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Management of urban flood risks-the development of a risk-based method

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MANAGEMENT OF URBAN FLOOD RISKS-THE DEVELOPMENT OF A RISK-BASED METHOD

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Key Words

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

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. In particular this presentation focuses on the risk methodology for attributing the Expected Annual Damage (EAD) to every part of the system, to enable the engineer to address its performance limitations.

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. These incidences just highlight the pressure water companies are already under 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.

This paper outlines very briefly all the various aspects of the study, and principally focuses on the risk based methodology.

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	

Development of stochastic tools for producing 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 catchment as rainfall is spatially very varied across a large area (especially for extreme events). The use of spatially varying rainfall offers the potential for this variability to be represented in studies for large catchments and would also explicitly 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. However its use for analysing the sewerage system for flooding is inadequate as a rainfall series in excess of 100 years would be needed to get a sufficient representation of the extreme loading conditions needed.

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.

The results of this exercise have shown limited success, but this is thought to be mostly due to the limited radar data set available, though the techniques used also have their limitations. This result has implications for the rest of the project as it is important to use existing more robust forms of rainfall representation to enable a useable procedure to be developed.

Development of tools for application of stochastically generated spatially varying rainfall data

The 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 rainfall time series which effectively samples relevant events and processes this information into a form which can be used in current drainage tools.

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.

Comparison of the impact of spatial rainfall with uniform rainfall on drainage systems

Although it is known that uniform rainfall is inapplicable to large drainage systems, no measurement has taken place of the implications of this assumption. The project has therefore investigated this aspect using traditional design rainfall, continuous time series with uniform rainfall across the catchment and also spatially and temporal continuous series.

The results do show that flood damage is over-predicted using uniform rainfall and a measure of the difference compared to spatially varied events have been quantified.

A risk based procedure for managing the urban flood system

The benefit of a risk-based approach, and perhaps what above all distinguishes it from a design standard approach, 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. A standards-based approach focuses on the severity of the load and not its impact.

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 a measure of the impacts.

The core objective of the DTI SAM project is to develop a risk based procedure for urban drainage systems that are capable of informing asset managers of the performance of the whole drainage system in terms of the impact of "failure" and to explore multiple flood management strategies within a single coherent analysis framework. At this stage the project aims to achieve the attribution of risk to the existing system to inform engineers about the system's characteristics, while developing optimal methods for assessing management strategies will only be developed in outline.

The critical challenges of developing such a procedure are:

- the massive computational requirements implicit in analysing the system using a risk approach, and
- the requirement for additional tools to allow an impact assessment to be measured

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. If a time frame is included, then asset management needs to also give consideration to other issues such as urban growth, climate change and asset deterioration. This time based component is not being considered in the project, and it is likely that any future system state would be assessed as a "steady state" condition rather than as a continuously varying state with a range of changes applied, simply because of the number of variables and the computational demands this would make.

To develop a complete risk-based approach to sewerage system performance it is necessary to consider both the system state as it is designed to perform (no system failures), but also to consider all other possible system states (pipe collapse and blockages). Also the drainage system has to be directly linked to the impact of failure and therefore attribution of the "damage" has to be made to each part of the system.

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 around 50% of flooding is associated with "failure" of the system, any procedure must include for this aspect. As a result, the risk-based methodology has taken into account both the probability of the occurrence of extreme rainfall events and asset failure, and also considers the large proportion of failures that occur under Dry Weather Flow (DWF) conditions.

The project is not undertaking specific research into failure mechanisms (and the factors that influence the likelihood of failure), but a methodology is being developed based on best available information on this subject from current research into asset failure. Correlation factors have been developed separately for blockage and collapse mechanisms.

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 (blocked, collapsed and un-failed), there are 3^{5000} potential system states. Obviously it is highly impractical to run all these combinations, and a method has been developed to select the relevant system states to be investigated.

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 or where expenditure might be most effectively spent.

The project has therefore developed a method of risk attribution, physically 'tracking' of flows from flood source (e.g. manhole) to the location of flooding. The damage associated with the flooding is computed using a depth/ damage / land use model.

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, 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.

As the procedure is computationally very demanding, existing tools have been modified and new tools developed.

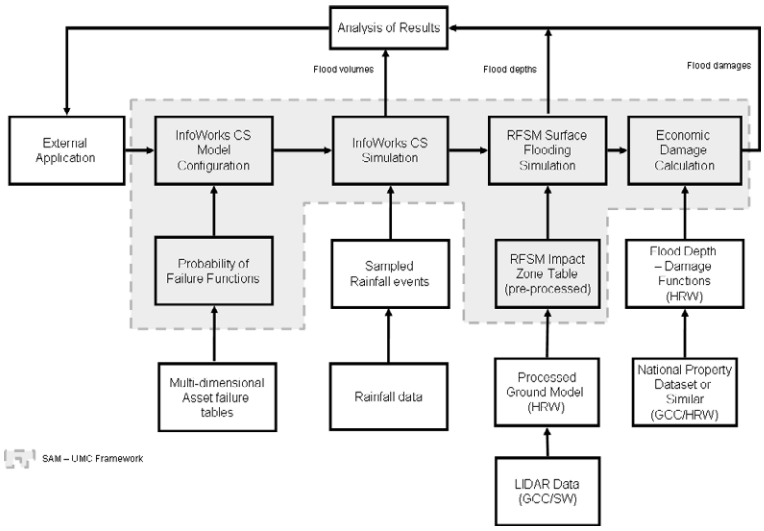

Figure 1 Schematic representation of the SAM-UMC framework

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. As a result of extensive research considering a range of different methods, only a limited speed gain has been achieved. This is primarily due to the continuing need for stability, reasonable accuracy and the ability to run systems which describe all possible drainage asset types.

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 assess its accuracy and identify any areas for future refinement and development.

The risk procedure methodology

This risk methodology has to take into account:

- Flooding from the un-failed system as well as blocked and collapsed drainage assets;

- The huge computational demands of considering all system state possibilities; and
- The limited accuracy / availability of certain data sets to allow the procedure to be used now.

To meet the last of these requirements the procedure has been developed to use both continuous spatial and temporal rainfall (which has been shown to have had only limited success in this project), and also use design storms. It should be noted that stochastically generated non-spatial rainfall tools have been shown to be sufficiently accurate and these could be used in lieu of the spatial series developed under this project.

Flooding resulting from sewerage systems is caused by both extreme rainfall that exceeds a system's capacity and/or partial or complete failure of an asset (e.g. blockage or collapse of a pipe). In this procedure, only total blockage or collapse is assumed. As this is an area of great uncertainty anyway, considering partial blockage is not seen as being of any value. The approach taken to address these various conditions has been to separate out the problem into 5 parts.

1. The un-failed system state assessed with extreme rainfall
2. The potentially "blocked" system states with all rainfall
3. The potentially "collapsed" system states with all rainfall
4. The potentially "blocked" system states with no rainfall
5. The potentially "collapsed" system states with no rainfall

The reason for breaking the analysis down into 5 parts is to minimise computational time and is explained later. Figure 2 illustrates the approach. As can be seen in the figure, shading indicates that it is assumed that many system states will not need to be analysed and that many rainfall conditions will not need to be assessed for the un-failed system. It is anticipated that in breaking down the system analysis into these sub-sets it will be computationally more efficient in getting convergence on damage costs (EAD – Expected Annual Damage) for all parts of the system.

These assumptions will be tested during the procedure development.

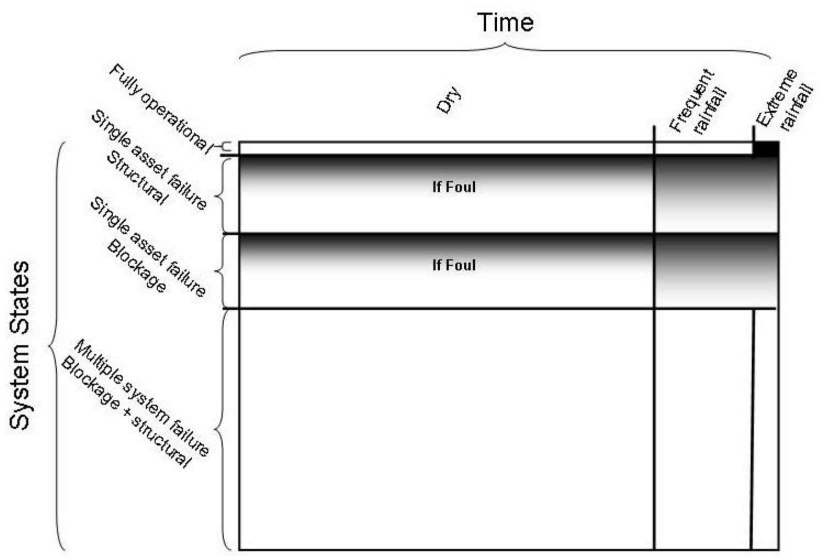

Figure 2 system analysis sub-sets

A The un-failed system state

Hydraulic failures of the un-failed system state are a function of the networks inability to cope with extreme events. Most rainfall (up to a 1 year return period or greater) will not result in any flooding. Thus rainfall from a continuous series need only consider a very limited number of events to assess its flooding performance characteristics. Similarly using design storm events, a limited data set is also required.

A-1 Design event (FEH) rainfall method

The use of FEH rainfall events explicitly defines the return period and therefore the probability of occurrence of every event.

Damage per return period (D_{rp})

Because events with the same return period will have the same probability of occurrence, a damage can be calculated for each return period (D_{RP}) with the expected annual damage for this return period (EAD_{RP}) being:

$$EAD_{RP} = D_{RP} \times \Pr ob_{RP}$$

Also, as we can see on the following graph, we know that for any return period, the maximum flood volume at any given node or group of nodes is associated with a specific duration.

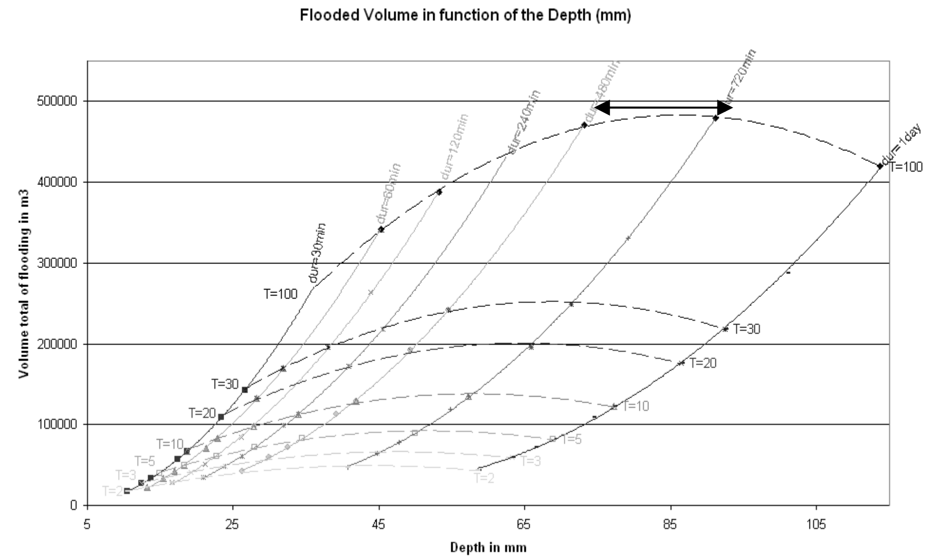

Figure 3 Influence of return period and duration on flood volumes.

All relevant durations for a system will need to be run as the critical duration at the top of the system will be in the region of 15 to 30 minutes, while it will lengthen to around 6 hours or more at the bottom end of large networks. Each part of the system will need to establish and use flooding from the critical duration.

Expected annual damage

Having calculated EAD for each return period, a simple calculation is needed to take account of all possible return periods.

Because it is not possible to simulate every single return period, a trapezoidal method will be used:

$$EAD = \sum_{j=1}^{n} \frac{\left| D_{RP}(q_j) + D_{RP}(q_{j+1}) \right|}{2} \times \left[F(q_{j+1}) - F(q_j) \right]$$

In practice, the simulations will start using a return period of 1 or 2 years (having established a threshold for no flooding) and increase return periods by stages until the additional damages at each node reduces to a marginal increase (around 1 to 5%). It is anticipated that this would normally be less than the 100 year return period, but this remains to be established, and will be different for each system being assessed.

The design storm un-failed system state methodology can therefore be summarised in the following flowchart:

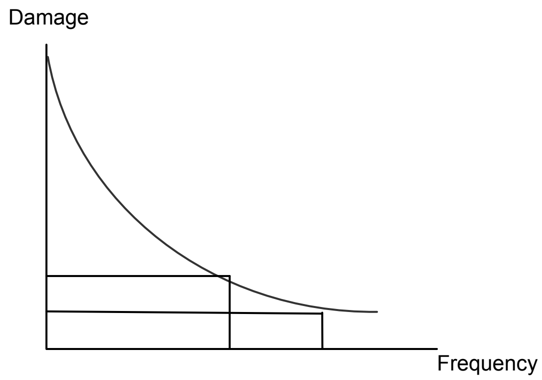

Figure 4 Damage frequency curve

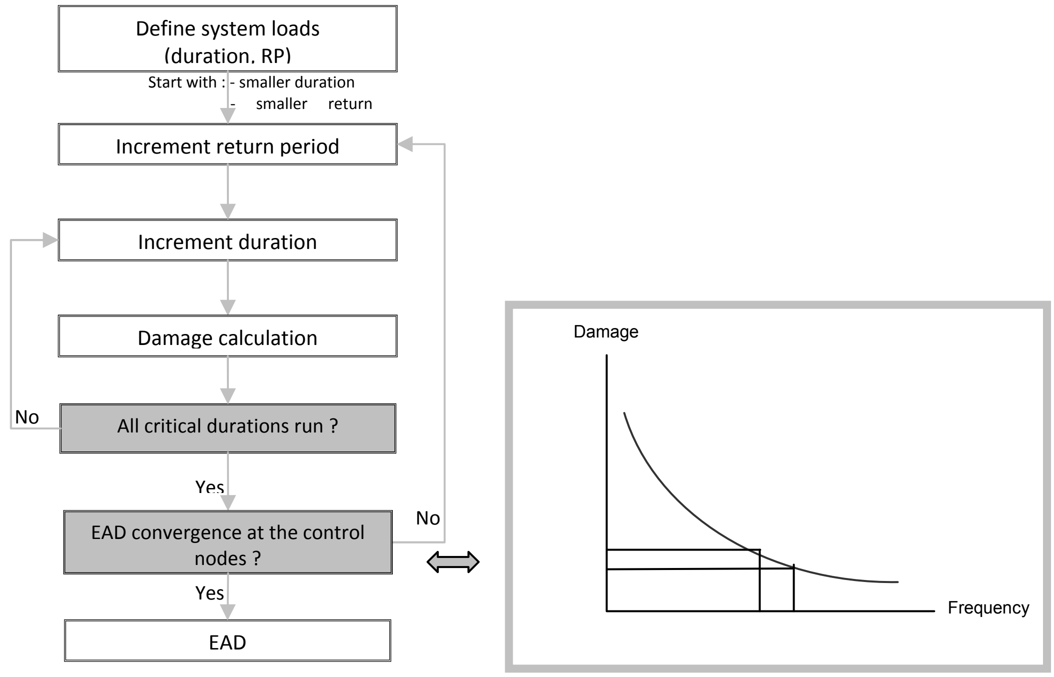

Figure 5 Methodology for un-failed system state using design rainfall events

A-2 Continuous rainfall method

Contrary to the design event method, every event in a continuous rainfall series is unique and does not contain a defined return period. Each event is effectively equally likely. As flooding will only take place in relatively extreme events, the continuous series can be processed to find events above a defined threshold and all remaining events can be ignored. In practice this means that only around 100 to 400 events are relevant, which significantly limits the computational requirements to obtain convergence.

The EAD would then be the sum of all the damages divided by the number of years of data:

$$EAD = \frac{1}{Length\ of\ data\ in\ year} \sum_{j=1}^{n} D$$

The above expression can be rewritten as follows with D_{avg} representing the average damage after all runs.

$$EAD = \frac{1}{Length\ of\ data\ in\ year} \sum_{j=1}^{n} D = \frac{number\ of\ events}{Length\ of\ data\ in\ year} \times D_{avg}$$

The more runs that are performed the more accurate D_{avg} becomes. Once convergence to a certain limit is achieved (degree of change), simulation can then stop. This can be linked to every node in the system, or to control points or an area of the system, when not all the network is of equal importance. This means that the analysis will not necessarily need to run all the loading conditions (rainfall events).

Further analysis may result in finding a surrogate storm return period event (probably between 2 and 5 years) which provides a similar damage cost to the EAD value. It is likely that this value will range fairly widely between all the system assets as sewerage systems develop local points of hydraulic weakness due to the relatively random process of growth of the system over time.

The continuous series methodology can be summarised as shown in Figure 7.

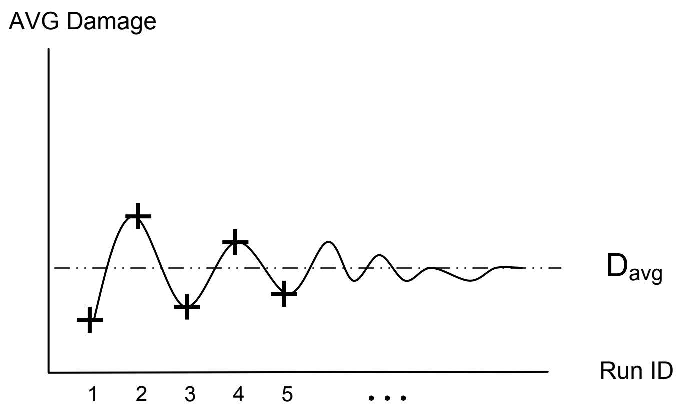

Figure 6 Iterative calculation of the average damage

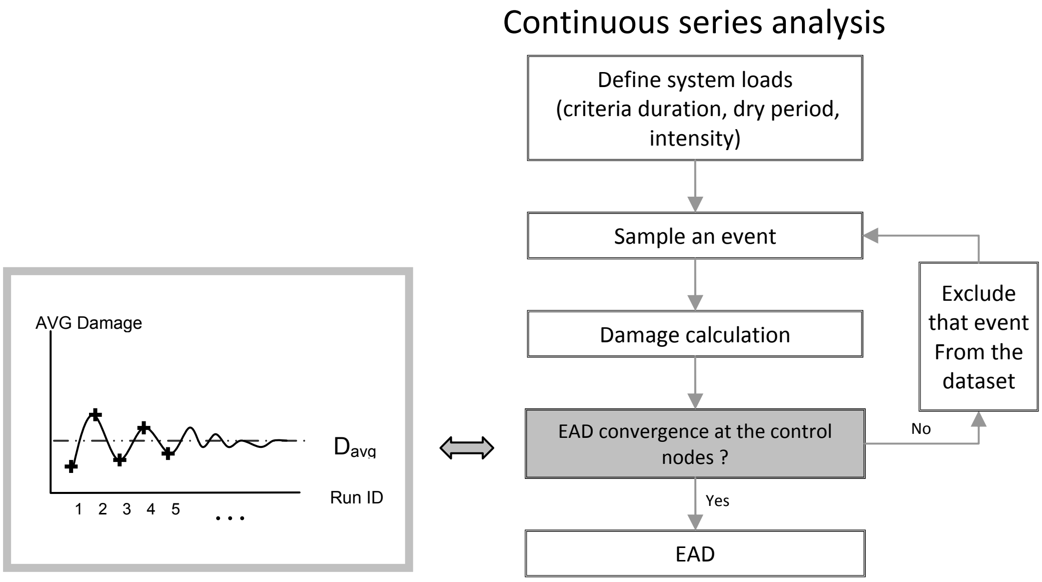

Figure 7 Methodology for un-failed system state with continuous series rainfall

B Asset failure: blockage and collapse.

System loads

Unlike the un-failed system state, an asset failure can generate flooding from any rainfall event and even during dry weather if it is a combined sewer. This means that all return periods from very small to very large (design storm methodology) need to be considered. Similarly all rainfall events in a continuous series will cause flood damage to some degree.

System states

To be able to calculate an EAD due to blockage or collapse, all the different possible network scenarios should theoretically be considered. For example, if the network contains 5000 pipes, there are 5000 system states with one blockage in the system and another 5000 with one pipe collapsed. If all possible combinations of failures are considered then there are 3^{5000} possible options. It is therefore important to limit the number of scenarios which need to be considered.

There are two principle approaches that can be used to develop a ranking process of possible system states. The first is the use of a Genetic Algorithm (GA) while the second is based on a simple assumption that the flood damage is a function of the probability of failure and the damage cost from say 6 or 12 hours of each asset failing. This second method assumes that two asset failures at the same time are so unlikely as to have a minimal impact on the assessment of EAD at any point in the system. This may need refinement at pumping stations where multiple failure of pumps may take place.

The advantage of this second approach is that the simulation model need not be run and only the RFSM used to assess the flood damage based on the pipe full capacity of the pipe discharging at the upstream node of the asset that fails factored by its probability of failure. A very rapid assessment of the ranking of the blocked or collapsed pipes can be developed in this manner. The subsequent analysis will show whether this simple approach is adequate in targeting the appropriate failed system states.

This approach can also be applied to “dry weather” failure when there is foul flow in the system, but using the dwf in the “failed" pipe. The frequency of a dry weather event can be assumed to be equal to 100% of the time as rainfall only occurs for between 5 and 10% of the time across most of the UK.

The ranking of blocked and collapsed pipes are likely to be very different as their respective failure probabilities will be very different due to the difference in the parameters that cause failure. However the RFSM analysis will be common to both. In addition the damage cost of rectifying the pipe state will have a different cost which will also need to be included.

The ranking calculation is therefore:

- Ranking of failed pipes during wet weather = $Prob_{failure}$ x $Damage_{6hr\ conveyance\ capacity}$
- Ranking of failed pipes during dry weather = $Prob_{failure}$ x $Damage_{6hr\ dwf}$

Each failed system state will only flood from one or two manholes. The additional EAD value for each failed system state could be compared to the un-failed system state to determine when to stop picking the next ranked system to run when the percentage increase in damage is small. However as some parts of the un-failed system may have very high values of EAD while others very small values, it is probably better to base it on a percentage (1% or 5%) of the average or top 10%ile EAD value for the un-failed system. This will avoid either premature termination or extending the number of runs unnecessarily. Although there may be systems that remain untested where the EAD value associated with failed pipes may be as high as the un-failed system, these parts of the system are likely to be of limited interest in terms of asset management and intervention requirements.

To test the adequacy of the ranking, a check can be made on the variability of the EAD values obtained down the ranking table.

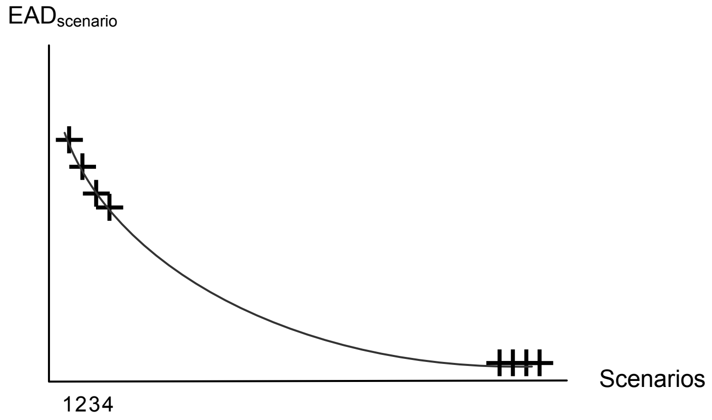

Figure 8 Evolution of scenarios' expected annual damages

Analytical approach to asset failure

The same methods defined for the un-failed system state can be applied on the failed system states with a few differences:

- Because all rainfall events need to be considered, all rainfall events need to be sampled, in excess of 100 times the number of events for the un-failed state.
- The majority of the network will not suffer from flooding with only one or two nodes requiring convergence.
- The dry weather scenario will only require one run to establish the EAD value.

The expected annual damage for each failed state ($EAD_{scenario}$) will therefore be the sum of EAD_{wet} and EAD_{dry} for both the blocked and collapsed condition. The number of events needed to be run to achieve an EAD value is unclear and remains to be determined.

The asset failure methodology can therefore be summarised in the following flowchart:

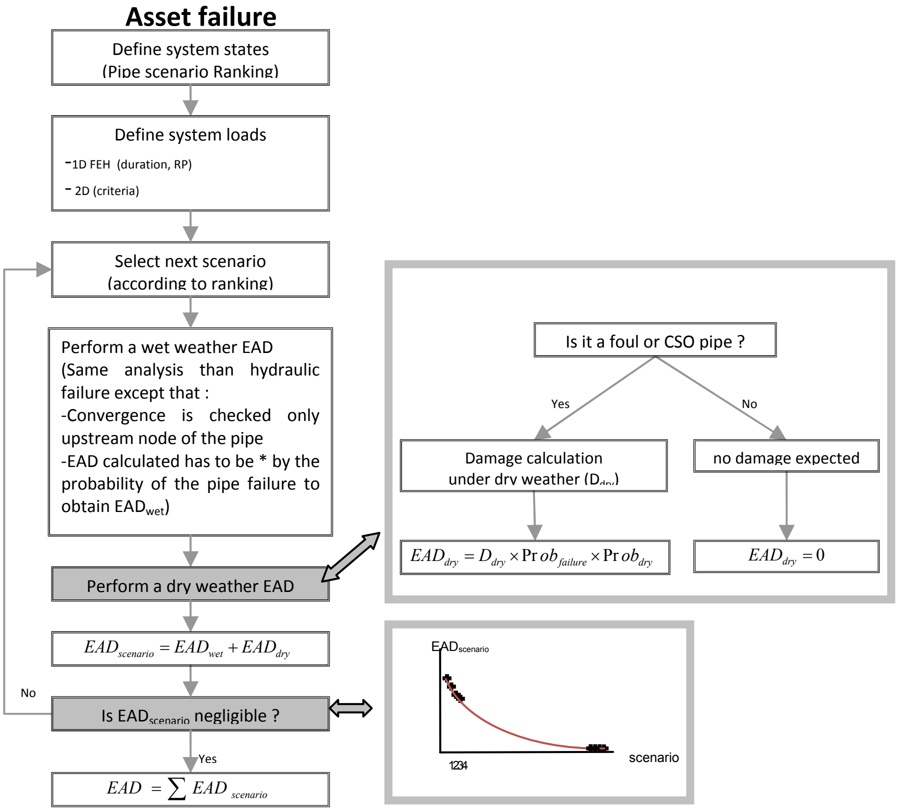

Figure 9 Methodology for system asset failure design events and continuous rainfall

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.

Acknoweldgements

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NOTES

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