Developing a risk-based approach to urban flood analysis

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ABSTRACT

Serious flooding in the UK over recent years has increased the attention on urban flooding and highlighted the need to better understand and manage urban flood risk. Further to this, water companies are under increasing pressure to reduce the number of flooding incidents as a result of inadequate network capacity and asset failure.

Recent reports have highlighted that flooding has to be managed in an integrated manner. As the responsibility for drainage assets is distributed between a number of organisations, there is not only a need to cooperate and collate data from a range of sources, but also to attribute flooding to the various assets and the responsible organisations.

This paper describes the work being undertaken on the DTI SAM project that is developing a procedure and supporting tools to enable decision-makers to take into account the probability and consequences of flooding, and attributing the flooding proportionally to assets that generate that flooding. The methodology will allow, for the first time, process-based quantified assessment of flood risks in urban areas, which is an essential requirement for flood risk management.

The procedures and tools are also being demonstrated on two pilot studies (Dalmarnock and Keighley) as part of the project.

KEYWORDS

Asset Failure; Integrated Urban Drainage; Risk-based procedure; Spatially varying rainfall; Systems-based approach; Urban flooding.

INTRODUCTION

Serious flooding in the UK over the last 10 years has lead to increased attention on urban flooding and highlighted the need to better understand and manage urban flood risk. This summer a number of UK cities suffered severe flooding due to two extreme rainfall events on June 25 and July 20 which overwhelmed drainage systems. Further to this, water companies are under increasing pressure to reduce the number of flooding incidents as a result of inadequate network capacity and asset failure.

Recent reports have highlighted that flooding has to be managed in an integrated manner. The responsibility for urban flooding in England and Wales is, at present, broadly divided between the water companies (urban drainage systems), the local authorities (road and rural drainage) and the Environment Agency (management of fluvial and coastal floods). This project builds upon the widely recognised belief that, to be effective, flooding has to be managed in a more integrated manner. Such an approach would consider flooding from fluvial, coastal and pluvial sources and all possible management responses.

The need for a system-based management approach has been reinforced through a number of recent documents, including: the OST Foresight Future Flooding project (Evans et al, 2004); Living with Rivers (ICE, 2001); and the DEFRA strategy Making Space for Water (Defra, 2005). The techniques and technologies to enable a fully integrated risk based assessment of urban flooding and the appraisal of strategic portfolios of options are, however, not yet developed.

Therefore, this project is developing new tools to model the complex urban drainage system and facilitate the delivery of a procedure for an integrated flood risk management approach. The specific advances being made on this project cover the following technical issues:

- Application of spatially varying rainfall to urban flood analysis;
- Development of a risk based approach to sewerage system performance;
- Development a risk based procedure for managing the urban flood system;
- Development of software tools to support the risk-based procedure.

HR Wallingford is leading this three-year project (partly funded by the DTI Design, Modelling and Simulation Technology Programme in the Modern Built Environment area) with the project partners listed in Table 1.

Table 1. Project partners

Project Partners		
HR Wallingford Limited	Wallingford Software	Imperial College
University of Newcastle	Yorkshire Water	Scottish Water
Mouchel Group	Black and Veatch	Thames Water
Glasgow City Council	University of Sheffield	UKWIR
Met Office	Environment Agency	

APPLICATION OF SPATIALLY VARYING RAINFALL

At present, rainfall is normally applied to drainage simulation models uniformly across the catchment. This has been recognised for a number of years as being a serious limitation with a number of companies exploring the use of radar data as a rainfall input for large catchments.

Rainfall is spatially very varied across a large area (especially for extreme events) and the use of spatially varying rainfall offers the potential for this variability to be represented in studies for large catchments and could also implicitly address the issue joint probability in ensuring that appropriate rainfall is applied at all locations within a catchment.

Accurate radar data at the resolution of one kilometre has only been available for the last five years and the DTI SAM project has explored the development of stochastic rainfall generators capable of generating rainfall data over an extended duration that is spatially as well as temporally representative across a catchment, with the recorded radar used to calibrate the developed models.

Radar data at 1 km resolution has been provided to the project by the UK Met Office for the three catchments of London, Bradford and Glasgow. Imperial College and Newcastle University have developed extreme series stochastic rainfall prototype tools at a resolution of 5 minute - 1km.

The Imperial College tool generates relatively high resolution (5 minute – 1km) data over the entire catchment which results in a large volume of data that needs to be stored and manipulated for use in urban flood analysis. The University of Newcastle approach is a two-stage process that initially generates relatively coarse data (1 hour - 10km) data over the entire catchment, but then disaggregates these data to 5 minute – 1km resolution over the areas of specific interest with resulting savings in the volume of data generated.

Imperial College

The method used by Imperial College to develop this time series involves the continuous-time spatial modelling of rainfall using the Gaussian displacement spatial-temporal model (GDSTM) of Northrop (1998), with the model spatially and temporally stationary.

Historic rainfall events have been identified from a 3.5-year record of Met Office weather radar data from 3 different radar datasets and the characteristics of the shape and structure of each event are represented by 11 parameters. For each month within the radar data record, a library of model parameters is obtained and used to develop simulations of 100 years of continuous, spatially varying rainfall at 5 minute - 1km resolution over three regions: London, Bradford and Glasgow.

Results to date

Imperial College has largely completed its work on this element of the project and has produced 100 years of continuous spatially varying rainfall for the three sites specified above.

Initial results have generally demonstrated the potential for generating stochastic spatial rainfall generators with the model able to reproduce different features of various datasets and produced encouraging results in terms of reproduction of standard statistics, although some issues with respect to Extreme Values have been observed.

Comparisons with Flood Estimation Handbook values for sub-daily extremes for higher return periods (above 50 years) has shown a potential consequence of using a limited historical dataset from which to calibrate the model. A further potential issue is the method used to select events from the recorded data for fitting to the model, which requires that rainfall is recorded in at least 15 % of the study area (70km x 70 km grid). This may result in more localised events not being sufficiently selected and consequently represented in the stochastically generated time-series.

University of Newcastle

At the time this paper was written, University of Newcastle is nearing completion of its work and has implemented and validated a catchment rainfall model at a temporal and spatial resolution of 1 hour - 10km using a Poisson model (cut-down version of the Neyman-Scott Rectangular Pulses model). Alternative methods for disaggregating these data to a temporal and spatial resolution 5 minute - 1 km have also been explored. It is anticipated that a summary of their results will be included in the formal presentation at ICUD conference.

Application of stochastically generated spatially varying rainfall data

Rainfall in urban drainage analysis has evolved from the intensity-duration approach in the Rational Method to the use of design profile storms in the Wallingford Procedure. The use of time series rainfall has become more common-place (recorded or stochastic) in recent years, but this still assumes uniform rainfall across the whole catchment. The development in this project of spatially varying rainfall has presented an opportunity to explore the use of such data in progressing towards a more realistic representation and analysis of critical events.

However, a consequence of using stochastically generated continuous spatially varying rainfall data is that to run an extended duration of relatively high resolution data over a large catchment is computationally very demanding. It is therefore important to devise an appropriate methodology for identifying significant events within the continuous timeseries which effectively addresses the particular reason for applying spatially varying rainfall to network analysis.

As a result, a supporting software tool has been developed that allows the stochastically generated data to be analysed and allows the user to identify rainfall events based on user specified criteria. Using this tool, events can be identified that meet threshold values for minimum event duration, inter event duration and rainfall intensity. The event selection process allows different criteria to be applied to different spatial scales to enable localised thunderstorm type events to be identified along with events covering larger spatial extents but with lower rainfall intensities.

These events can then be exported in an appropriate format for use with existing drainage modeling software (InfoWorks CS) with appropriate rainfall time-series and antecedent conditions specified for each sub-catchment. The tool also calculates annual, seasonal and monthly rainfall depths and number of wet days, along with annual maximum series of rainfall depths for a specified critical duration to support Extreme Value Analysis.

Comparison with uniform rainfall
To enable an initial appraisal of the impacts of using spatially varying rainfall instead of uniform rainfall, a comparison using a model of one the project pilot study sites is being undertaken. The performance of the two methods is being compared in terms of the number of flood locations and the magnitude of flooding and will be reported along with the practicalities and implications of adopting a spatially varying rainfall approach in contrast to using uniform rainfall. Initial results from this appraisal will be included in the formal presentation at the ICUD conference.

RISK BASED APPROACH TO SEWERAGE SYSTEM PERFORMANCE

The probability of flooding is dependent upon system performance under different loading (rainfall) conditions, changes in system state over time including the possibility of pipes collapsing and pumps failing (as well as other issues such as urban growth, climate change and asset deterioration) and the characteristics of the local topography - which all add considerable complexity to the urban flood problem.

The contribution towards risk from different flooding sources and components of flooding pathways, including infrastructure components, is critical information to support risk-based decision-making. As part of this project new techniques are being developed to represent the potential variability in the system state as well as improvements in the representation of spatial and surface information, and provide scenario specific probabilities taking account of both the severity of a range of storm loadings and postulated system state (i.e. possible changes to the system within the whole drainage network). Traditional deterministic methods fail to capture this interaction to a limited degree, representing one system state for analysis and provide decision makers with very limited information.

In terms of looking at a risk-based approach to sewerage system performance, the following three activities are being explored in detail to support the development of a risk based procedure:

- Integration of spatial-temporal rainfall;
- Asset failure;
- Risk attribution.

An outline of the work being undertaken for each of these activities is provided below, along with an overview of the SAM – Urban Model Control Framework (SAM-UMC) which has been developed to enable the above activities to be undertaken.

Integration of spatial-temporal rainfall
The use of extended spatially varying timeseries potentially adds considerable computational expense to the risk calculation. Practical methods to overcome this problem are being explored through application to one of the project pilot sites. A methodology is being developed to identify a limited set of parameters to characterize the spatially varying rainfall events and use these parameters to identify a flooding threshold to enable events below that threshold to be excluded. The flood events are then classified in terms of the flood volume or damage they are responsible for and flood risk estimated on the basis of the frequency of events in each relevant class.

Asset Failure
Flooding resulting from sewerage systems is caused by both extreme rainfall that exceeds a system's capacity and as a result of the partial or complete failure of an asset (e.g. blockage or collapse of a pipe). As a result, the risk-based methodology needs to take into account both the probability of the occurrence of extreme rainfall events and asset failure, also considering that a large proportion of failures occur under Dry Weather Flow (DWF) conditions.

Fluvial and Coastal flood defence performance is now described using fragility (Dawson and Hall, 2003) which enables the strength assessment to be separated from the hydraulic loading regime. Depending on the level of analysis, the fragility can be estimated using a range of methods from expert judgement through to full reliability analysis. Sewer and drainage networks present a different problem as much of the infrastructure is sub-surface, making conditional failure probabilities difficult to estimate and also that failure is seldom just a function of the hydraulic load. Moreover, the performance of the pipe is not just limited to whether it has collapsed or not, but its degree of blockage.

Whilst the project is not undertaking specific research and analysis into failure mechanisms (and the factors that influence the likelihood of failure), a methodology is being developed that will make use of the best available information on this subject to allow asset failure to be included within the risk analysis.

However, including asset failure within the risk analysis also adds significant computational complexity to the problem. In a network with 5000 assets, and only considering two possible states for each asset (failed and unfailed), there are 2^{5000} potential system states. Obviously it is highly impractical to run all these combinations, and as part of the project, methods are being explored to decrease the number of simulations that need to be undertaken including identifying and excluding redundant combinations, random sampling (with consideration given to each asset's likelihood of failure) and the running of multiple, independent failures within a single run.

Risk Attribution

Several organisations are responsible for flood risk management and the contribution towards flood risk that specific flooding sources and components of flooding pathways (including particular infrastructure components) make is a critical piece of information to support risk-based decision-making and optimisation of intervention strategies (including inspection, maintenance, capital works etc.).

Risk attribution is therefore required to determine what proportion of risk is the responsibility of different organisations and to enable decision-making to target those assets that contribute most to flood risk and compare potential intervention measures with the cost of implementing those measures in order to develop an optimum intervention strategy.

Therefore, this project is investigating the use of alternative methods for risk attribution, including physically 'tracking' of flows from flood source (e.g. manhole) to the location of flooding as part of the model simulations along with sensitivity-based approaches.

SAM-Urban Model Control Framework (SAM-UMC)

To enable the risk based tools and procedure to be developed, the SAM-UMC risk model framework has been set-up as part of the project. The SAM-UMC incorporates the following:

- SAM-UMC interface;
- InfoWorks CS drainage model;
- RFSM Surface flow model (described below);
- Depth-damage functions.

The SAM-UMC framework allows external applications to modify the urban drainage system (currently a limited set of both 'failures' and 'interventions' are available), specify a rainfall event, simulate the below and above ground flow (as sequential non-dynamically linked processes) and output results in terms of flood volumes, depths and damages. This process is automated to enable a large number of simulations to be set-up and run automatically. A schematic representation of the SAM-UMC is presented in Figure 1.

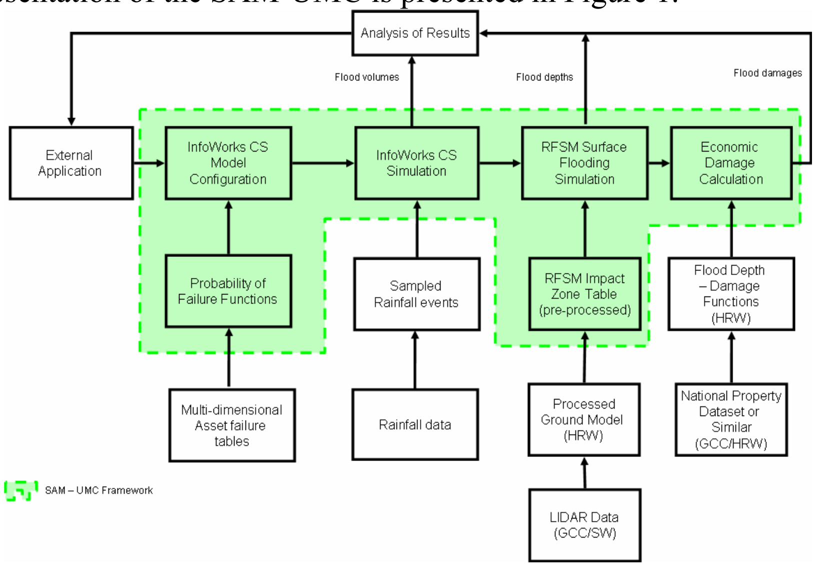

Figure 1: Schematic representation of the SAM-UMC framework

A RISK BASED PROCEDURE FOR MANAGING THE URBAN FLOOD SYSTEM

The urban flood system includes the physical process of flooding, the inhabitants of floodplains, their infrastructures and ecosystems, and the people and organisations in the public and private sector that influence or are subject to flooding and its impacts. This represents a spatial complex system that varies with time. To add further complexity the responses available to manage flood risk are numerous ranging from traditional engineering interventions above and below ground (i.e. defence strengthening, sewer enlargement) through to development control as well as risk transfer instruments such as insurance (Sayers, 2005).

To help overcome this complexity the Source-Pathway-Receptor conceptual model is widely used to assess and inform the management of environmental risks across Government. It has now been adopted to describe the coastal and fluvial flooding system (see Figure 2) and forms the central framework for risk assessment and management currently adopted within the Environment Agency.

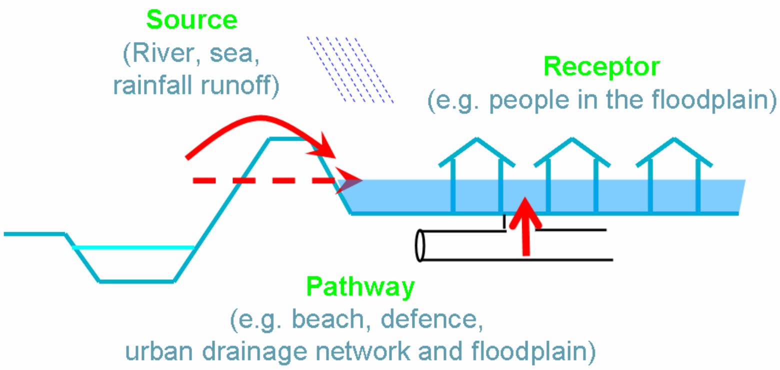

Figure 2: Source / Pathway or Barrier / Receptor can be used to breakdown the components of the flooding system (adapted from Sayers et al, 2002)

Sources of flooding can be fluvial, coastal or pluvial (intense rainfall), or a combination of all of these and the hazard posed by all of these is likely to be increasing due to climate change. Pathways of flooding include the processes (e.g. below and above ground systems) by which a connection is established between a particular source and a receptor (e.g. a property) that may be harmed.

Why adopt a Risk-based approach?

The benefit of a risk-based approach, and perhaps what above all distinguishes it from other approaches to design or decision-making, is that it deals with outcomes. Thus in the context of flooding it enables intervention options to be compared on the basis of the impact that they are expected to have on the frequency and severity of flooding in a specified area. A risk-based approach therefore enables informed choices to be made based on comparison of the expected outcomes and costs of alternative courses of action. This is distinct from, for example, a standards-based approach that focuses on the severity of the load that a particular asset has been designed for.

Risk-based options appraisal and design involves modifying the variables describing the flooding system in order to estimate the effect that proposed flood risk management options will have on flood risk. The risk calculation therefore requires probability distributions for the loadings (that include spatial, temporal and inter-variable dependencies), physics-based models of fluid flows from source to receptor and a mechanism for integrating loading distributions, uncertainties in the model parameterisation and damage functions in order to derive risk estimates.

The DTI SAM Risk-based Procedure

One of the key objectives of the DTI SAM project is to develop a risk based procedure capable of exploring the performance of multiple flood management strategies within a single coherent analysis framework. Achieving this represents a significant challenge. In particular, systematic techniques to enable options to be tested and appraised within the context of a large-scale and complex system of sources, pathways and receptors of flood risk need to be developed and proven.

Figure 3 provides a schematic overview of the steps that, depending upon the level of complexity being considered, may need to be undertaken. Figure 3 also highlights how the SAM-UMC risk model framework, developed as part of the project, supports the development and application of the procedure. Figure 4 highlights how it is envisaged the risk based procedure will be applied by end-users at a strategic planning level as part of an overall asset management function.

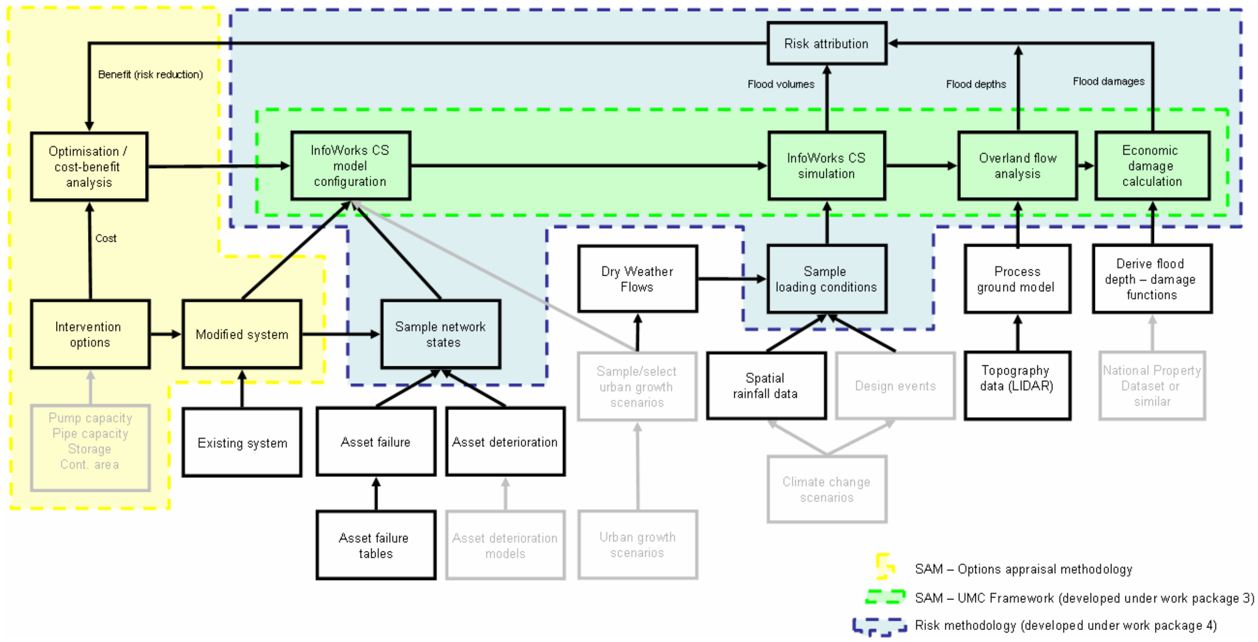

Figure 3: Schematic overview of the application of the procedure

However, to apply a comprehensive risk based approach is a significant change to existing practices and will require additional data to be collated and enhanced software packages to be developed. Further to this, including all potential factors in an analysis may not always be cost effective or necessary. Consequently, the risk based method is being developed so that it can be applied at different levels of complexity appropriate to the task in hand and the availability of computational resources and supporting data.

SUPPORTING SOFTWARE TOOLS

Currently, it is computationally very demanding to undertake the above analysis using existing tools due to the large number of simulations necessary. As a result, rapid simulation tools to enable the computational work necessary to be achievable are being developed as part of the project, including a rapid drainage network solver and a rapid overland flow tool.

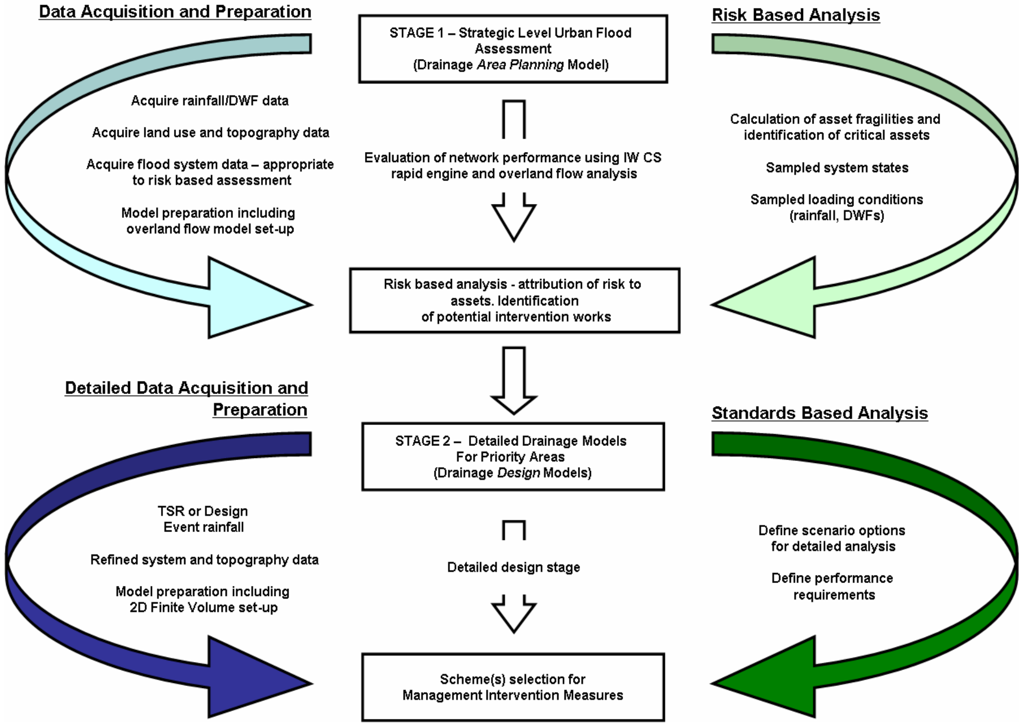

Figure 4: Conceptual overview of the system based approach to urban flood analysis

Rapid drainage network solver

Wallingford Software has explored alternative approaches for developing a rapid network solver that would significantly reduce simulation runtimes for urban drainage models. The approaches investigated have included evaluating the use of a packet solver approach and making simplifications and refinements to the InfoWorks CS software.

Initial results indicate that the use of a packet solver presents too many limitations for it's use on a typical drainage model but reasonable performance improvements can be made to the InfoWorks CS software to reduce resulting runtimes to help facilitate a risk based procedure.

Rapid overland flow tool (RFSM)

A rapid overland flood tool (RFSM) is being developed by HR Wallingford for use in the urban environment and below ground drainage systems. The RFSM enables flood volumes to be taken from the InfoWorks CS simulation and spread across the topography to determine flood depths across the catchment, with simulation runtimes significantly reduced in comparison to using other surface flow modelling packages. As part of the project, the performance of the RFSM will be compared to the more complex Info Works 2D software recently developed by Wallingford Software, to identify any areas for future refinement and development.

CONCLUSIONS

The DTI SAM project is focussing on meeting the needs of the urban flooding community in developing improved techniques for use in the design and management of urban flooding. In meeting these needs, a key emphasis of the project is to provide effective and practical procedures and tools for use within the drainage industry on completion of the project.

The project is making significant progress towards developing a systematic risk-based approach that will enable strategic decision-making to be made on the basis of consequences. This approach is significantly different to current practice which adopts a standards-based approach, in which drainage is designed to meet a specified level of performance.

The methodology will allow, for the first time, process-based quantified assessment of flood risks in urban areas which is an essential requirement for flood risk management and will support asset managers in the prioritisation of intervention works and in making the most cost effective use of available funds. The ability to attribute the solution to specific parts of the network means that drainage system ownership issues are not an impediment to finding the most appropriate solution.

As part of the project, a number of new tools are being developed including spatial and temporal rainfall stochastic generators (trained on radar data), a supporting spatial rainfall analysis tool, a rapid overland flow modelling tool for urban areas, a prototype drainage network solver to provide a rapid network simulation tool and the SAM-UMC modelling framework to link the drainage and overland flow models and a damage-inundation model to enable a large number of different model configurations (allowing for asset failures and alternative management interventions) to be evaluated automatically.

The procedures and tools, once developed, are also being applied to two pilot studies (Dalmarnock and Keighley) as part of the project.

ACKNOWLEDGEMENT

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