risk" (green), as "tolerable risk" (yellow), and "unacceptable risk" (red), levels respectively. The most significant risks and associated uncertainty arise from inadequacies in current drainage capacity and mitigating controls, in terms of the appropriate management of overland flows from impermeable urban surfaces. Such surface water flows are the fundamental cause of pluvial out-of-sewer flooding and diffuse pollution with for example, two-thirds of the damage associated with the extreme summer 2007 urban floods being attributed to such sources (Pitt, 2008).

Identified threat	Likelihood of Occurrence		Level of Consequence		Likelihood of Occurrence		Level of Consequence		Risk score	
	Within the next 5 years	Score	Within the next 5 years	Score	In 25-30 yrs time	Score	In 25-30 yrs time	Score	Within the next 5 yrs	In 25-30 yrs time
Increased flooding	- Surcharging of surface water sewers from combined system during extreme (>1:10RI) wet weather events - Increased and more frequent summer storm intensities - Backing-up of surface water outfalls/drains by river flooding - Increased likelihood of pluvial surface water flooding with exceedance flows - Ageing sewer infrastructure; insufficient hydraulic capacity - No record of surface flooding for Eastside area and July 2007 floods (>1:80-60 RI) did not seriously impact on the surface water drainage system. -High level of service protection (>M75-60 event) provided by deep, culverted Rea channel - Urban creep and re-development extending impermeable surface area.	**3**	- Flood risk consequences are currently minimal given channelled depth of the Rea and extent of urban dereliction within the Eastside floodplain area. - Flood nuisance to local traffic and pedestrian movement - Routing of overland exceedance flows (storms >1:30RI) along street and gutter pathways - Blockage and damage to surface water outfall flaps - Blockage of gullies and surface drains due to low cleaning frequencies	**1/2**	- Introduction of upstream flood controls will help to reduce downstream flood occurrence - Works on flood control employing upstream detention basins; control target stated as 50-year return period. - Reduction in CSO spillages resulting from rehabilitation and repair drainage asset planning (DAP) programmes - Increased likelihood of flood potential with climate change, urban creep and ageing sewer infrastructure	**2**	- Reduction in frequency and volume of CSO spillages - Dwellings relocated from high-risk areas; increased flood resilient building - Increased land and property values following development	**2**	**3 - 6** Level of risk: low to medium	**4** Level of risk: low

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Figure 2 (cont.)

Identified threat	**Likelihood of Occurrence**		**Level of Consequence**		**Likelihood of Occurrence**		**Level of Consequence**		**Risk score**	
	Within the next 5 years	**Score**	**Within the next 5 years**	**Score**	**In 25-30 yrs time**	**Score**	**In 25-30 yrs time**	**Score**	**Within the next 5 yrs**	**In 25-30 yrs time**
Persistent pollution of receiving waters	- Very high, due to lack of interceptors, cross connections and Combined Sewer Overflows (CSOs) and Stormwater Outfalls (SWOs) - no provision for sewer separation in drainage asset management planning process (AMP) - Untreated separate surface water flows from impermeable surfaces associated with all wet weather events. - Surcharging from combined to surface water sewers during extreme (>1:10) storm events - Fly tipping, debris and litter	**4/5**	- Consistently poor surface water quality with high concentration of pollutants associated with extensive impermeable areas on commercial, retail and industrial land uses - Poor quality due to lack of interceptors, presence of illicit cross connections and CSO/SWO outfalls/spillages - High BOD and low DO especially during/after wet weather (strong first-flush); marginal eco-chemical (GQA) compliance with standards - Contaminated bed sediments; micro-pollutants, oils etc. - Unsightly aesthetic channel appearance due to litter, debris etc. - Degradation of river banks ; strongly engineered watercourse - Poor quality groundwater leakage from historical industrial heritage; lack of strategy for groundwater management	**5**	- Planned improvements in the sewer system: construction of interceptors and reduction in cross connections and CSOs. - Target of eliminating all cross connections not totally feasible. - EU Water Framework Directive (WFD) implementation but probably derogation under highly modified water body (HMWB) status; likely to suppress urgency for future quality improvements - Climate change resulting in more frequent and polluting SWO flush discharges - Upstream source BMP and SUDS controls	**3/4**	- Reduced BOD and improved DO as a result of planned improvements under asset management planning (AMP) programmes in the sewer system and reduction in CSO frequency: construction of interceptors and reduction in cross connections etc. - Improved aquatic quality and habitat resulting from implementation of national diffuse pollution control programmes by central government agencies (e.g Defra, OFWAT etc) - Achievement of higher biochemical GQA quality status (~ Grade 2/3). - Research work on hyperoic zone interaction and natural groundwater remediation.	**3/4**	**20 - 25** Level of risk: high	**9 - 16** Level of risk: medium to high (but low confidence in rating)

Figure 2. Birmingham Eastside Flood and Water Quality Risk Assessment Matrix

2.1.1 Assessment of flood risks

Increased frequency and intensity of storm events, coupled with increased intensity of urban land use, has resulted in repeated fluvial and urban flooding from exceedance flows (for events >1;30RI) within the upper River Rea catchment (Birmingham City Council, 2008). The river channel in the immediate vicinity of the Eastside development area has been protected to a large extent to date from the increased incidence of fluvial floods by the high level of service protection (>M75-60 storm event) afforded by a deep (5m x 12m), culverted engineered structure, as indicated in Figure 2. However, surcharging from combined to surface water sewers, backing-up of surface water drains by high in-channel river levels and in-street pluvial flooding are all becoming an increasing concern for Birmingham City Council (BCC), the Severn-Trent Water (STW) company and the regulatory Environment Agency (EA). Thus the prime flood risk within the Eastside development area is associated with impermeable surface flows generated by extreme storm events which pond-up on streets, footpaths and driveways for extended periods, during and immediately following intense rainfall conditions.

2.1.2 Assessment of pollution risks

The receiving water quality of the River Rea in the Eastside area is officially classified as of RE4 status which reflects a fair to poor chemical condition. In recent years there has been only marginal compliance with this classification status, and prior to 2003, significant and frequent failure was recorded. This was primarily caused by persistently high BOD and ammonia levels averaging 5 mg/l and 0.4 mg/l respectively. The extensive and uncontrolled non-point pollution from impermeable surface flushing, together with illicit cross-connections, numerous sewer outfalls and the engineered channelisation are the basic causes of the poor water quality, and collectively inhibit any medium-term alleviation to the risks posed by poor water quality. Biological surveys also classify the receiving water as being of poor (Class E) quality in ecological terms, with a heavily depressed biodiversity reflected in a near-sterile receiving water which has little if any public amenity or aesthetic value. The brick-lined, fast-flowing river channel combined with an endemic flashy regime and episodic flush-fed pollutant innoculum, all predicate against any substantial future water quality or ecological improvements. If, as likely, the urban River Rea receives derogation status as a "heavily modified water body" under the EU WFD, the risks of continued long-term depressed water quality and ecology will remain high for the city-of-the-future.

2.2 Barriers to Integrated Urban Stormwater Management (IUSM)

There is currently little basis for the structured, systematic or integrated adoption and management of surface water facilities within urban catchments in the UK. The various stakeholder organisations and agencies having interest in and responsibility for urban drainage, have differing incentives, accountabilities and investment planning horizons, with responsibility for urban pluvial surface flooding lacking both strategic direction and legislative clarity (Pitt, 2008). There are clear tensions between the need for the city council to promote urban growth-point initiatives such as Eastside and the realisation of capital receipts, against the need for effective sustainable drainage and the minimisation of surface flooding and associated pollution risk.

Currently, large scale development proposals such as the Eastside regeneration are dealt with on a "piecemeal" basis with drainage essentially addressed at the site/local level, with little if any consideration of the accumulative effect of the "streaming" of individual development parcels on long term, strategic catchment level objectives. The streaming of the Eastside proposals over a 5 to 10 year

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period also causes difficulties in ensuring a progressive, consistent and integrated infrastructure policy for the differing spatial and temporal development elements. Figure 3 summarises the principal barriers and difficulties to achieving an integrated stakeholder consultation process for strategic urban flood and pollution management. Surface water flooding control has essentially evolved organically and there is a history of cooperation and joint action between Birmingham City Council (BCC), Severn Trent Water (STW) and the regulatory Environment Agency (EA) in dealing reactively with emergency events. However, under existing legislative and regulatory frameworks, the boundaries of responsibility and leadership lack clarity which gives rise to clear risks in achieving fully effective and efficient surface water drainage management. The Highways Agency (HA) who hold separate responsibility for trunk road and motorway drainage, have hitherto not participated in stakeholder consultation processes, which further exacerbates the problem.

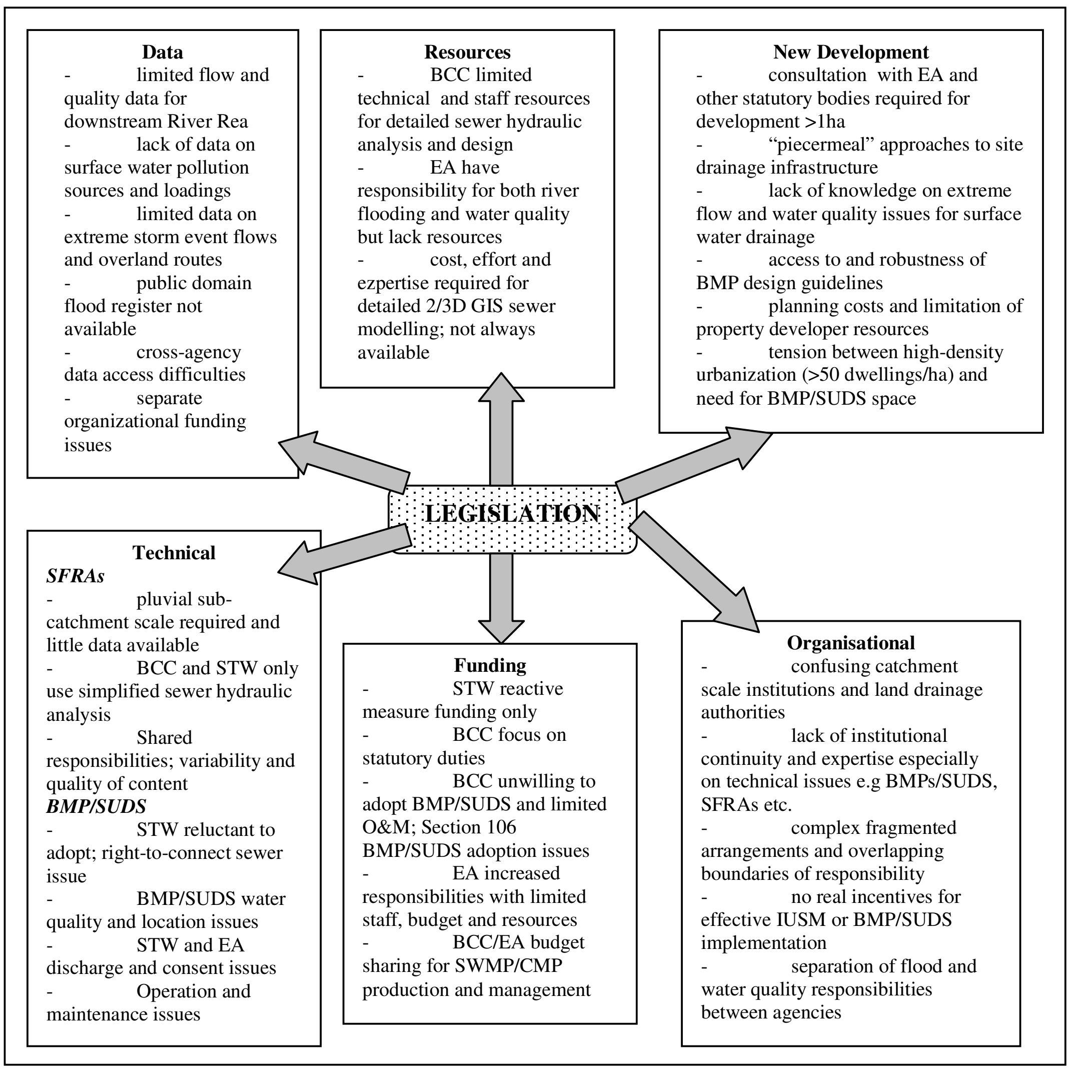

Figure 3. Barriers to IUSM within the Eastside Rea Sub-Catchment

There are also issues regarding the development by the local authorities such as BCC, of Strategic Flood Risk Assessments (SFRAs) for the urban Rea catchment. It is not clear how far SFRAs will be incorporated into the catchment (or river basin) management plans (CMPs/RBMPs) being concurrently developed by the EA as part of their remit under the EU WFD. In addition, local authorities will also be charged with separately developing and implementing stormwater management plans (SWMPs) as part of their Local Develepment Framework (LDF) planning process. There is therefore considerable possibility of confusion and incompatibility between the various agency surface water risk assessment management plan arrangements and procedures.

3 Stormwater Flood and Pollution Risk

3.1 Extreme Event Pluvial Risks

It is now generally acknowledged that urban flooding and pollution are frequently the result of multiple sources associated with a combination of overland flow from impermeable surfaces, sewer surcharging and receiving watercourse overloading (Balmforth *et al*., 2006). The intra-urban response to flood and pollution flows operates through various process mechanisms and acts on differing spatial scales, combining above and below ground systems, storage facilities and flow routes. Four individual systems collectively comprise the urban drainage network; a foul (combined) sewerage system, a separate surface water sewer system, a receiving water channel (normally "heavily modified") and exceedance surface flows during extreme wet weather conditions. Interconnections, including system cross-connections, infiltration and inflow pathways as well as system abstractions further complicate the process interactions. The interactive nature of these urban drainage systems require a fully integrated, nested modelling approach to replicate the real flooding and pollution situation during extreme events (>1:20 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 include spatial considerations from the level of the individual building (and curtilage), through the plot, site and sub-catchment levels as well as interactions with the surrounding peri-urban region. The key control interaction is the ability to discharge excess flows away from the development site (for flood control) and in terms of pollution control, to capture the majority of small scale events (<1:1 RI). In many cases, it will be most effective to resolve local flooding and pollution problems through addressing and disentangling sources, changing the volume and pattern of surface runoff (e.g through disconnection, infiltration etc.) and/or by increasing available storage capacity. In addition, above-ground flood routes and temporary storage for extreme events need to be identified rather than seeking to expand traditional below-ground conveyance systems.

The operational efficiency of surface water outfalls to the River Rea becomes seriously affected when the receiving water channel runs close to bank-full capacity. Surface flooding caused by backing-up and surcharging from the stormwater pipe can become a substantial problem under these hydraulic conditions (Birmingham City Council, 2008). The varying storm design standards shown in Figure 1 for the differing parts of the sewer system, further illustrate how the hydraulic capacity of the minor (road kerb-gutter-gully) system is readily overcome during extreme events with highway 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. Urban surface flooding during such extreme events can be further exacerbated by source contributions from groundwater and overflows from local ditches.

The majority of current modelling approaches for surface water flooding are based on 2D overland routing of an assumed uniformly distributed rainfall event (or "blanket" approach) which significantly overestimates the extent of flooding, but which is suitable for initial, high-level screening analysis. Figure 4a illustrates simulated surface flood pathways for a 1:10 storm event using a decoupled 1D sewer model and digital elevation data as applied to a GIS base and routing the flood volumes from over 100 manholes and gully chambers. The 2D "rolling-ball" routing algorithm tracks flood paths

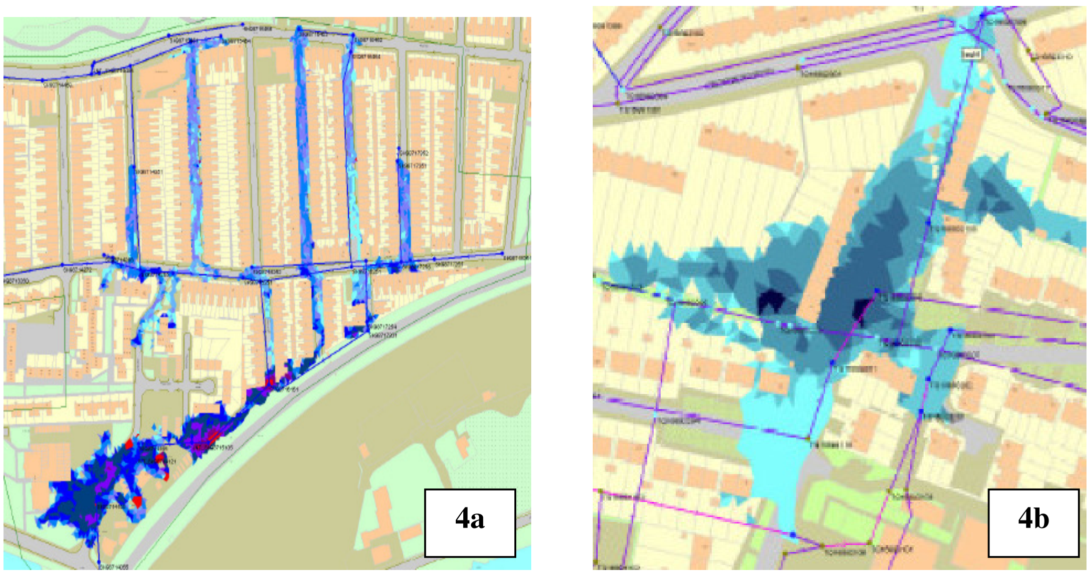

Figure 4. Modelled Surface Flow Paths During an Extreme Event.
(After Gill, 2008)

from flooded gullies and manholes, replicating the actual physical process of surface flooding (Hankin *et al*., 2008). This approach provides a considerable improvement over previous 2D hydraulic modelling capabilities. However, it still overestimates 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. A coupled sewer modelling approach applying a 1D sewer model coupled with a 2D overland flow routine (Figure 4b), provides for a more realistic interchange of flows between the various types of drainage system as well as taking into account receiving water (fluvial) flood effects.

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, will provide a much firmer strategic foundation for urban drainage risk management. This philosophy has been the basis for the 15 Integrated Urban Drainage (IUD) pilot studies organized by the Department of the Environment, Food & Rural Affairs (Defra) in the UK (http://iudpilots.defra.gov.uk; 1 October 2008). The real-time, surface and sub-surface hydraulic modelling techniques allow the flow complexity to be spatially and temporally analysed, and provide a much better understanding of the extreme event problem and the management of potential solutions including the location of sacrificial flood storage areas. However, such modelling requires detailed data on the geo-spatial flooding and the generating storm event which is not always available or requires considerable effort and cost as well as "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. Such common urban features can lead to shortcutting and/or blocking of surface flow routes within the internal GIS methodology (Boonya-aroonnet *et al*., 2007), although procedures are now coming forward which will "by-pass" such artificial constraints and generate more realistic flood path routes within the urban GIS fabric (Evand, 2008). However, the time and effort involved in such real-time spatial risk mapping is only likely to be cost-effective for flood and/or pollution "hotspots" of high vulnerability and/or damage costs. It is clear that such integrated modeling approaches which generate flood hazard maps rather than pure risk maps, will require the support platform of powerful spatial GIS-based tools.

3.2 Application of Stormwater BMPs/SUDS for Risk Management

The application of GIS approaches to collect and manage spatial data as input for urban hydraulic modelling, and its use as a communication tool for multiple stakeholder decision-making is becoming increasingly familiar (Makropolous *et al*., 2001; Booyna-aroonnet *et al*., 2007). In addition, there is increasing interest in the application of nested 2D/1D hydraulic modeling for the identification of exceedance flow depths and velocities as well as flow routeing during extreme events within urban situations using GIS-based platforms (Boonya-aroonet *et al*., 2007; Dell *et al*., 2008; Gutierrez-Andres *et al*., 2008). However to date, the GIS modelling approaches have not incorporated a water quality dimension into the hydraulic analysis. A GIS decision-support tool which facilities the integration of data from a variety of sources to investigate the potential benefits of BMP/SUDS implementation within the Birmingham Eastside area is being developed as an integral component of the SWITCH WP2.1 and 2.3 programmes. The modelling approach allows the user to identify potential locations and appropriate BMP/SUDS types that might be installed to mitigate local flood and pollution problems based on site-specific "characteristics" criteria. The GIS approach incorporates a procedure which quantifies pollutant loadings associated with differing urban land use types which has been developed as a separate methodology (Ellis and Revitt, 2008). In addition, a multi-criteria tool developed within a previous EU DayWater 5th Framework project, has been included in the GIS methodology to enable decision-makers to assess the comparative pollutant removal potentials of different BMP/SUDS facilities and to generate a ranking preference for BMP/SUDS performance effectiveness (Scholes *et al*., 2008) at a specific location.

The structure and methodological procedure of the GIS modelling approach has been described in detail elsewhere (Viavattene *et al*., 2008). The GIS interface is capable of operating at individual site/plot level, at development area/sub-catchment level or through direct user-driven investigation of a specific BMP/SUDS type across a development site. The tool is still to be integrated into a full hydrodynamic stormwater model which will enable the incorporation of spatial exceedance flow data into the GIS display (a focus of a future task within SWITCH WP2.1). This will provide an integrated analytical approach capable of addressing the tri-level requirements, and temporal event distribution, for both urban flood and pollution as identified in Figure 1. The GIS methodology promotes an holistic approach to the management of urban flood and diffuse pollution risk, and facilitates stakeholder engagement in the urban drainage decision-making process. This engagement process is a critical component to successfully deliver IUSM, although adaptation to future climate change, legislation and development pressures will need to be effectively addressed. Nevertheless, the principles and tools embedded in the GIS modelling approach offer the opportunity to deliver effective sustainable solutions which will provide long term community and environmental benefits.

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