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An urban drainage flood risk procedure
A comprehensive approach

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AN URBAN DRAINAGE FLOOD RISK PROCEDURE - A COMPREHENSIVE APPROACH

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ABSTRACT

This paper describes the work being undertaken on the Dti SAM project (a 3 year research project completed in 2009) that developed a procedure and supporting tools to enable a risk based approach for assessing the consequences and cost of flooding and to attribute these costs back to the drainage system to enable effective management of drainage assets. This procedure has the potential to radically change the current approach to drainage management which is focused on system performance standards, and does not directly consider flood consequences or take into account potential systems failure.

The methodology allows, for the first time, process-based quantified assessment of flood risks in urban areas based on a range of system states, which is an essential requirement for flood risk management. The methodology not only looks at the performance of the system as it is designed to operate using all possible loading conditions (rainfall, river level), but also considers the risks associated with all possible system states; taking into account the possible collapse and blockage in pipe systems, which are responsible for up to half of all flooding incidences. The methodology is designed to allow an integrated approach which allows consideration of other systems to be assessed together with drainage systems, such as river and coastal flooding.

The procedure will enable asset managers to prioritise their investment and make the most cost effective use of available funds.

INTRODUCTION

In the last decade there have been a number of national and international flooding incidents which have elevated the importance of developing procedures and tools to address the massive amounts of damage and disruption of these events. With climate change promising even worse to come, this is a matter of considerable urgency.

The need for a system-based management approach and integration of stakeholders 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 were, however, not yet developed.

Therefore, this project aimed to produce new tools to model complex urban drainage systems to facilitate the delivery of a new procedure for an integrated flood risk management approach. The specific advances being made on this project cover the following technical topics:

- Application and evaluation of spatially varying rainfall to urban flood analysis;
- Development of a risk based approach for assessing sewerage system performance;

- Development of software tools to implement the risk-based procedure.

HR Wallingford has lead 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.

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 of 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 few 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 data used to calibrate the models.

3.5 years of recorded radar data at 1 km resolution was 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 to produce rainfall data at a resolution of 5 minute - 1km.

The method used by Imperial College to develop this time series involved 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. Radar data from the 3 different radar datasets and 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.

University of Newcastle has implemented and validated a catchment rainfall model at a temporal and spatial resolution of 1 hour – 5 km using a Poisson model (cut-down version of the Neyman-Scott Rectangular Pulse model) with a finer scale 1 km 5 min model to disaggregate the outputs of the first where more detail is required (i.e. over the urban area).

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	

The results have generally demonstrated the potential for generating stochastic spatial rainfall series with the models able to reproduce different features of various datasets and produce encouraging results in terms of reproduction of the observed rainfall statistics, although the accuracy of the data is not yet adequate for these tools to be used by industry at this stage. It is considered that one of the principal limitations is the length of the calibration data set. In 10 years time it is thought that these spatial rainfall tools will become part of the normal tool set used by the water industry.

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 rainfall and its impact.

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 time series which effectively addresses the particular reason for applying spatially varying rainfall to the network analysis.

As a result, a 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 modelling 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 has being undertaken. The performance of the two methods was compared in terms of the number of flood locations and the magnitude of flooding.

Results from this study have shown that the use of uniform rainfall tends to over estimate flood volumes and locations for large catchments. Although only based on one catchment, the results seem to indicate that the spatial nature of rainfall becomes important in producing significantly different results for catchments larger than 350 to 500ha.

RISK BASED APPROACH TO SEWERAGE SYSTEM PERFORMANCE

The benefit of a risk-based approach, and perhaps what above all distinguishes it from existing approaches to design or decision-making, is that it deals with consequences rather than the system performance. 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 consequences. A key feature of the method is that it is not limited to one or more specific levels of service, but considers a range of events from frequent to extreme. This is distinct from, for example, a standards-based approach that focuses on a specific load that a particular asset is expected to be able to serve.

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 analysing urban flooding problems.

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 have been 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 generally fail to capture these interactions, representing one system state for analysis and provide decision makers with very limited information on system performance. (
Figure 1).

The following three topic areas had to be addressed in detail to support the development of a risk based procedure:

- Asset failure;
- Risk attribution;
- Solutions based on optimisation techniques.

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 a risk based analysis to be made.

Asset Failure

Flooding resulting from sewerage systems is caused by both extreme rainfall that exceeds a system's capacity, and also 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 also asset failure, bearing in mind that a large proportion of failures occur during Dry Weather Flow (DWF) conditions.

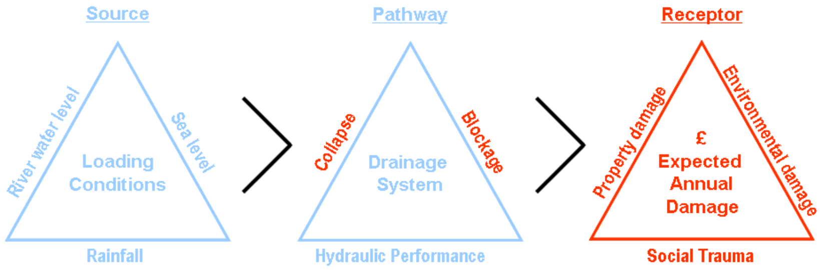

Figure 1: Additional value of a risk based approach

Fluvial and Coastal flood defence structures performance is now described using "fragility" (Dawson and Hall, 2003) which enables the strength of a structure to be defined as a probability distribution of the chance of failure linked to the hydraulic loading on it. 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 because failure is not strongly linked to hydraulic load. Moreover, the performance of the pipe is not just limited to whether it has collapsed or not, but its degree of failure.

Whilst the project is not undertaking specific research and analysis into failure mechanisms (and the factors that influence the likelihood of failure), a methodology has been developed that makes 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 pipes, 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 have been explored to find an approach which provides a reasonable system evaluation without the time of computation for carrying out the analysis becoming unrealistically long.

Risk Attribution

Because several organisations are responsible for flood risk management, risk attribution back to the system which is the source of the flood damage is required to assist in determining the relative responsibility of each of the various organisations. Therefore, this project has investigated 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.

It should be noted that the risk attribution back to the source is of no interest to those who get flooded. Therefore, the key driver of the development of an intervention strategy must be the reduction of the consequences to the receptors and not the reduction of the attributed damage values.

Solutions based on optimisation techniques

One of the key achievements of the Dti SAM project was to develop a risk based procedure capable of exploring the performance of multiple flood management strategies within a single coherent analysis framework through the use of a genetic algorithm in order to identify solutions that offer a good balance between cost and the level of risk reduction.

There are a number of ways that solutions can be developed using genetic algorithm techniques; the three principal methods are:

- Development of the most effective reduction of flood damage for a given budget;
- Find a solution which provides the greatest cost/benefit ratio;
- Find the least cost solution for reducing the expected annual damage to a given level or the minimum value possible.

The procedure was trialled on a part of Scottish Water's Dalmarnock sewer system that serves part of the Glasgow conurbation. In the test carried out, the third of these options was applied.

Figure 2 illustrates the process showing the continuously reducing value of expected annual damage against the "best" capital investment solution derived as the analysis progressed.

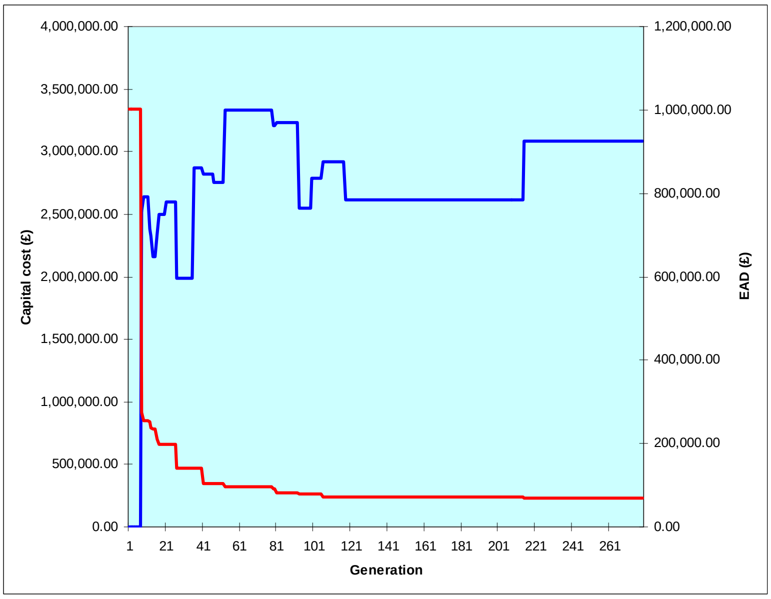

Figure 2: Risk based optimisation results

IMPLEMENTATION SOFTWARE TOOLS

Currently, it is computationally very demanding to undertake this risk based analysis using existing tools due to the large number of simulations that are needed. As a result, rapid simulation tools to minimise the computational time to do the analysis have being developed as part of the project, including an Urban Model Control framework (SAM-UMC), a rapid drainage network solver and a rapid overland flow tool.

SAM-Urban Model Control Framework (SAM-UMC)

To enable the risk based tools and procedure to be applied, the SAM-UMC risk model framework was created as part of the project. It incorporates the following:

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

The SAM-UMC framework allows external applications to modify the urban drainage system, 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.

Figure 3 highlights how the SAM-UMC risk model framework, developed as part of the project, supports the development and application of the procedure.

Rapid overland flow tool (RFSM)

A rapid overland flood tool (RFSM) has 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 has been compared to the more complex InfoWorks 2D software to justify its accuracy.

CONCLUSIONS

The Dti SAM project focussed 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 was to provide effective and practical procedures and tools for use within the drainage industry.

The project made significant progress towards developing a systematic risk-based approach that enables 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 allows, for the first time, process-based quantified assessment of flood risks in urban areas which is an essential requirement for flood risk management and supports 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 were 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 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.

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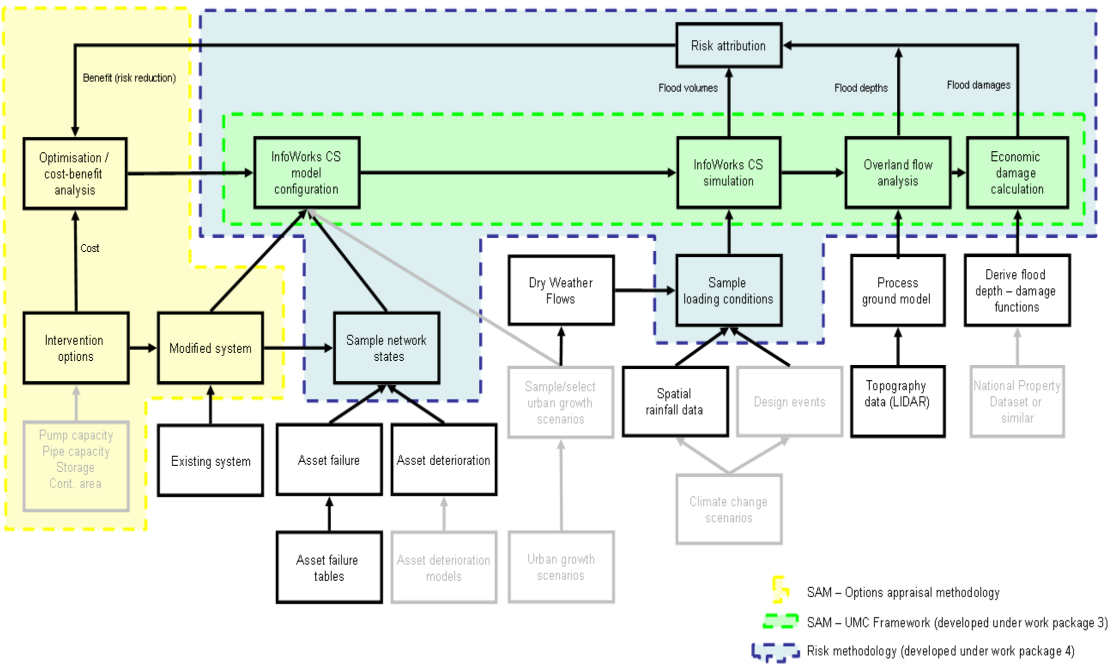

Figure 3: Schematic overview of the application of the procedure

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