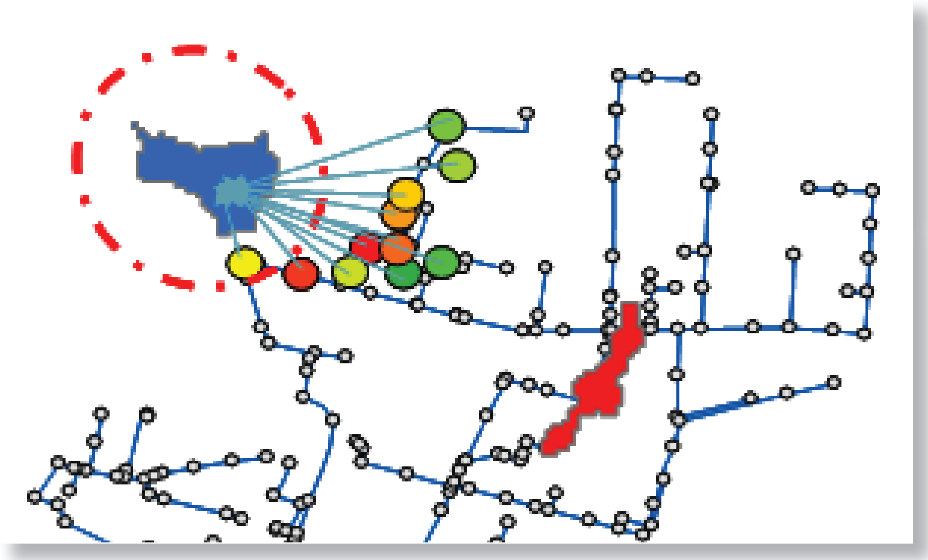
HR Wallingford
Working with water

SR 700

SAM – System-based analysis and management of urban flood risks

A new procedure for performance assessment of sewerage systems



Report SR700
Release 1.0
December 2009

Document Information

Project	SAM Based Analysis and Management of Urban Flood Risks
Report title	A New Procedure
Client	Dti
Client Representative	R Wolstenholme
Project No.	MCS0441
Report No.	SR 700
Project Manager	R Kellagher
Project Director	P Sayers

Document History

Date	Release	Prepared	Approved	Authorised	Notes
23/12/09	1.0	YC	RK	RK	First issue
28/01/13	1.0	YC	RK	RK	Authorised copy

Prepared

Approved

Authorised

Summary

SAM Based Analysis and Management of Urban Flood Risks

A New Procedure

Report SR 700
December 2009

This document is aimed at summarising a new procedure for drainage system analysis which is based on the assessment of risk, rather than focusing on the performance of the network. This enables investment decision targeted more effectively to areas of greatest need.

Contents

Title page i
Document Information ii
Summary iii
Contents v

1. Introduction ... 1
   1.1 Drainage methods; the past to the present day ... 1
   1.2 Present and future challenges of urban flooding ... 2
   1.3 Risk assessment – the concept and its development ... 2
   1.4 The research project ... 3
      1.4.1 Current limitations and assumptions used in drainage analysis ... 4
      1.4.2 Computational speed limitations ... 4
      1.4.3 Risk Procedure tools ... 5
      1.4.4 Development of solutions ... 5
      1.4.5 Project tasks and deliverables ... 5

2. A Risk based approach to urban flood management ... 6
   2.1 All possible system states performance measured in term of consequence ... 6
   2.2 Integration of spatial rainfall ... 7
   2.3 Asset Failure ... 8
   2.4 Network and Risk Attribution ... 8
   2.5 Additional data requirements ... 9
   2.6 DTI SAM Risk-based procedure overview ... 9

3. Risk based analysis methodology (EAD evaluation) ... 11
   3.1 Hydraulic failure (single system state) ... 11
      3.1.1 Design storm rainfall (FEH type) ... 11
      3.1.2 Timeseries rainfall ... 13
   3.2 Structural failure (all system states) ... 14
      3.2.1 Design storm approach (FEH type) ... 15
      3.2.2 Timeseries rainfall ... 18

4. Supporting Software Tools ... 19
   4.1 SAM-Urban Model Control Framework (SAM-UMC) ... 19
   4.2 Rapid drainage network solver ... 19
   4.3 Rapid overland flow tool (RFSM) ... 19
   4.4 Damage calculation ... 20
   4.5 Risk shell ... 20

5. Application of the procedure ... 20
   5.1 Running the tools ... 20
   5.2 Output information ... 21
      5.2.1 EAD for the drainage system ... 21
      5.2.2 EAD for all system states and only ‘failed’ system states ... 22
      5.2.3 EAD for impact zones ... 23
      5.2.4 Flood frequency ... 24

6. Solution development ... 25
   6.1 Traditional scheme development ... 25
   6.2 Optimisation techniques to scheme development ... 25

Contents continued

7. Future development of risk based management of urban drainage systems 26
7.1 Regulatory measurement of drainage system performance 26
7.1.1 Water quality 27
7.1.2 Resilience and National Productivity 27
7.2 Future developments to the procedure and tools 27
7.2.1 Incorporation of Uncertainty 28
7.2.2 Spatial rainfall 28
7.2.3 Future change and system transition analysis 28
7.2.4 'Failed' system states 28
7.2.5 Other sustainability measures 28
7.2.6 Tool developments for optimisation methods 28
7.2.7 Integration of flood spreading with the drainage system 29
7.2.8 Depth – damage information and floor levels 29

8. References 29
8.1 Impact Zone Outputs 54
8.1.1 Manholes EAD distribution 54
8.1.2 Impact zone EAD 55
8.2 Assets failure results 61

Tables

Table 1 Project partners 6
Table 2 Model characteristics 43
Table 3 Pipe system 44
Table 4 subset model characteristics 44
Table 5 Catchment EAD using reduced matrix of events 48
Table 6 Manholes EAD using reduced matrix of events 49
Table 7 Critical duration and damage associate for the seventh critical manholes at each return period (using 20 Durations and 35 return periods) 49
Table 8 Improvement of manholes EAD using reduced matrix of events – Threshold of flooding of each manhole 50
Table 9 Improvement of manholes EAD using reduced matrix of events – Capturing the critical duration of each manhole 51
Table 10 Example of probabilities of collapses and blockages 59
Table 11 Example of the impact of dry weather flows on EAD 60
Table 12 Validation of inflow file utilisation in EAD evaluation 61
Table 13 Validation of structural failure analysis with 0% probability of failure (using hydraulic failure tool) 61

Figures

Figure 1 Source / Pathway or Barrier / Receptor can be used to breakdown the components of flooding system 3
Figure 2 Additional value of a risk based approach 7
Figure 3 Identification of extremes (red) and frequents (green) events from a rainfall timeseries (Appendix 1) 7
Figure 4 Example of allocation back to manholes of damage done to receptors (Appendix 2) 9
Figure 5 Schematic overview of the application of the procedure 10

Contents continued

Figure 6 Conceptual overview of the system based approach to urban flood analysis 10
Figure 7 Influence of return period and duration on flood volumes 12
Figure 8 Integration of the Expected Annual Damage based on annual probability of non-exceedance 12
Figure 9 Methodology for un-failed system state using design rainfall events...................... 13
Figure 10 Methodology for un-failed system state with continuous series rainfall 14
Figure 11 Difference in duration(s) processed according to the system state picked for a return period (Appendix 1) 15
Figure 12 EAD calculation progression for structural failures analysis (Appendix 1) 16
Figure 13 Methodology for structural failure analysis with design storm rainfall.................. 17
Figure 14 Time periods of time-series for assessing system states damage 18
Figure 15 Time slice damage evaluation process.. 18
Figure 16 EAD attribution for a network 21
Figure 17 Expected annual damage per pipe group (a) and per unit length of pipe (b) 22
Figure 18 Illustration of impact zones' EAD map 23
Figure 19 Impact zones' flood frequency map 24
Figure 20 Manholes flood frequency map 25
Figure 21 Risk based optimisation results.. 26
Figure 22 Integration of the Expected Annual Damage based on annual probability of non-exceedance 34
Figure 23 Example of Expected Annual Damage curve using a design storm event approach.. 35
Figure 24 Identification of extreme events from a rainfall time series against an Intensity-Duration flooding threshold analysis of the drainage system 36
Figure 25 Example of Expected Annual Damage curve for time series rainfall approach 37
Figure 26 Difference in duration(s) processed according to the system state picked for a return period.. 38
Figure 27 EAD calculation progression for structural failures analysis 38
Figure 28 Time periods of time-series for assessing system states damage 39
Figure 29 Illustration of the different cases rainfall into a time slice..................................... 40
Figure 30 Time period damage evaluation process.. 40
Figure 31 Dalmarnock Infoworks CS model 43
Figure 32 Dalmarnock pilot study model.. 44
Figure 33 Dalmarnock combined, foul and storm pipes system 45
Figure 34 Pilot study Expected Annual Damage 46
Figure 35 Catchment Expected Annual Damages profiles for a range of durations 46
Figure 36 Catchment Expected Annual Damage using a single duration for all return periods 47
Figure 37 Variation of targeted manholes according to duration considered 47
Figure 38 Variation of damages according to duration considered.. 48
Figure 39 Damages at 2 manholes for different durations for a range of return periods 50
Figure 40 Dalmarnock catchment flooding threshold... 52
Figure 41 Damages due to the selected 97 extreme events... 52
Figure 42 Dalmarnock Expected Annual Damages using Time series events........................ 53
Figure 43 Convergence of manholes Expected Annual Damages 53
Figure 44 Comparison of Dalmarnock EAD using design storm or time series rainfall 54
Figure 45 Example of damage locations identification (Impact Zones) 54
Figure 46 Distribution of damages due to a manhole across impact zones 55
Figure 47 Catchment map of Expected Annual Damages 55
Figure 48 Illustration of the difference in focussing manholes and impact zones 56

Contents continued

Figure 49 Manholes contributions to one of the top 5 impact zones....................................... 56
Figure 50 Impact zones flood frequency map (all return periods) 57
Figure 51 Impact Zones flooded by events up to a 50 years return period 57
Figure 52 Validation of the conversion of dry weather flows into inflow file......................... 61
Figure 53 Catchment assets failure EAD comparing to Hydraulic failure EAD...................... 62
Figure 54 Influence of the blockages and collapses on the manholes EAD (using very high probabilities of failure) 62
Figure 55 Influence of the blockages and collapses on the catchment EAD (using unrealistic probabilities of failure)... 63
Figure 56 SAMRisk I user interface... 67
Figure 57 SAMRisk II user interface 70

Appendices

Appendix 1 Risk calculation – mechanics and mathematics.. 33
Appendix 2 Dalmarnock pilot study... 43
Appendix 3 SAM-Risk tool... 65

1. Introduction

This section outlines the current challenges with regards to urban drainage and the control of flooding and looks at this in the context of past and present technical developments. It highlights the need to move on from the use of current methods by taking advantage of recent technological improvements to manage drainage assets in a completely new way to best address the flood management issues facing engineers.

1.1 DRAINAGE METHODS; THE PAST TO THE PRESENT DAY

Analysis methods for understanding the behaviour of drainage networks have evolved over the last 50 years from not really being able to predict system limitations (with total reliance on local knowledge of the system) through to the ability now of being able to predict location, frequency and depth of flooding. There are still areas where the science still needs to be progressed, but engineers now have the tools to meet the needs of the modern urban environment (subject to the availability of the necessary data) for both understanding the impact of the effects of rainfall and other loads on drainage systems and to provide solutions to mitigate their effects.

The development of the technical capability to understand and design drainage systems has tended to be by step changes linked to technological advances.

1. The Rational Method was dependent on developing an understanding the frequency of rainfall along with an ability to calculate pipe-full flows.
2. The TRRL Road Note 35 was an initial exploration into the use of computers using routing techniques to look at network capacity though it was targeted at being used as a manual methodology.
3. In 1981, the Wallingford Procedure arrived along with the micro-computer, which allowed the simulation and evaluation of the hydraulic performance of drainage systems.

Since the development and successful take-up of the Wallingford Procedure there have been advances in the ability to analyse bigger systems and more complex networks, but in principle there has not been a major change in the approach to drainage systems analysis – until now.

The recent advances in the ability of LiDAR to provide low cost high quality ground level information, together with the development of stable and fast 2D overland flow modelling, has allowed the development of reasonably accurate ways of assessing the impact of drainage systems for events which exceed the system capacity. Up until this time the impact of sewerage incapacity (flooding) could not be easily evaluated. This development comes at a time when organisations such as the Environment Agency have been promoting the need to develop risk based tools and apply a risk based approach to all relevant studies.

This emphasis on risk methods resulted in a research project to develop a new procedure for assessing and managing sewerage systems which is focused on consequences (probability and hazard impact) rather than achieving a specific level of service performance for the network. This guide provides a summary of this procedure along with an explanation of tools developed, data requirements and how studies should be carried out.

1.2 PRESENT AND FUTURE CHALLENGES OF URBAN FLOODING

Serious flooding in the UK and elsewhere in the world over the last 10 years has led to increased attention on urban flooding in particular and has highlighted the need to better understand and manage urban flood risk. The threat that climate change will enhance flooding problems over the coming decades lends added urgency to the development of appropriate methods and tools for addressing this problem in as cost effective a manner as possible. In particular sewerage undertakers have been under increasing pressure over the last decade to reduce the number of flooding incidents as a result of inadequate drainage system capacity and asset failure.

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). These reports have also 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 new procedure has been developed specifically in recognition that flooding has to be managed in an integrated manner, and has to involve all stakeholders. The procedure, although developed specifically for urban drainage systems, has a common root to other relatively new risk based procedures addressing coastal and fluvial flooding and allows an integrated approach to be taken for studies involved in any form of flood analysis.

In addition to the pressure to find an improved procedure which is based on a system and a risk based approach looking at hydraulics, other considerations such as sewer aging, climate change, carbon use reduction, resource consumption and major growth in cities need to be able to be incorporated into the method.

1.3 RISK ASSESSMENT – THE CONCEPT AND ITS DEVELOPMENT

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.

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 1) and forms the central framework for risk assessment and management currently adopted by the Environment Agency.

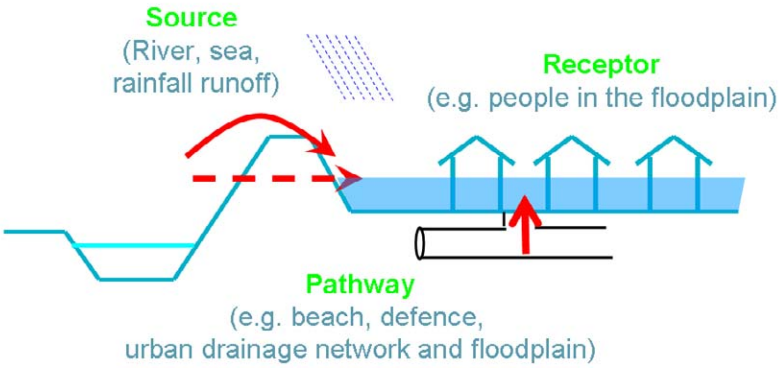


Figure 1 Source / Pathway or Barrier / Receptor can be used to breakdown the components of flooding system

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 increase 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.

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 consequences rather than system performance. Thus in the context of flooding it enables intervention options to be compared on the basis of the mitigation that they achieve 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 is that this approach is not limited to one or more specific levels of service, but can consider all events whatever their frequency of occurrence. 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.

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.

1.4 THE RESEARCH PROJECT

The DTISAM procedure has been developed by a research consortium led by HR Wallingford and part funded by BERR. The research project ‘SAM – System Based Analysis and Management of Urban Flood Risks’ commenced in March 2006 and was completed in August 2009.

The objective was to develop a risk-based approach to drainage system analysis and also to investigate some of the areas where known limitations in current drainage practice still needs to be addressed. The aim of a risk based approach is not to evaluate what the system can cope with hydraulically, but to focus on “failures” to enable asset management to be carried out based on consequences of the system operation. The DG5 register is effectively a form of risk approach as the properties being flooded are a consequence which is considered to be unacceptable for a given return period (probability). Properties which are flooded due to mal-operation of the system (e.g. pump failure or collapsed pipe) are an important additional element of the service provided and yet this cannot be picked using current systems analysis methods looking at the drainage system performance.

1.4.1 Current limitations and assumptions used in drainage analysis

As with all "models" of the physical environment, drainage tools and methods include a number of approximations and assumptions. In defining the research for developing a risk based method, consideration was given to these various limitations and assumptions which are made in current practice.

Overland flooding
Models have not been able to properly represent flooding performance on a catchment once flood water escapes from a network. Approximations have been made since the early 90's in representing streets as surface conduits, but this project has addressed the need to route flood water to enable the consequence of flooding to be measured.

Spatial rainfall
Drainage modelling in terms of representing in-put of flows from areas, waste water and the conveyance process in the system of conduits is as accurate as the information collected. However the assumption that rainfall is applied uniformly across the catchment has remained unchanged even though models of systems now extend to looking at whole towns and cities.

The consequence of this limitation in terms of providing inaccurate results is not known, but it is likely that in certain subject areas (such as assessing water quality impact on rivers, developing Real Time Control rules) it is likely that this limitation is significant. For large drainage systems, although the assumption is clearly wrong, it does not mean that the results are necessarily invalid for assessing flooding or spill performance and further work is needed to investigate this issue.

Where a drainage system interacts with another system, such as a river where response times are very different, current approaches utilise joint probability techniques. Spatial rainfall across both catchments provides a way of avoiding using joint probability methods.

Although there is this general understanding as to what is more or less affected by the assumption of uniform rainfall, the 'error' in the results is not known and requires investigation. The project has therefore investigated the possibility of developing spatial rainfall data and to assess the difference this makes to drainage system performance, particularly in terms of flooding.

1.4.2 Computational speed limitations

Computational speed is now rarely an issue for projects of even very large systems when assessing the network performance where analysis is based on a set of design storms or a limited time series.

However moving to a risk based approach requires both the 2D overland flow evaluation to be made as well as carrying out multiple runs considering various system states together with a large range of events. Thus the chance of failure of any part of the system, together with the weather conditions pertaining at the time, adds massively to the number of possibilities that need to be considered.

Notwithstanding this increase in computational load which enables an assessment to be made of the existing system, there is the additional possibility of using optimising techniques to arrive at asset management decisions to address the current limitations of the existing system. This potentially further increases the computational load by one or two orders of magnitude.

At present therefore, this limitation is seen as a significant barrier to an effective use of a risk based method. To overcome this, it is important that progress is made in terms of computational power and development of faster tools and techniques as well as devising appropriate methods which minimises the computational demands. The project involved development of tools to address this limitation.

1.4.3 Risk Procedure tools

To actually apply a risk based procedure, although the tools exist in general terms for carrying out this analysis, in practice there is a need for a significant amount of tools development to automate the whole process for the multiple runs needed and the calculation of 'risk', which is usually evaluated as Expected Annual Damage (EAD).

Tools were therefore developed along with a methodology to enable the integration of existing tools to be used in a risk based process.

1.4.4 Development of solutions

The upgrading of networks is largely based on practical constraints along with the guidance of an experienced engineer in being able to develop a suitable solution to address the deficiencies of the network. However optimisation techniques are available to help target the most effective solutions and the project investigated the use of Genetic Algorithms (GAs) to develop solutions.

1.4.5 Project tasks and deliverables

The research therefore not only developed a new drainage procedure, but also carried out a range of tasks which resulted in the development of a number of prototype tools. Tools developed include:

- Two spatially varying extreme series stochastic rainfall tools (Imperial College and Newcastle University)
- A rainfall database and processing tool (HR Wallingford)
- A Rapid Flood Spreading Model (HR Wallingford)
- An interactive 1D/2D flood spreading tool (Wallingford Software)
- A tool to calculate Damage costs (HR Wallingford)
- A tool to attribute damage costs to the network (HR Wallingford)
- A tool to enable the risk based approach for calculation of EAD for all system states (HR Wallingford)
- Modification of a drainage optimisation tool to evaluate optimum solutions based on the risk-based method (Mouchel & HR Wallingford)

In addition to the tools the following investigations and analyses were carried out:

- Assessment of the temporal accuracy of the spatial rainfall data
- How to assess the spatiality of spatial rainfall data
- Urban drainage flood analysis assessment of the differences between the use of uniform rainfall and spatial rainfall;
- Flood spreading comparison between the use of RFSM and InfoWorks CS;
- How to evaluate Damage associate with water depths
- How to incorporate probabilities of failure and blockage
- Development of a risk based procedure for evaluating the urban flood system;
- Testing the risk based procedure on two pilot areas (Dalmarnock and Keighley)
- Testing the optimisation tool for developing solutions

Information and reports on these various developments and outputs can be found on the SAM web site http://www.dti-sam.co.uk/.

HR Wallingford led the three-year project which was part funded under the DTi "Design, Modelling and Simulation Technology Programme in the Modern Built Environment area" with the assistance of project partners which are 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	

2. *A Risk based approach to urban flood management*

Section 2 outlines the different components that are needed to apply a risk based analysis to a drainage system. It also provides an overview of the methodology developed.

2.1 ALL POSSIBLE SYSTEM STATES PERFORMANCE MEASURED IN TERM OF CONSEQUENCE

The probability of flooding is dependent upon the drainage 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. Techniques have had to be developed to represent the potential variability in the system state as well as improvements in the representation of spatial and topographic information. The methodology has to 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 only presume one system state for one or more loading conditions and provide decision makers with very limited information on system performance (Figure 2).

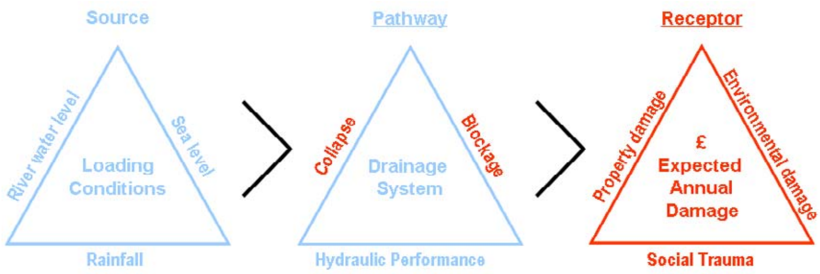


Figure 2 Additional value of a risk based approach

The procedure developed under the project has included the following aspects:

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

2.2 INTEGRATION OF SPATIAL RAINFALL

The use of extended spatially varying timeseries potentially adds considerable computational demand to the analysis. An approach has been developed which enables potential flooding events to be distinguished from the many small events which will not cause flooding. All small storms are still relevant, but only if the system state is in a state of failure at one or more locations, otherwise the model does not need to be run. As there are at least 100 events that are non-flooding events for every extreme event, this allows considerable potential for computational savings to be made.

Spatial rainfall also provides difficulties in recognising the beginning and end of events and also in classifying their size. This is because the start and end time and rainfall depth in each rainfall area differs.

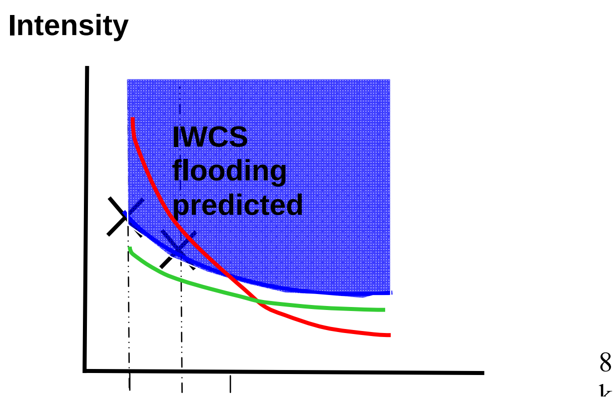


Figure 3 Identification of extremes (red) and frequents (green) events from a rainfall timeseries (Appendix 1)

2.3 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 procedure needs to take into account both the probability of the occurrence of a rainfall event as well as the system state with one or more of the assets failed. It should be noted that extreme rainfall represents only a few hours in the year compare to 10% of the year when "ordinary" rainfall takes place and 90% of the year where there is no rainfall and the system only serves the dry weather flow (DWF) conditions.

The performance of river and coastal flood defences is now considered in terms of 'fragility' which enables the possibility of failure of embankment structures to be linked to the hydraulic loading. 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 in as much as the sub-surface infrastructure has conditional failure probabilities that have yet to be shown to be a function of rainfall load, but limited correlation with age and several other parameters has been established. Moreover, the performance of the pipe is not just limited to failed / blocked or not-failed / not blocked, with most poorly performing systems being a function of partial failure or blockage. However for an integrated approach it is important that the risk method devised allows an integration of the use of fragility of embankments and other defences with the analysis of the drainage system.

The methodology utilises the current best knowledge on the probability of failure for both collapse or blockage of pipe systems. At this stage it is considered too difficult to include partial failure status. More information regarding the assessment of predicting pipe failure is reported in the technical note Water Wastewater Infrastructure: Likelihood-of-failure modelling.

Including asset failure within the risk analysis adds significant computational complexity to the problem. In a network with 5000 assets (pipes), and only considering three possible states for each asset, (un-failed, failed by blockage, failed by collapse), there are 3^{5000} potential system states. Obviously it is highly impractical to run all these combinations, but the methodology has developed a technique based on convergence which arrives at a reasonable approximation of the system performance without having to run all possible system states.

2.4 NETWORK AND RISK ATTRIBUTION

Several organisations are responsible for various drainage assets and flood risk management. A risk methodology which can attribute the damage to the source of the flooding has two advantages. Firstly it helps focus on the parts of the network that most needs addressing, and secondly it highlights the deficiency to the owner of the asset.

Flood flows are therefore physically 'tracked' from the flood source (manhole) to the locations of flooding and the damage caused by the node flood volume is associated with the node.

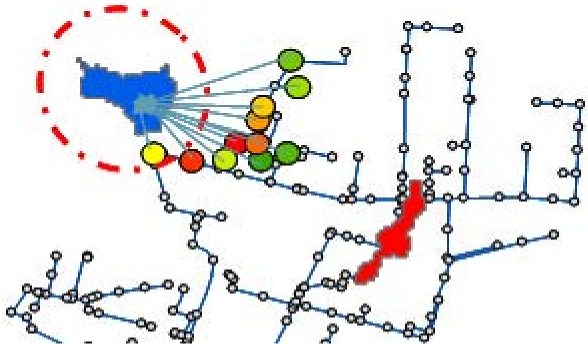


Figure 4 Example of allocation back to manholes of damage done to receptors (Appendix 2)

2.5 ADDITIONAL DATA REQUIREMENTS

As with any detailed drainage analysis, standard information on the drainage network is needed along with the "drivers" of rainfall, contributing area and waste water discharges. The difference between the risk methodology and traditional modelling is the need to be able to route flood flows to low points and estimate the damage associated with the flooding. Therefore only three additional data sets are required. These are:

1. LiDAR – to provide an accurate representation of the ground levels to route the flows to low points; and
2. A GIS based database of property together with a flood depth - damage cost relationship for the various types of property.
3. Finished floor levels.

The Environment Agency has a national data set of the property information and they also hold much of the existing archive of LiDAR information. At present there is no national data set for floor levels and therefore assumptions need to be made. The cost of LiDAR is relatively small with respect to carrying out a significant drainage flood study of an area and therefore the cost penalty for carrying out a risk based approach compared to a traditional study is not great. Issues that are relevant in making a choice in the study type is only linked to decisions related to availability of the data together with an assessment of the uncertainties involved which exist in either method.

2.6 DTI SAM RISK-BASED PROCEDURE OVERVIEW

One of the key objectives of 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. 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 5 provides a schematic overview of the steps that, depending upon the level of complexity being considered, may need to be undertaken.

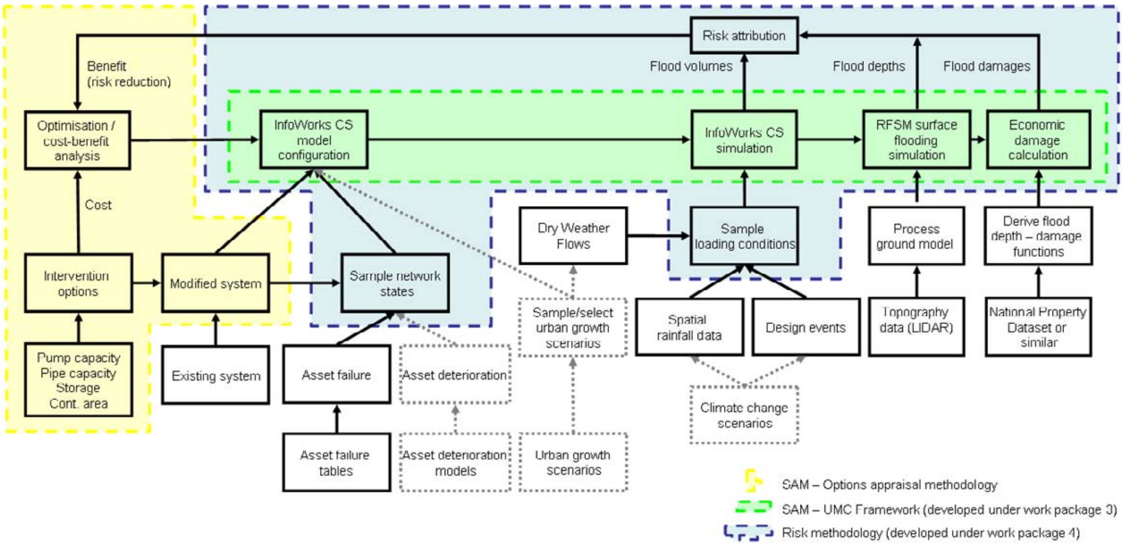


Figure 5 Schematic overview of the application of the procedure

To apply a comprehensive risk based approach is a significant change to existing practices. Including all potential factors in an analysis may not always be cost effective or necessary. Consequently, the risk based method has being developed so that it can be applied at different levels of complexity appropriate to the study objectives and the availability of computational resources and supporting data.

Figure 6 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.

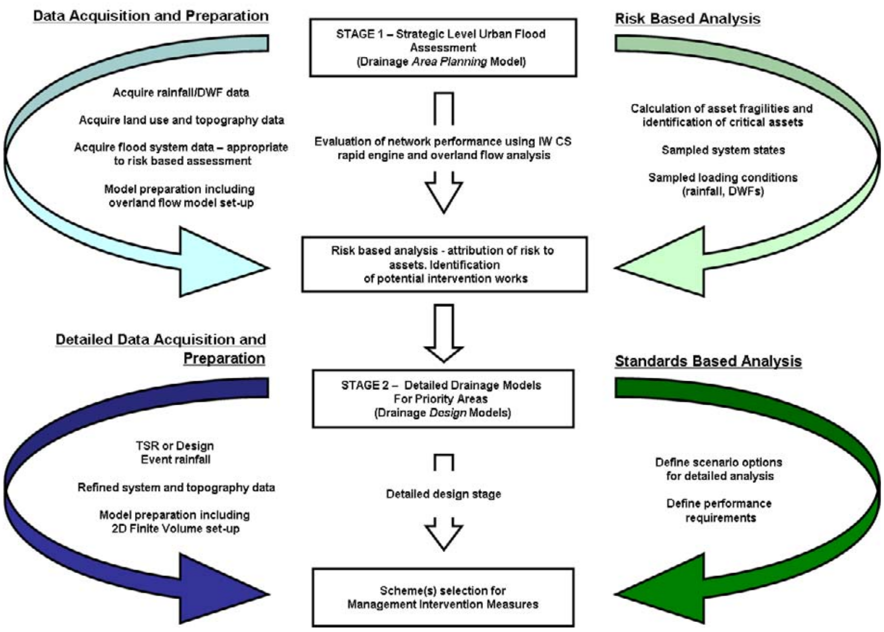


Figure 6 Conceptual overview of the system based approach to urban flood analysis

3. Risk based analysis methodology (EAD evaluation)

Section 3 describes the risk methodology in detail which has been developed by the DtiSAM project. The method allows the following approaches to be used:

1. Normal system state using design rainfall,
2. Normal system state using timeseries rainfall,
3. All system states using design rainfall,
4. All system state using timeseries rainfall.

The options are ranked in order of analytical complexity and therefore the computational time needed to do the analysis.

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). The approach taken to address these various conditions has been to separate out the problem into 2 parts.

1. The un-failed system state is only assessed with extreme rainfall (hydraulic failure)
2. The potentially "blocked" or "collapsed" system states are assessed using all rainfall events (structural failure)

The methodology takes into account, the potentially huge computational demands of considering all system states and the limited accuracy / availability of certain data sets which may not be available at present.

The procedure has been developed to use both continuous spatial and temporal rainfall as well as design storms. In principle continuous series, especially spatially varied rainfall, represents the real loading conditions that exist. However design storms have been derived to facilitate drainage analysis for two reasons; firstly because the number of events that need to be run is much reduced and secondly the difficulty of getting a sufficiently representative series of rainfall which includes extreme events.

It should be noted that stochastically generated non-spatial rainfall data have been shown to be sufficiently accurate to use for extreme series and these can be used in lieu of the spatial series developed under this project which aimed to provide spatial rainfall, but which at this stage, are insufficiently accurate to be used yet by the water industry.

3.1 HYDRAULIC FAILURE (SINGLE SYSTEM STATE)

Hydraulic failures of the un-failed system state are a function of the networks inability to cope with extreme events. As drainage systems are designed to cope with most rainfall events without causing any flooding, most rainfall (up to a 1 year return period) 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.

3.1.1 *Design storm rainfall (FEH type)*

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

As can be seen in Figure 7, for any given return period, the maximum flood volume at any given node or group of nodes is associated with a specific duration.

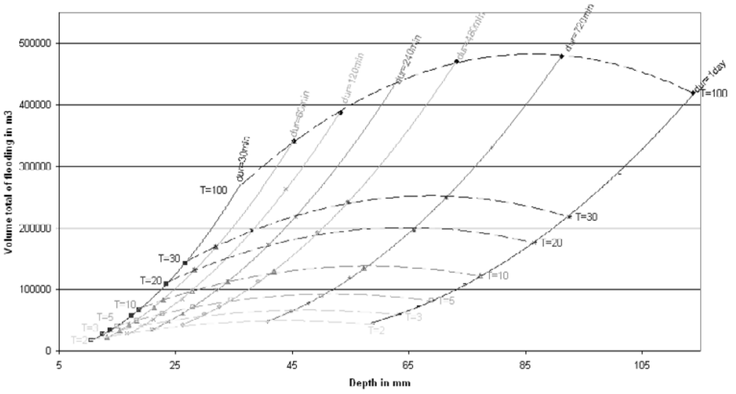


Figure 7 Influence of return period and duration on flood volumes

Therefore, 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 therefore needs to be run with the critical duration events.

The Expected Annual Damage is then the integration of the Damage across the different return periods/probabilities of non-exceedance:

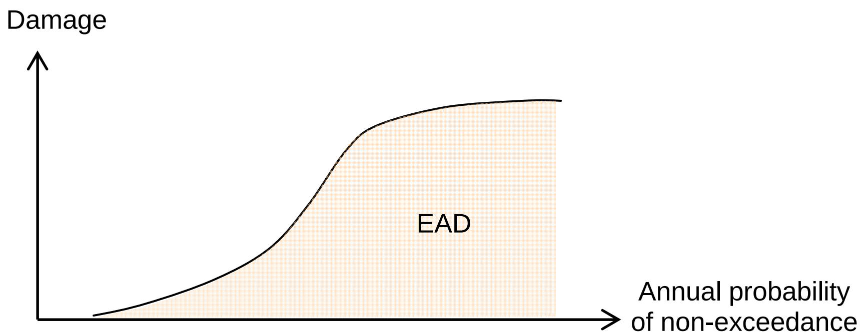


Figure 8 Integration of the Expected Annual Damage based on annual probability of non-exceedance

Details on the calculation of the probability of non-exceedance and on the integration of the EAD are reported in appendix 1.

It should be noted that the return period threshold of flooding of every manhole/impact zone, has to be found in order to avoid an overestimation of the damage where calculating the EAD value. Similarly the critical duration event for every flood location is needed to avoid an underestimation.

In practice, the simulations will normally 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 to a specified impact zone/manhole, or a set of impact zones/manholes (if only some of the network is of particular importance), or the catchment as a whole reduces to a marginal increase in EAD (around 1 to 5%).

The design storm un-failed system state methodology can be summarised as follows:

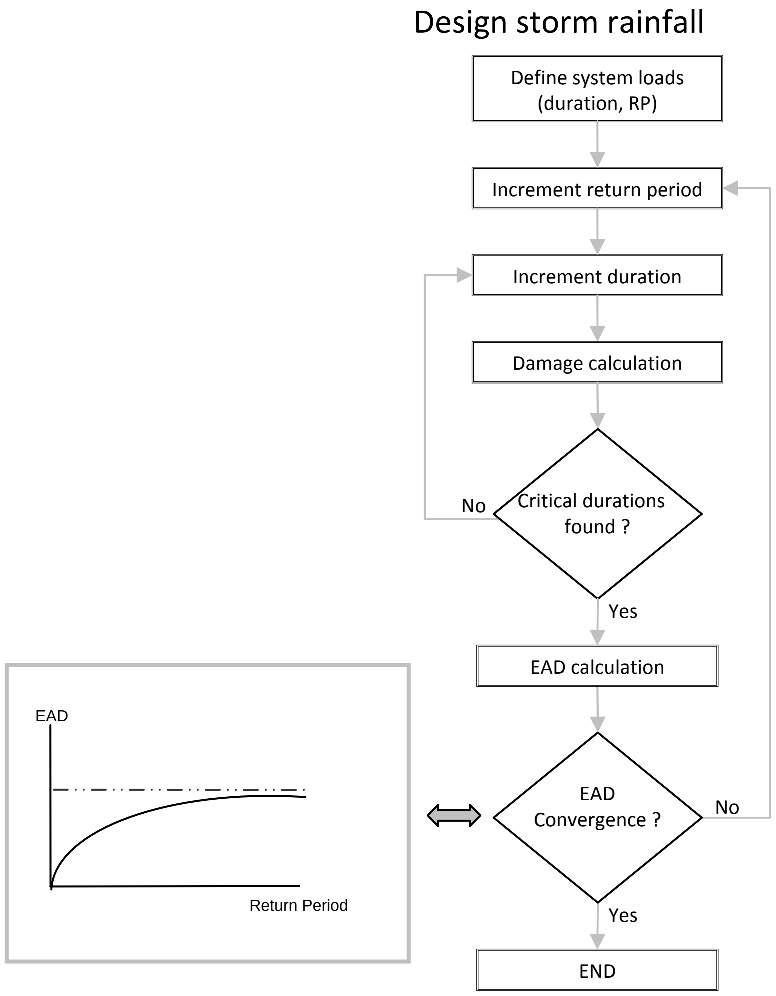


Figure 9 Methodology for un-failed system state using design rainfall events

3.1.2 Timeseries rainfall

Every event in a continuous rainfall series is unique and does not contain a defined return period. Each event is effectively equally likely. Thus, because the probability of non-exceedance of any given event can not be evaluated (especially if it varies spatially as well as temporally) a more systematic approach had to be used.

In theory, all events in the timeseries should be used to assess the damages and divide the total value by the length of the time series (in years) in order to evaluate the Expected Annual Damage. However, for efficiency and computational limitation reasons, this approach is not efficient or really practicable. But as already mentioned, for un-failed system state we can assume that only extreme events generate flooding and therefore dry periods and frequent rainfall events can be ignored. Only extreme rainfall events are therefore of interest.

To identify those extreme events, rainfall events can be compared with a known flooding threshold from the drainage model. This is explained in detail in appendix 1.

Convergence of EAD for any impact zone/node or group of impact zones/nodes can be checked after every rainfall event, by tracking the average value of EAD. Once convergence to a certain limit is achieved (based on degree of change), the simulation can then be stopped.

The timeseries rainfall methodology can be summarised as shown in the following flowchart:

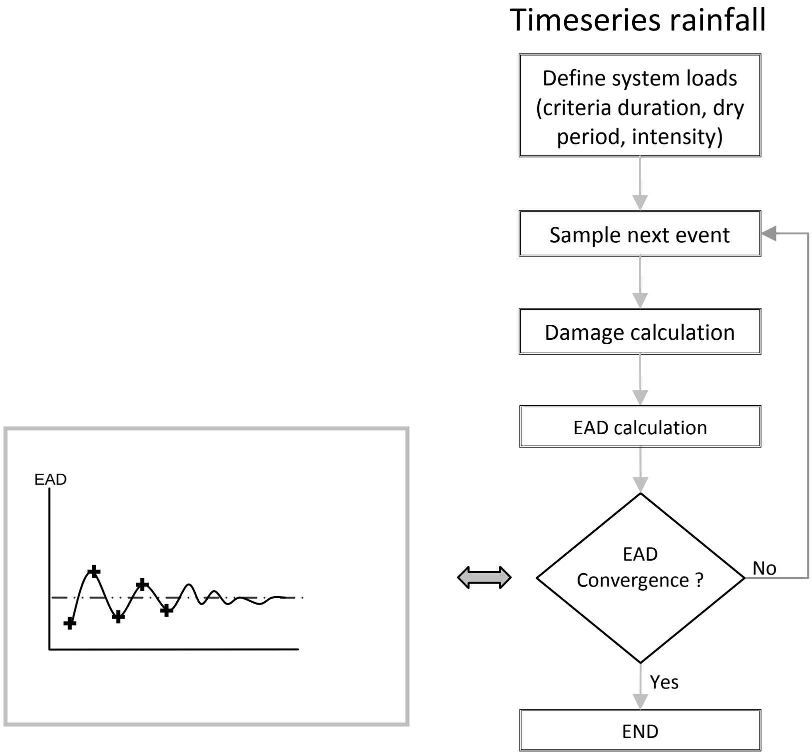


Figure 10 Methodology for un-failed system state with continuous series rainfall

3.2 STRUCTURAL FAILURE (ALL SYSTEM STATES)

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 rainfall events and dry periods have to be considered whether a design storm approach or timeseries rainfall methodology is used.

In a network with 5000 assets (pipes), and only considering three possible states for each asset; un-failed, failed by blockage, failed by collapse, there are 3^{5000} potential system states that should be considered.

Obviously it is highly impractical to run all these combinations, and the methodology developed incorporates a technique based on convergence which arrives at a reasonable approximation of the evaluation of EAD without having to run all possible system states.

3.2.1 Design storm approach (FEH type)

To incorporate the system state variability into the procedure means that the "system state" is a variable and has to be sampled for every possible return period based on the annual probabilities of collapse and blockage of each single pipe.

If a system state is selected which has at least one failed pipe, flooding will occur during a dry period (assuming it is a combine system). Critical duration is not a relevant concept in this system condition (longer events will automatically generate more flooding and damage), a duration is randomly selected and run. Damage associate to that annual probability of non-exceedance (i.e. return period) is then the damage associated with that randomly selected duration.

If the system state is fully functional, all durations will be processed as previously described, but only for return periods that might generate flooding.

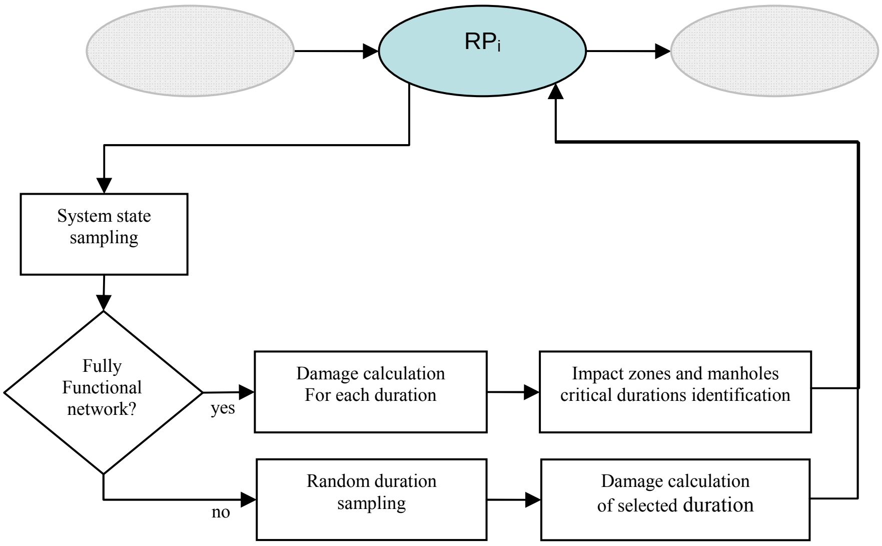


Figure 11 Difference in duration(s) processed according to the system state picked for a return period (Appendix 1)

However, because of the multitude of possible system states that can be considered, the system state needs to be sampled many times for each return period, and an updated averaged EAD calculation performed after each set, until convergence is reached (after a minimum number of iterations is considered):

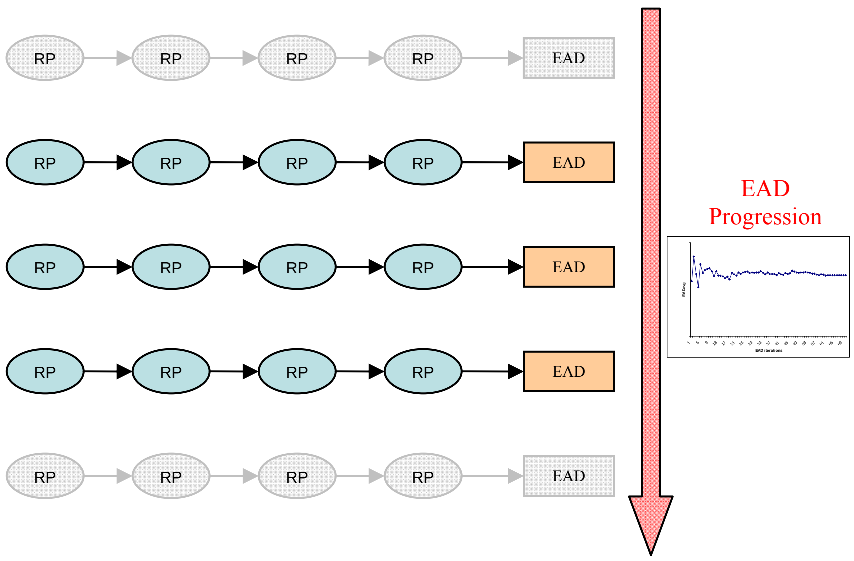


Figure 12 EAD calculation progression for structural failures analysis (Appendix 1)

In addition to the risk due to the occurrence of wet weather events, dry days also need to be considered for each set of return period. This risk is calculated based on a percentage of dry time per year and the damage associated to the impact zones/manholes.

The Global methodology flowchart of structural failure analysis using design storm event is therefore:

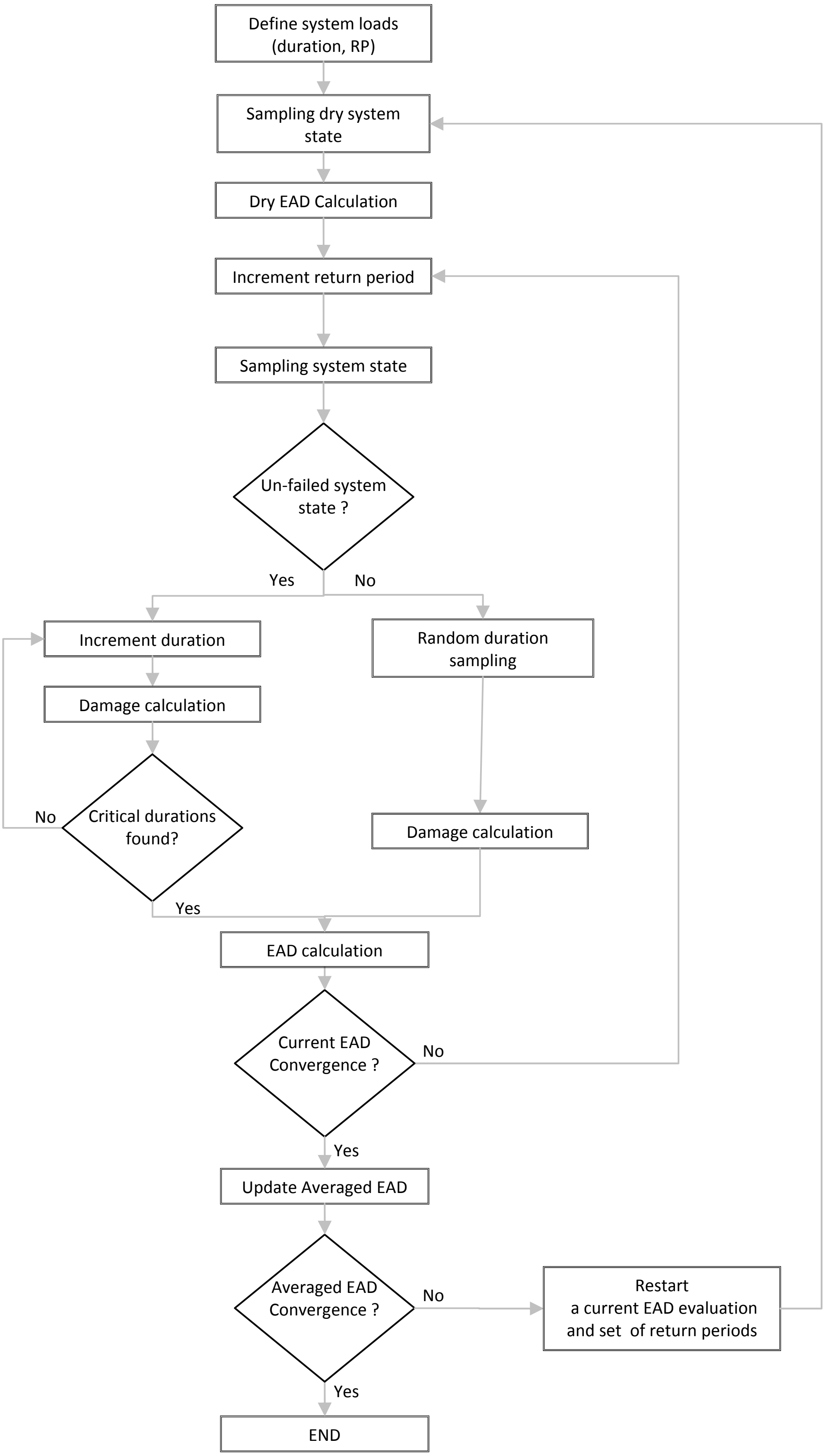


Figure 13 Methodology for structural failure analysis with design storm rainfall

3.2.2 Timeseries rainfall

With time series rainfall, the return periods of the events are unknown, but the dates of occurrence are known. Therefore, when considering structural failure, damage can happen at any time (during extreme events, frequent rainfall events or dry periods), it was considered necessary important to incorporate a “time of recovery” delay, during which properties that are damaged by an event, are assumed not to be damaged by another event within that period, unless the subsequent event in that period causes greater damage.

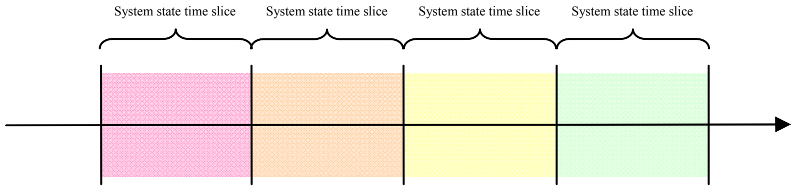


Figure 14 Time periods of time-series for assessing system states damage

The timeseries is therefore divided into time slices for which only the worst damage is considered for any impact zone:

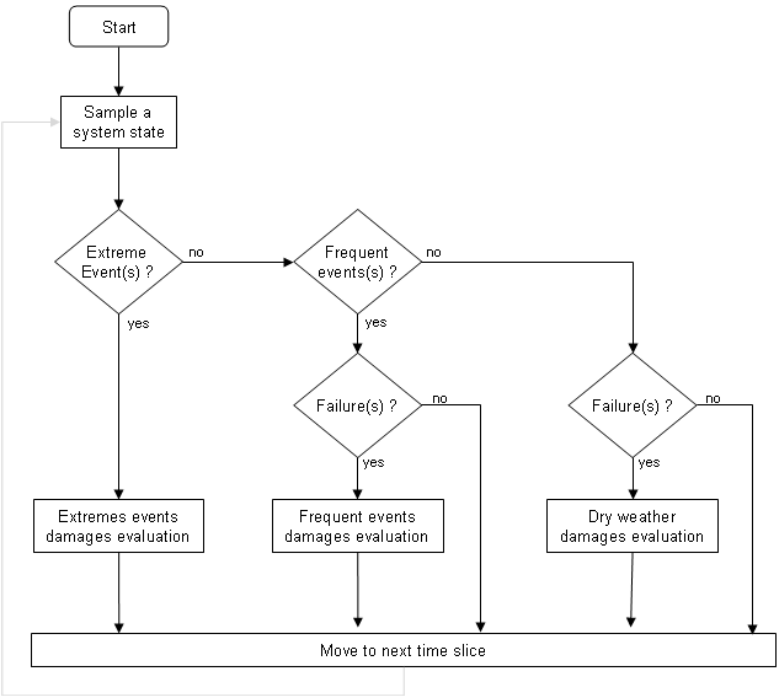


Figure 15 Time slice damage evaluation process

Notice that this breakdown (Figure 15) enables the calculation of risk associated with each population of events (extreme events, frequent events and dry days) for each manhole/impact zone.

4. Supporting Software Tools

Section 4 outlines the different software tools developed under the project that enable the risk procedure to be applied.

Currently, it is computationally very demanding to undertake a risk based analysis using existing tools due to the large number of simulations that are needed. As a result, rapid simulation tools and integration of various elements of the process have been developed to minimise the computational time to do the analysis have being developed as part of the project. These include an Urban Model Control framework (SAM-UMC), a rapid drainage network solver, a rapid overland flow tool, a damage calculation tool and a risk shell for evaluating convergence of EAD.

4.1 SAM-URBAN MODEL CONTROL FRAMEWORK (SAM-UMC)

The SAM-UMC risk model framework has been developed as part of the project to support the application of the procedure by integrating and automating most of the steps required.

SAM-UMC incorporates the following elements:

- InfoWorks CS drainage model;
- RFSM Surface flow model;
- 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 5 shows how the SAM-UMC risk model framework sits in regards to the overall procedure.

4.2 RAPID DRAINAGE NETWORK SOLVER

Wallingford Software has explored alternative approaches for developing a rapid network solver that significantly reduces 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.
An alternative solution technique has been developed which does provide speed increases up to 4 times compared to the standard solver for the current version of Infoworks.

4.3 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 Info Works 2D software to justify its accuracy. Information on this is available from the project report RFSM vs. InfoWorks CS 2D: differences in predicted flooding.

4.4 DAMAGE CALCULATION

In order to determine economic consequences of flooding to properties, depth/damage curves are derived for each cell or impact zone from the Middlesex Multi-Coloured Manual (MCM) and the Environment Agency's National Property Dataset (NPD). Details on the methodology used to build damage curves are reported in SR report 703, Damage – Cost tool development.

For each rainfall event, a flood depth grid is outputted from the spreading model, from which water depth at every location is compared to the depth/damage curve built for that location, and economic damage associate extracted.

4.5 RISK SHELL

The Risk Shell was designed as a probabilistic risk tool for integrated urban drainage and surface flooding. While the SAM-UMC tool enables the setting up and running rainfall/system states scenarios and calculate the associate damages, the Risk Shell performs the probabilistic analysis needed for the calculation of risk (EAD) and identifies the next scenario for the SAM-UMC to consider.

The Risk shell is designed to enable the use of both design storms and time-series rainfall. The Risk shell has also been designed for use for assessing hydraulic failure only or structural analysis. The choice between the four types of evaluations depends on the availability of data concerning the pipes' probability of failure and the level of analysis required.

To do this, the Risk shell was designed as two separate tools: **SAM-Risk I**, which calculates the risk concerning only hydraulic failure, and **SAM-Risk II,** which calculates the risk taking into account the probability of failure due to pipe failure (collapse and blockage) and therefore considers all system states.

More information on the Risk shell is available in appendix 3.

5. *Application of the procedure*

Section 5 outlines how to apply the risk methodology along with the typical output that such analysis can provide.

5.1 RUNNING THE TOOLS

The procedure and tools have been designed in such way that in order to perform a risk analysis the end user only needs to set up and run the appropriate SAM-Risk GUI. SAM-Risk tool will control the SAM-UMC, which will itself control the sewerage network simulation (Infoworks CS), the above ground spreading process (RFSM) and the damage calculations.

Details on the inputs required for each Risk shell and rainfall input type, please refer to the appendix 3.

However, two elements are worth mentioning here when using design storm rainfall. Firstly, it is important to capture the threshold of flooding of each manhole in order to avoid an overestimation of the damages and therefore of the risk. Secondly, it is very important to capture the critical duration of each manhole to avoid an underestimation of the damages. These two points are illustrate in the Dalmarnock pilot (see appendix 2).

5.2 OUTPUT INFORMATION

The output of the risk based procedure must provide sufficient information to enable decisions to be made in managing the system and making appropriate and informed decisions.

The EAD allocated to any manhole represents a single accumulated value for the following information which represents the network behaviour at that location and its capacity limitations downstream. This includes aspect of blockage and structural failure if this option has been run.

However more information can be provided from the analysis. The methodology can output information which enables more effective decision making to be made.

The following information is therefore produced:

- The total EAD at each manhole
- The EAD at each manhole associated with blockage
- The EAD at ach manhole associated with collapse
- The EAD /m length of the pipe or pipes downstream of the manhole with the same diameter
- The EAD at each impact zone
- The frequency of flooding at each manhole
- The frequency of flooding at each impact zone

5.2.1 EAD for the drainage system

The EAD value at each manhole is a composite value assessed over a long period of time for the flood (or any other) damage associated with that manhole. Figure 16 schematically illustrates this information.

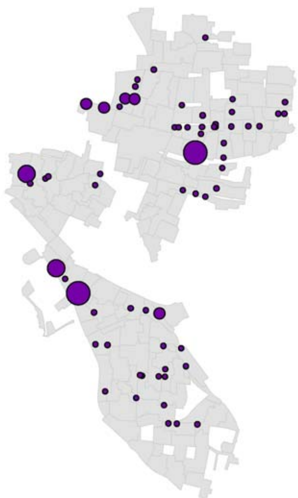


Figure 16 EAD attribution for a network

In reality the flooding is not necessarily caused by the pipe immediately downstream of the manhole from which the flooding takes place, but the cumulative effect of the pipe sizes downstream and flows joining the system. In addition some component of the EAD (usually small) is associated with the potential for collapse or blockage.

Although over-simplified, it might be assumed that the pipe downstream of the manhole is the principle constraint, and if it continues at the same size for the subsequent pipes then these might also be associated with the flooding. However it is possible to have EAD values on the intermediate manholes along this same sized length of sewer. Therefore an alternative way of illustrating costs associated with these pipe lengths is to add all EAD values on this section and divide by the cumulative length of the pipes.

This information draws attention to pipe lengths with common pipe sizes and reduces the relative importance of very long lengths of pipe thus drawing attention to the potentially reduced benefit of dealing with this problem by simply upsizing the pipes.

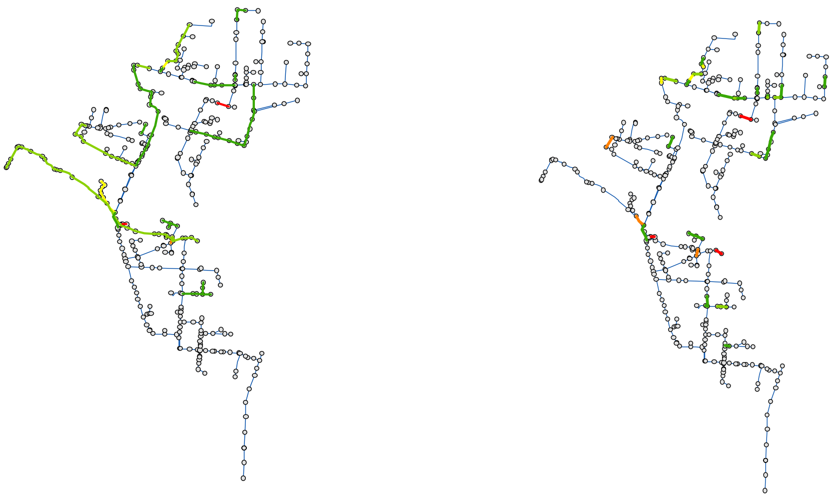


Figure 17 Expected annual damage per pipe group (a) and per unit length of pipe (b)

5.2.2 EAD for all system states and only 'failed' system states

Statistics indicate that 50% of flooding events are associated with failed systems. However a risk analysis tends to show that the probability of failure of a pipe is small with respect to its hydraulic risk of flooding. This means that the EAD value is dominated by the hydraulic performance (normal operating system state).

The importance of providing a good level of service emphasises the need to address pipes at risk of blockage and collapse.

The depth damage function used for flooding may not be equally applicable to stormwater as for foul discharges.

For these reasons it is felt that it is useful to produce risk maps of the drainage system which are specifically focused at the structural (collapse and blockage) condition and the consequences of their failure. As the correlation equations for collapse and blockage have very different parameters and weightings, these maps have to be produced separately.

However, contrary to the assumption of looking at the total EAD in terms of common pipe size lengths, as parameters for failure are pipe length specific based on a number of measures, this information is only provided on a pipe length basis (between consecutive manholes). This is also because the pipe status information may be provided from field information rather than derived from pipe characteristics.

5.2.3 EAD for impact zones

The EAD values are associated to the network, but the information has been obtained from flooding of impact zones to which the flood water was routed. As the flooding location is a principal feature of any record, it is important to not only identify the source of the flooding, but also provide information on the location in which flooding and damage take place. This allows individual properties to be targeted and checks made as to whether flooding has ever been recorded at the location. This can be regarded as being the other side of the coin to providing EAD to the network system. The total value of attributed damages and impact zone damages are the same, but it should be noted that flooding of a specific location may well be due to several sources of flooding. Similarly one manhole may also be the source of flooding for several impact zones. Figure 18 illustrates the EAD map for impact zones.

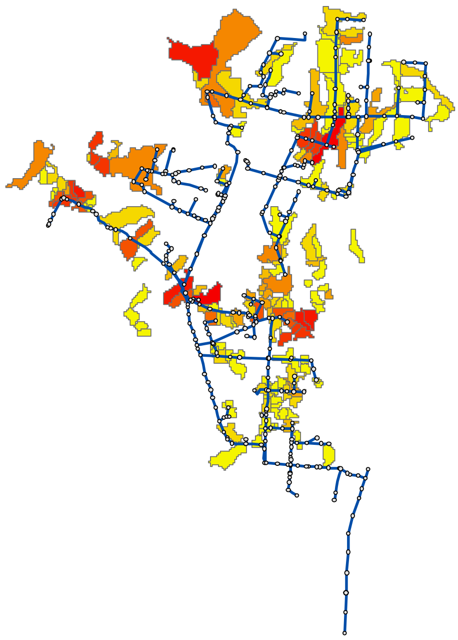


Figure 18 Illustration of impact zones' EAD map

5.2.4 Flood frequency

EAD is a measure of damage for all events, rare or otherwise. It is possible that a high value of EAD could be the result of very rare, but catastrophic flooding, or very frequent rainfall.

Decisions on addressing flooding may be influenced by frequency of an event (in accordance with the OFWAT DG5 measure for instance) and therefore a map or series of maps reflecting the frequency of flooding should be produced. Although this is not a risk based output, the simple depth damage cost function does not provide all the information needed to make a completely informed decision.

As with EAD output, it is equally useful to provide a flood frequency map of the network characteristics as well as for cells/impact zones. It should be recognised that this does not take into account the state of the pipework, but unless the probability of failure in terms of structural or blockage is particularly high, this omission is not seen as being important.

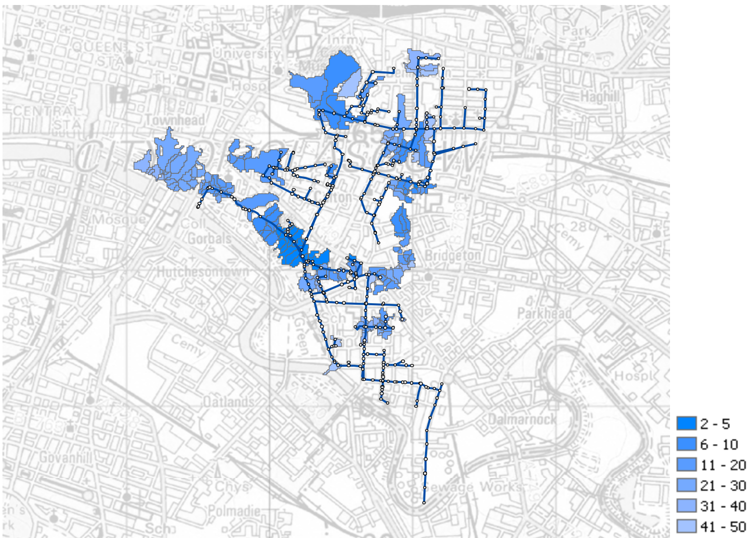


Figure 19 Impact zones' flood frequency map

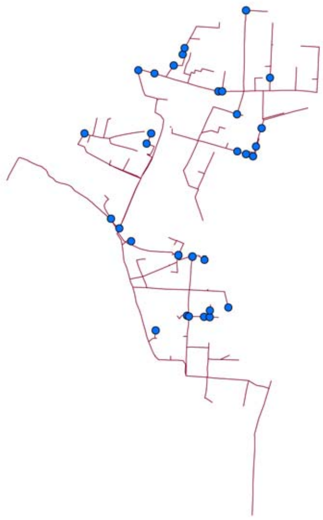


Figure 20 Manholes flood frequency map

6. Solution development

Section 6 highlights the fact that the calculation of EAD is just a measure of sewerage system performance, and describes how those outputs can be used by engineers to develop a solution to flooding problems.

6.1 TRADITIONAL SCHEME DEVELOPMENT

EAD evaluation does not solve any flooding problems; it just provides a measure of performance (current or future) of the sewerage system in term of risk.

Traditionally the engineer has to use his engineering judgment and bases his decisions on reducing the flooding at selected locations. However evaluation of the impact of any decision on the risk across the whole catchment requires a re-evaluation of EAD. This is a long iterative approach and a good cost-effective solution may not be developed.

6.2 OPTIMISATION TECHNIQUES TO SCHEME DEVELOPMENT

One of the 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.

Within the project, the optimisation procedure was trialled on part of Scottish Water's Dalmarnock sewer system that serves part of the Glasgow conurbation. In the test illustration, the third of these optimisation options is shown.

Figure 21 illustrates the process showing the continuously reducing value of expected annual damage against the "best" capital investment solution derived as the analysis progressed.

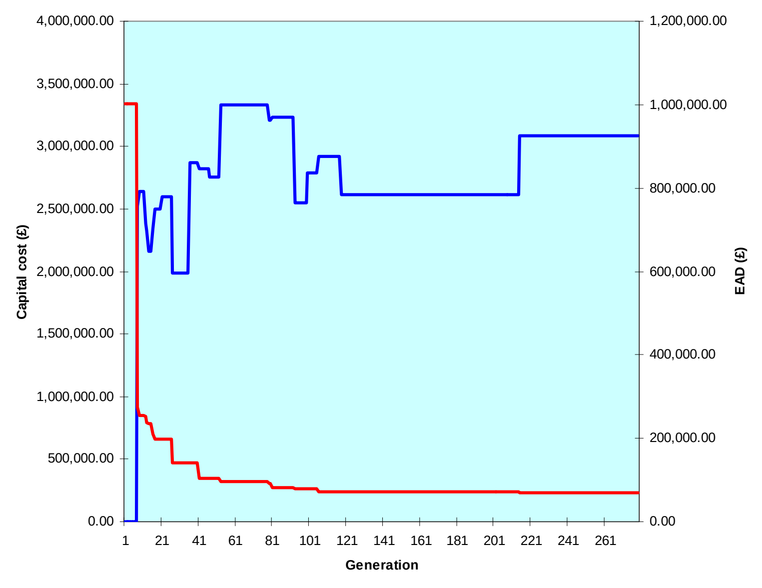


Figure 21 Risk based optimisation results

More information on the use of genetic algorithm and trial of this technique on Dalmarnock sewerage system is available in the technical note Fastnett optimisation assessment.

7. *Future development of risk based management of urban drainage systems*

This project is proposing a radically different approach to sewerage asset management and the performance assessment of systems. Although the tools are at a prototype stage, in theory these could be polished and utilised by the water industry. In practice the use of any procedure is a function of the need for the information produced. The water industry, the water companies, regulatory bodies and other governmental organisations need to agree that this information is needed to form opinions and make decisions. This section therefore discusses both the technical and other constraints that need to be overcome before this methodology is actually used in practice.

7.1 REGULATORY MEASUREMENT OF DRAINAGE SYSTEM PERFORMANCE

The Regulator effectively defines the performance expectations of drainage systems. These requirements translate into the measurement techniques applied to check to see that these are met, or if not met, measured to assess the degree of non-compliance.

The Common Framework, which is currently in place, is not a risk based approach. Measurements such as DG5 are all based on specific levels of service. Recent flooding such as that in July 2007 indicate that although flooding of that nature is rare and accepted as being beyond reasonable expectation, in practice the impact of such events are often unacceptable because no consideration of their impact has ever been made. It is unlikely that the concept of a minimum level of service will be replaced by a risk based procedure, but it is likely that a combination of a risk approach and minimum level of service will be used at some time in the future.

There is one major impediment other than outstanding technical issues to the move towards a risk based approach. This is the concept of equity. A risk approach is based on the premise that investment is needed where damage is greatest. However this clearly does not value the rights of individuals equally. To provide an equitable approach and also use a risk approach would need the integration of a minimum level of service and distinguish the reasons as to why preferential expenditure is needed in certain locations than others. For instance, although it would still be risk based, the measure could be made on the basis of social trauma where the measure is entirely based on treating individuals the same and where investment was targeted at those who suffer more from flooding. This might be based on just depth and frequency, but also could be a more complex measure of financial impact relative to the wealth of the individual.

7.1.1 Water quality

Although this project has been focused at flooding, it is obvious that this approach is equally applicable for being used to assess water quality impact on rivers. With the Water Framework Directive it is important to recognise that this approach can also be used to look at the environment and the impact of the sewerage system on rivers.

7.1.2 Resilience and National Productivity

Although damage is usually quantified as a cost, it is important to recognise that the measures used need not be monetary. With the growing emphasis on sustainability, aspects such as minimising the use of carbon based energy, use of resources, and other measures can be equally important measures. This leads through to the ability to address the more recent concept of resilience and looking at parameters which are relevant for assessing the recovery rate of cities or communities from any form of “loading” condition.

It can therefore be seen that a risk based approach has a lot of merit, but that there is some way to go in terms of both research and the action needed by the water industry to move away from a performance measure based on a level of service to one of risk.

7.2 FUTURE DEVELOPMENTS TO THE PROCEDURE AND TOOLS

The methodology is new and the tools and assumptions made are likely to improve quite quickly. In addition, much of the data used (spatial rainfall, correlation of pipework system state for collapse and potential blockage, fragility curves for embankments) are still in their infancy and further development is needed in these areas. This data uncertainty means that the values derived for EAD may well be fairly inaccurate.

The risk methodology lends itself to taking into account any future change although tools need to be developed to enable this to occur. All aspects of change could theoretically be addressed; these include;

- Increased probability of drainage system failure with age;
- Investment over a period of time on network rehabilitation;
- Climate change (rainfall) based on Hadley model output
- Land use and population change using databases to generate appropriate models

At present no procedure has implemented such a time based analysis. However it is recognised that there is a need to transform sewerage systems from their current state to be much more sustainable in the future. The ability to have tools to examine this transition is important to ensure that 'bottlenecks' in the process are highlighted.

The following sections briefly itemised the various tools and other aspects that require further development and investigation. They are not ranked in any particular order.

7.2.1 Incorporation of Uncertainty

It is recognised that much of the data used is uncertain (damage-depth curves, floor levels, system state failures, assumptions such as dry weather flooding etc). The procedure does not include any way for incorporating the degree of uncertainty for any of the parameters used in the modelling.

7.2.2 Spatial rainfall

Spatial rainfall has been shown to produce less flooding than uniform rainfall. In addition an integrated approach to modelling taking into account river performance together with the different time scales of the drainage system response, makes the long term goal of developing accurate spatial rainfall series an important goal. The work to date on this topic in this project has shown the potential to produce such tools, but further work is needed to produce tools suitable for the water industry to use.

7.2.3 Future change and system transition analysis

With the pressure to adapt modern living to be more sustainable, particularly in terms of energy use, drainage systems will need to evolve quite rapidly to achieve this goal in the next few decades. The transitional process is as important as the end state to assess all implications (cost, performance etc) of change. The procedure and tools will need to incorporate this aspect to be able to study the transition process.

7.2.4 'Failed' system states

The correlation equations for predicting system state failures are based on extensive research. However it is recognised that the degree of correlation is low and this has implications as to how this aspect of the procedure is applied in practice.

7.2.5 Other sustainability measures

Flooding has been the focus of this procedure. It clearly has the potential to be expanded to look at a wider range of impacts such as water quality and energy etc.

7.2.6 Tool developments for optimisation methods

The project has demonstrated that the use of optimisation methods is feasible for applying to the procedure. However considerable development of the network model is needed to allow changes to the system network to be modified by the optimisation tool.

It is important to recognise that the damage attribution will change as the system is modified, thus the attribution process cannot be separated out using a look-up table and must be assessed for every run.

7.2.7 Integration of flood spreading with the drainage system

InfoWorks CS 2D allows the overland flood flows to exchange flows into and out of the under-ground drainage system. At present, to gain the necessary computational speed, the RFSM model only spreads the flood flows and does not interact with the 1D system. This limitation is seen as a necessary approximation at present, but it needs to be removed as soon as it is practicable to do so.

7.2.8 Depth – damage information and floor levels

Information on the damage function for different forms of property is built into the NPD data. A major deficiency at present is based on the need to assume floor levels. A database which incorporates this information will improve the accuracy of the procedure.

8. References

Water Wastewater Infrastructure: Likelihood-of-failure modelling.
Richard Long, Mouchel Group. July 2008

RFSM vs. InfoWorks CS 2D: differences in predicted flooding
Julien Lhomme, HR Wallingford. October 2008

Damage – Cost tool development
HR Wallingford Report SR 703, 1.0. September 2009

Fastnett optimisation assessment
R Long, Mouchel Group. September 2009

Appendices

Appendix 1 Risk calculation – mechanics and mathematics

1. Hydraulic Failure

1.1. A- DESIGN STORM APPROACH

The classic formula for quantifying risk refers to the magnitude of damage and probability:

$Risk = Probability \times Damage$

The assumption is that because we are evaluating Expected Annual Damage due to flooding, the probability of non-exceedance of the rainfall events is the same as the probability of flooding and the damage consequences.

1.1.1. *Annual probability of non-exceedance*

Because the probability of all possible outcomes must sum to one, if P is the probability of the threshold being equalled or exceeded on any given event, 1-P is the probability that the threshold is not equalled or exceeded in any given event. The probability that the threshold is not equalled or exceed in one year is then $(1\text{-}P)^{\text{No of events in one year}}$. (Defra/EA R&D Technical Report FD2302/TR1)

Because the return period of design storm is explicit and therefore has a specific probability, the probability of the threshold not being exceeded on any given event can be calculated as:

$$Annual\ \ probability\ of\ \ non\,exceedance = \left(1 - \frac{1}{No\ of\ \ events\ in\ one\ \ year \times RP_i}\right)^{No\ of\ \ events\ in\ one\ year}$$

1.1.2. *Associated damages*

The main objective of a risk based method is to evaluate the damages (receptor impact) but it should be noted that these vary for any given location for the same return period depending on the duration of the event used when applying a design storm approach.

It is therefore important that the damage associated with each probability of non-exceedance is based on the critical duration for each location.

Because it is desirable to associate the assets which flood with the damage this causes, it is necessary to proportionally redistribute the total damages occurring at all impact zones to the manholes, based on the damage of the critical duration event:

$$Damage\ at\ manhole_i = \frac{Damage\ at\ manhole_i\,(\text{using manhole critical duration})}{\sum_{manholes} Damage\ at\ manhole_i\,(\text{using manhole critical duration})}$$
$$\times \sum_{IZ} Damage\ at\ impact\ zone_j\,(\text{using impact zone critical duration})$$

This will ensure consistency in associating damages at impact zones to the manholes which generate the flood water:

$$\sum_{manholes} Damage\ at\ manhole_i = \sum_{IZ} Damage\ at\ impact\ zone_j$$

1.1.3. Expected Annual Damages

The Expected Annual Damage is the integration of the risk due to every probability of non-exceedance:

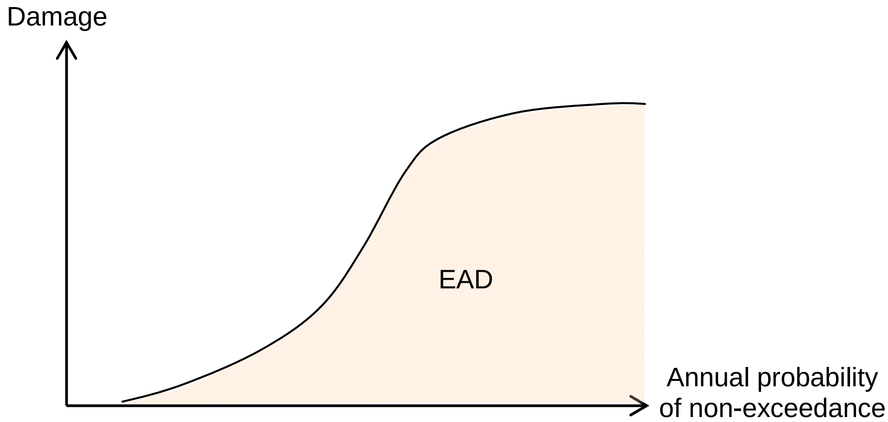


Figure 22 Integration of the Expected Annual Damage based on annual probability of non-exceedance

By using the simple trapezoidal integration method, the Expected Annual Damage for every impact zone and manhole can be written as a function of the probabilities (P_{RP_i}) and damages associated (D_{RP_i}) with every return period (RP_i) as follows:

$$\text{Expected Annual Damage} = D_1 \times P_1 + \sum_{i}^{\text{nbr of RP}} \frac{D_{RP\,i} + D_{RP_{i-1}}}{2} \times \left(P_{RP\,i} - P_{RP_{i-1}}\right)$$

where P_1 and D_1 are probability and damage of the shortest return period event.

In practice, the Expected Annual Damage is evaluated starting with the shortest return periods and in ascending order, until convergence is achieved.

It should be noted that the threshold of flooding of every manhole (and also impact zone), has to be found in order to avoid an overestimation of the damages. Similarly the critical duration event for every flood location is needed to avoid an underestimation.

This means that D_{1_i} should be zero or very near zero and that P_{1_i} is an event for which flooding starts to take place.

As can be seen in Figure 23, Expected Annual Damage calculation progression increases asymptotically:

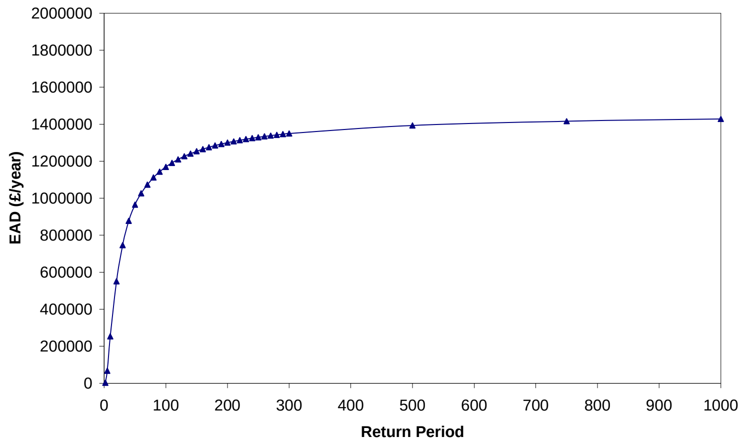


Figure 23 Example of Expected Annual Damage curve using a design storm event approach

1.2. B- TIME SERIES RAINFALL APPROACH

The time series based approach is completely different to that used for design storms. This is because the probability of any given event to be equalled or exceeded is difficult to calculate. Thus, a more systematic approach has to be used.

All events in the time series could be used to assess the damages and this value is divided by the length of the time series (in years) in order to obtain a value for the Expected Annual Damage. However for efficiency in minimising computational demands, this approach is modified.

As drainage systems are designed to cope with most rainfall events without causing any flooding we can assume that only extreme events will generate flooding. This requires identification of what constitutes an extreme event for any given drainage system.

As consequence, dry periods and frequent rainfall events can be ignored.

1.2.1. Extreme event identification

Extreme events identification can be carried out by comparing every rainfall event with a known flooding threshold. This can be done in 3 steps:

1. All rainfall events (frequents and extremes) have to be extracted from the continuous time series, along with their individual intensity duration curves using a threshold approach. As flooding can come from very localised high intensity rainfall, intensity duration curves are based on the intensity of the wettest cell for each duration if spatial rainfall is being used.

2. An Intensity Duration curve for flooding of the catchment (i.e.catchment flooding threshold) has to be produced. This is achieved by running the model against various constant intensities for a range of durations.

3. Intensity Duration curves of every rainfall events are then compared to the catchment flooding threshold, and events for which the I/D curve is above the catchment curve for at least one duration are identified as extreme events which need to be used in evaluating the value of EAD.

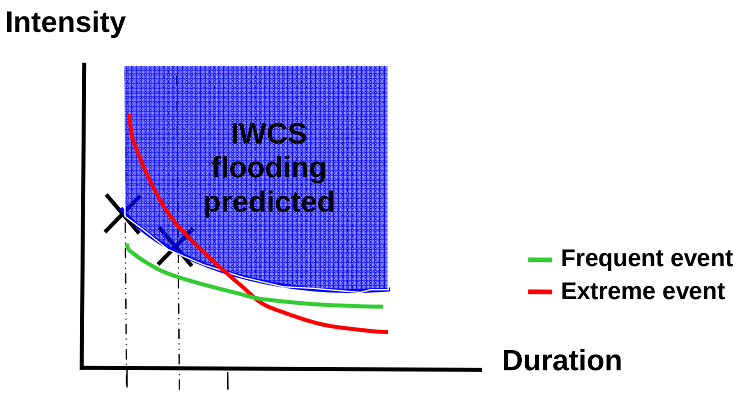


Figure 24 Identification of extreme events from a rainfall time series against an Intensity-Duration flooding threshold analysis of the drainage system

It should be noted that in using the wettest cell for the event Intensity Duration curves, this leads to an over-estimation of the number of extreme events, but it ensures that all relevant rainfall is captured.

1.2.2. Expected Annual Damages calculation

The Expected Annual Damage at impact zones or attributed to manholes is simply the sum of the damages obtained at each element (using all the extremes events), divided by the total time of the series:

$$\text{Expected Annual Damage} = \frac{\sum \text{Damage}}{\text{Time series period}}$$

As can be seen in Figure 25, contrary to the design event approach, the Expected Annual Damage calculation using time series rainfall is convergent but in a very different manner:

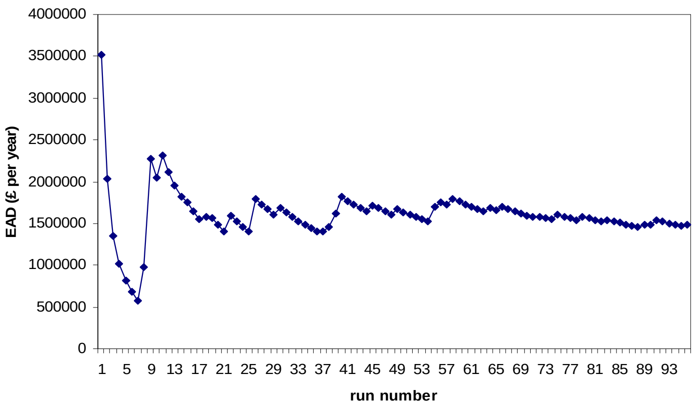


Figure 25 Example of Expected Annual Damage curve for time series rainfall approach

2. *Structural Failure*

When we consider structural failure, a pipe can have 3 possible states; it can be either blocked, collapsed, or operational. Under normal operation flood damage can only occur under extreme rainfall conditions, however for a structural failure analysis flooding can also occur during a frequent event or even during a dry day.

2.1. A- DESIGN STORM APPROACH

When performing a structural failure analysis using design storms, smaller return periods (i.e. frequent events) have to be considered as they could generate flooding.

In contrast to the method of approach used when the system is assumed to be operating normally (referred to as the hydraulic method) a "system state" has to be sampled for every possible return period. This sampling is based on a generation of 2 random numbers between 0 and 1 for each pipe, which are compared to the annual probabilities of collapse and blockage, to define the probable state of every pipe in the system.

If a system state with at least one failed pipe is sampled, because critical duration is not a relevant concept for a failed state (longer events will automatically generate more flooding and damage), a duration is randomly selected and run. Damage associated with that annual probability of non-exceedance (i.e. return period) is then the damage associated to that randomly selected duration. Otherwise, if the system state is fully functional, because the critical duration of impact zones (and manholes) has to be selected, all durations will be processed, but only for return periods that might generate flooding (Figure 26).

Notice that the sampling of the duration of the event, when a failed system state is selected, is based on the fact that each duration is equally probable (within a range of 30min to 24hrs).

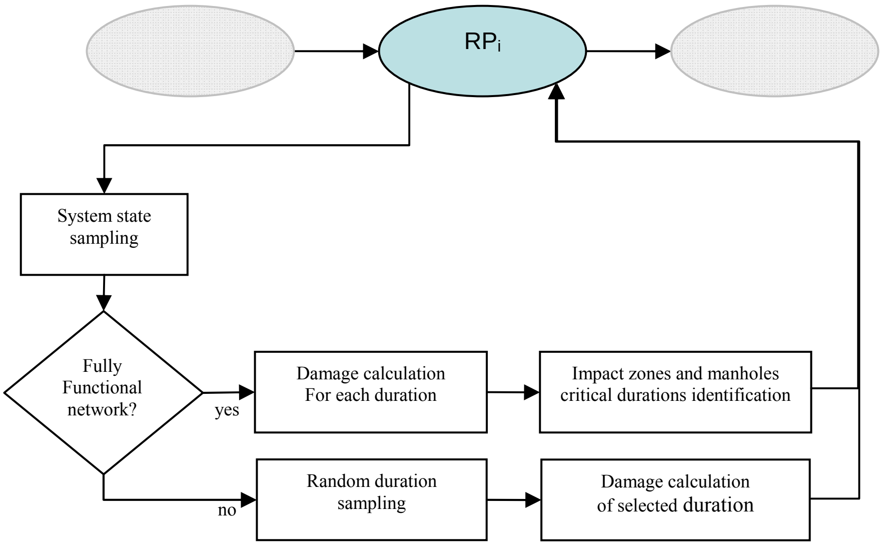


Figure 26 Difference in duration(s) processed according to the system state picked for a return period

However, because of the multitude of possible system states to consider, the set of return periods has to be addressed several times, and an updated averaged EAD calculation performed after each set, until convergence is reached (after a minimum number of iterations is considered):

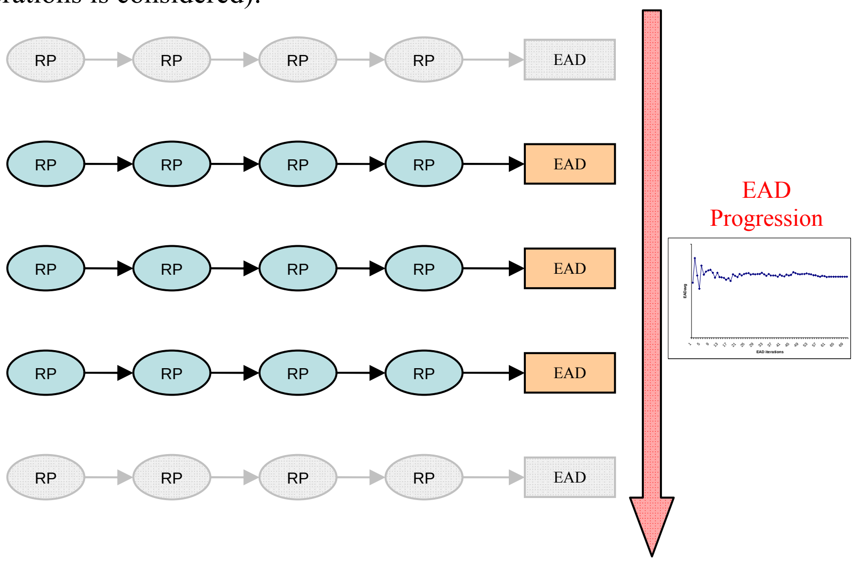


Figure 27 EAD calculation progression for structural failures analysis

As mentioned previously, in addition to the risk due to the occurrence of wet weather events, dry days also need to be considered. This risk is calculated based on a percentage of dry time per year and the damages associated with this period:

$$Risk_{dry\ days\ population} = Percentage\ dry\ time\ in\ a\ year * Damage$$

For each EAD evaluation, one system state is sampled for the dry weather period and the associated damage calculated if a failed system is sampled.

Notice that for reasons of speed of calculation, instead of running InfoWorksCS under a dry condition each time a failed system is selected for dry days, an IWCS simulation is carried out at the beginning of the analysis to measure the 6 hours dry weather averaged flow for each pipe and these volumes are used at the upstream manhole of every failed pipe.

Thus, because wet and dry days are mutually exclusive, risks can be summed:

$$Risk = Risk_{wet\ weather\ population} + Risk_{dry\ days\ population}$$

2.2. B- TIME SERIES RAINFALL APPROACH

In comparison to the design storm approach, when using a time series, we know the date when rainfall events are occurring. Therefore, when a property is damaged by an event, that property is assumed not to be damaged within a “time of recovery”. The damage repair time is divided into time slices for which only the worst damage will be considered for any location (Figure 28).

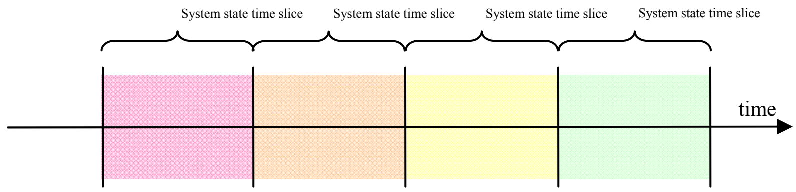


Figure 28 Time periods of time-series for assessing system states damage

If one or more extreme events occurs during a time slice (Figure 29a) only those events will be run to assess the maximum damage from all events in the time slice at each manhole/impact zone.

If only frequent events occur during a time slice (Figure 29b), no damage will occur if no pipes are “failed”. However, if the system state is different from the fully functional state, all frequent events should be performed and the worst damage at each manhole/impact zones recorded.

Notice that due to the number of InfoWorksCS simulations that would be required (e.g. up to 200 frequent events per year), it was decided to use the same logic as for dry weather days and use 30 randomly selected frequent events to produce an average flow for each pipe which is then used as the flood volume to spread at the upstream manhole of every failed pipe.

If no extreme or frequent events occur during a time slice (Figure 29c), no damage will occur if there is no collapse or blockage. But, if there is one or more pipes “failed” (for a foul or combined system), damage due to dry weather flows will be processed as described in design the storm approach. Any rainfall event below the frequent threshold (a very small event) would not have been extracted from the timeseries because no runoff is likely to take place for these events and therefore, they are also considered to be a “dry” event.

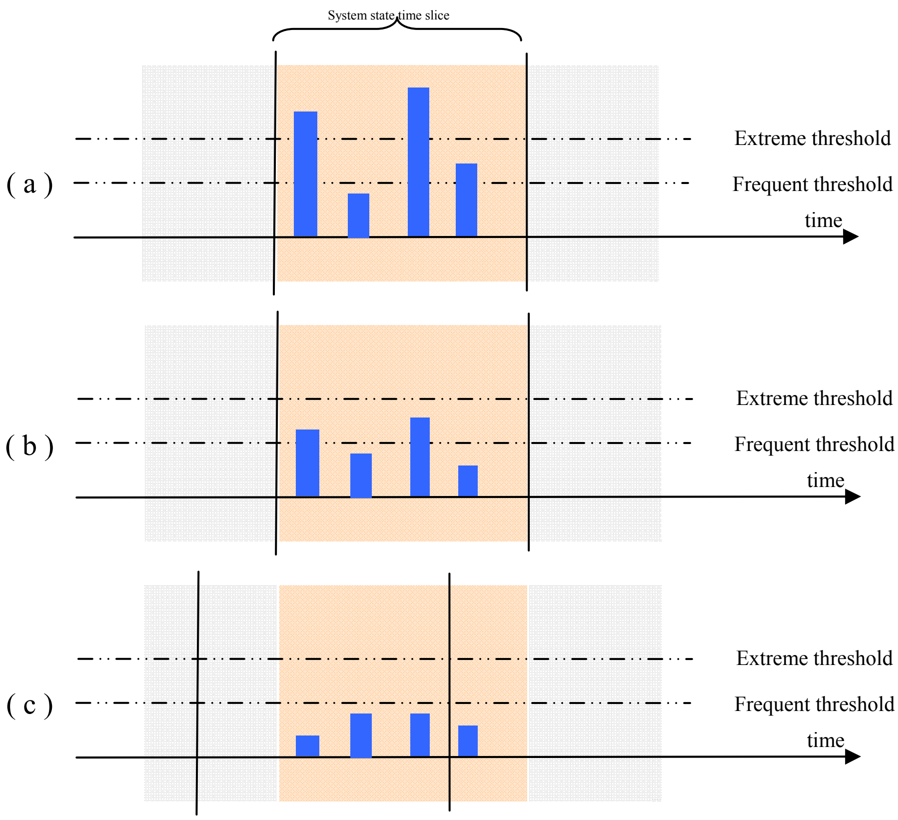


Figure 29 Illustration of the different cases rainfall into a time slice

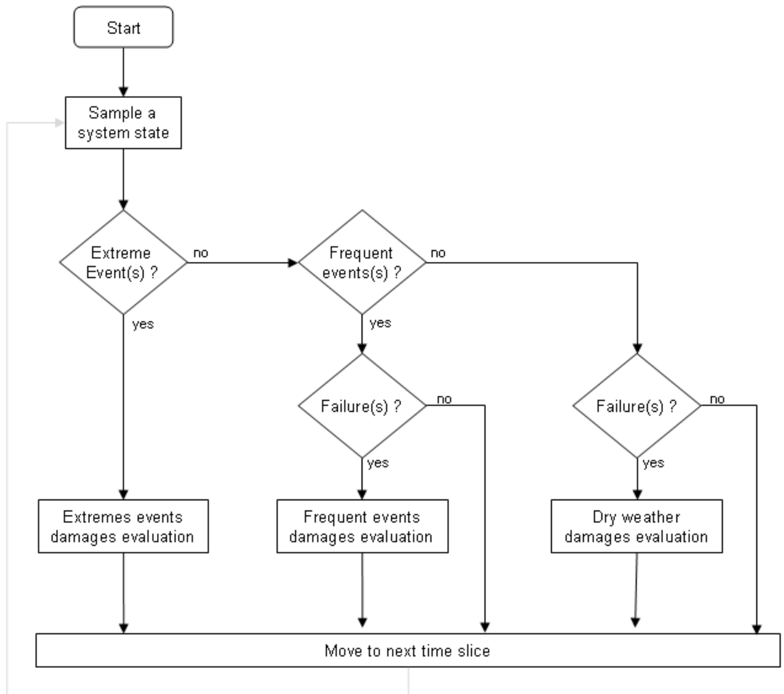


Figure 30 Time period damage evaluation process

Notice that this breakdown (Figure 30) enables the calculation of risk associated to each population of events (extreme events, frequent events and dry days) for each manhole/impact zone. The global risk is then:

$$Risk = Risk_{extreme\ events} + Risk_{frequent\ events} + Risk_{dry\ days}$$

3. Reference

Sayers, P.B., B.P. Gouldby, J.D. Simm, I. Meadowcroft, and J. Hall. 2002. Risk, Performance and Uncertainty in Flood and Coastal Defence – A Review. R&D Technical Report FD2302/TR1 (HR Wallingford Report SR587), Crown copyright, London, U.K.

Appendix 2 Dalmarnock pilot study

1. Introduction

The objective of the DTI SAM project was to develop a procedure and supporting tools for a risk based approach. The focus of the study was on the impact of flooding measuring the damage in terms of the probability and consequence. An important element of the study was attributing the flooding costs proportionally to specific assets that generated the flood damage.

This procedure has the potential to radically change current best practice of drainage management which is focused on system performance standards, and does not take into account potential system failure and its consequences, nor applies an objective cost-benefit measure of what is the most appropriate level of service that should be applied.

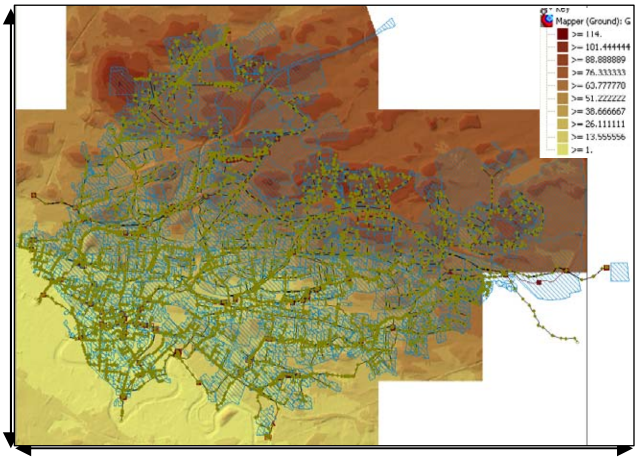
This report illustrates the use of this risk based approach as well as describing the prototype tools that have been developed by the project.

2. Pilot Study

2.1. DALMARNOCK CATCHMENT

As part of the project, 2 pilot studies have been selected based on known catchment wide problems and the existence of good data and models: Dalmarnock catchment and Keighley catchment; used as pilots by HR Wallingford and Sheffield University respectively. The first pilot is focused specifically on testing of the tools and the mechanics of the risk approach and the second had more emphasis on measuring the value of the procedure and the ability to apply it. The Keighley pilot study is reported separately and is not detailed in this statement.

The full Dalmarnock model is a relatively large verified model covering 77km^2 and including 5501 nodes, 5468 links, and 2172 subcatchments.



12 km

Figure 31 Dalmarnock Infoworks CS model

Table 2 Model characteristics

Area (km2)	96
Number of Nodes	5501
Number of Links	5468
Number of Subcatchments	2172
Number of weirs	145
Number of sluices	46
Number of pumps	10
Number of flumes	1
Number of orifices	41
Number of screens	1
Number of flap valves	11
slope m/m	0.01

It is mainly a combined system with a limited amount of separate foul pipework (Table 3).

Table 3 Pipe system

	conduit length (km)	conduit length (%)	Number of conduits (nbr)	Number of conduits (%)
Combined network	238.79	69.1	3823	69.9
Foul network	23.6	6.8	363	6.6
Storm network	83.08	24.0	1281	23.4
TOTAL	345.47	100	5467	100

2.2. PILOT STUDY MODEL

Because the purpose of Dalmarnock pilot study was to test tools and methods, and because it was anticipated that the application of the risk methodology would involved a significant number of InfoWorks CS simulations it was decided to use a small part of the model (Figure 32):

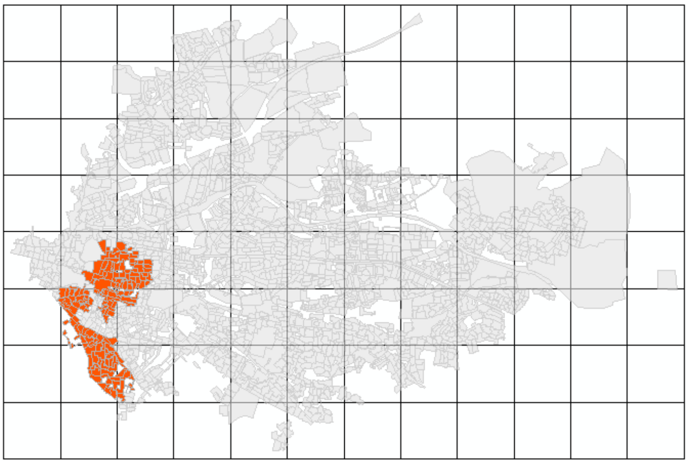


Figure 32 Dalmarnock pilot study model

Table 4 subset model characteristics

Area (km2)	14.73
Number of Nodes	376
Number of Links	377
Number of Subcatchments	153
Number of weirs	0
Number of sluices	1
Number of pumps	2
Number of flumes	0
Number of orifices	3
Number of screens	0
Number of flap valves	0
slope m/m	0.01

This pilot area is also dominated by the combined system, but it also had a culverted watercourse which provided a useful addition due to the different catchment response characteristics compared to the urban areas.

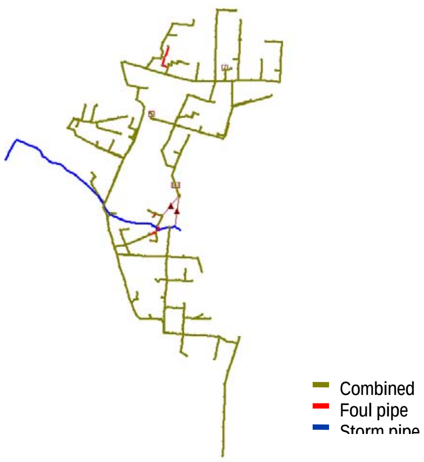


Figure 33 Dalmarnock combined, foul and storm pipes system

All the results reported in this report are based on the pilot network.

3. Hydraulic Failure Evaluation (Single system state)

The procedure allows for 2 alternative methods for analysing the system, firstly the use of a continuous rainfall series, and alternatively, the more traditional approach of using design storm events.

3.1. DESIGN EVENTS

One of the main advantages of a risk based analysis compared to the usual method of network performance analysis is that it incorporates the contribution of damages due to all possible events and evaluates the results in the form of Expected Annual Damages (EAD) which is an integral of the damage costs which occur on average every year due to flooding. To carry out the analysis requires the definition of a “matrix of design events” that are relevant for the system analysis.

For this study 700 events were used, based on 20 different durations (from 30 min to 600 min) and 35 return periods (from 2 years to 1000 years).

Using this matrix of events and the risk tool SAMRisk I (which assumes the system operates as normal); we obtained for the Dalmarnock catchment, the following Expected Annual Damage (EAD) curve was developed as shown in Figure 34.

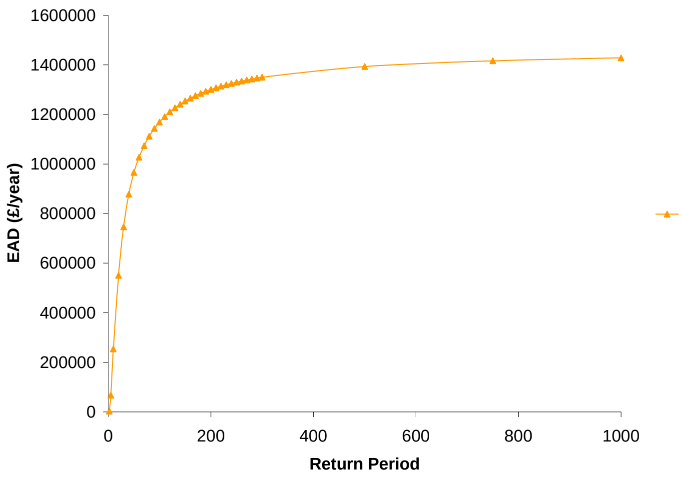


Figure 34 Pilot study Expected Annual Damage

As we can see in Figure 34, there is an EAD convergence by around 200-250 years return period but that 80% of the damage can be attributed to events up to 50 years. It should be noted that this may be catchment specific.

Even if this result is different for another catchment, it shows that less rare events, although generating less damage than rare events, due to their frequency of occurrence, they tend to be more important in terms of contribution to annual damage. This can also be observed on the value for EAD calculated using a single duration per return period (Figure 35) which shows that this phenomenon is not related to a specific duration, but is true for all durations.

It should be noted that the proportion of contribution to EAD for any return period or duration is dependant on the "shape" of the damage curves in terms of the flood depth/damage relationship, as well as catchment topography and network characteristics.

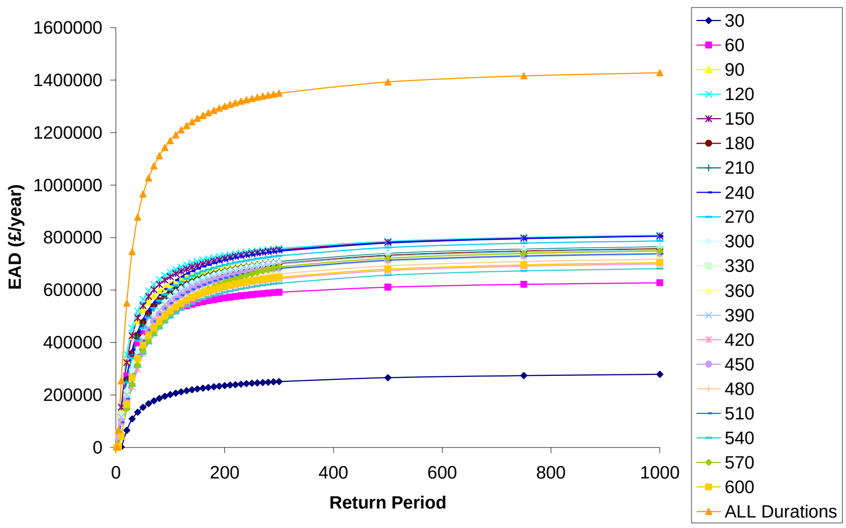


Figure 35 Catchment Expected Annual Damages profiles for a range of durations

We can also see from Figure 36 that using only one duration for each return period would lead to a serious underestimation of the EAD: 50 % or less for the pilot study model.

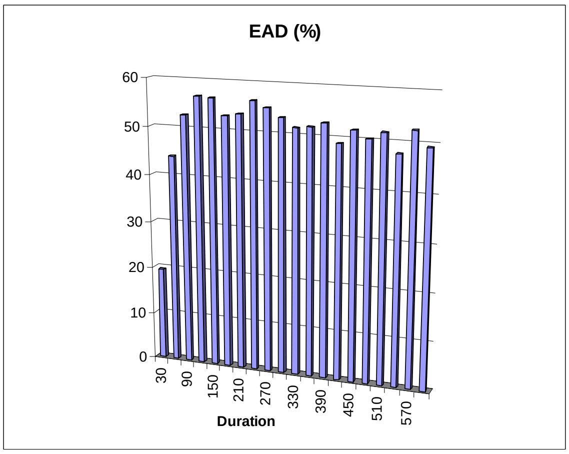


Figure 36 Catchment Expected Annual Damage using a single duration for all return periods

Not only would the EAD value be underestimated, but depending on which duration is considered, it would target specific parts of the network with short durations tending to be more critical for manholes upstream in the system while long durations generally being more critical for manholes further downstream (Figure 37 and Figure 38)

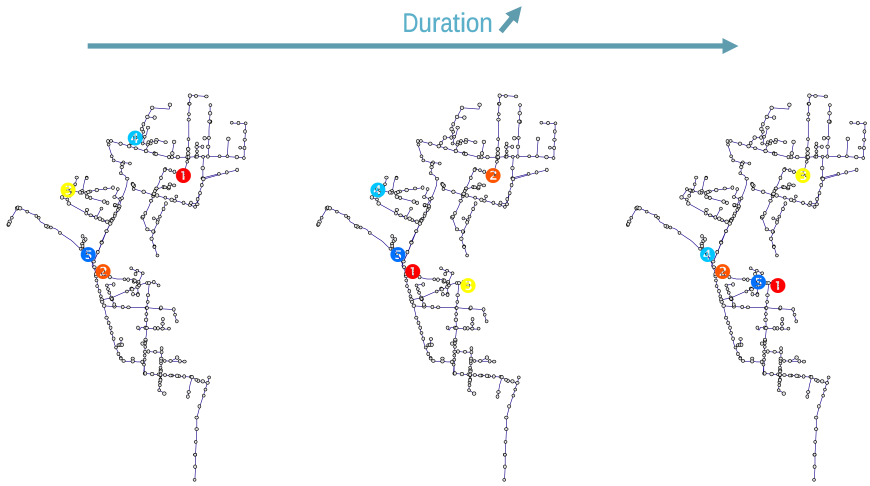


Figure 37 Variation of targeted manholes according to duration considered

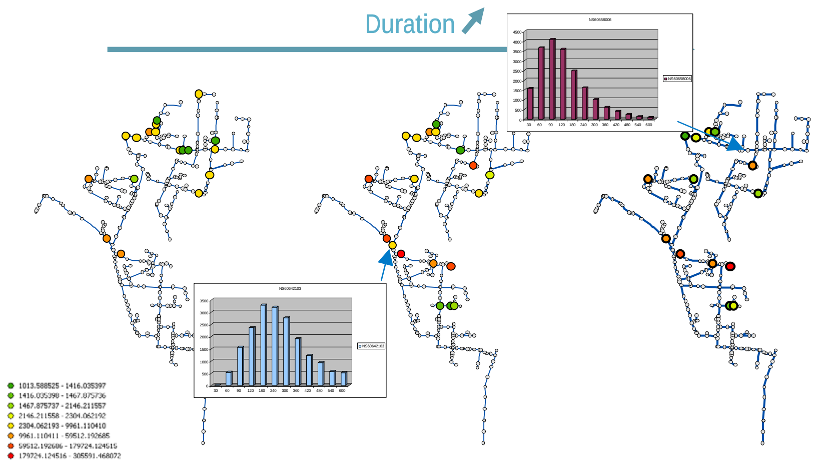


Figure 38 Variation of damages according to duration considered

Because any one duration per return period will not give a correct catchment EAD, and because different durations target different manholes, it is crucial to include in the matrix of events an appropriate set of durations suitable for the network to make sure that all manholes are assessed for their maximum flood volume. In addition it is important to stress that short return periods were also found to have a significant impact on EAD and therefore that it is important to include them in the matrix of events.

However it is obvious that a complete matrix of 700 events (20 durtations and 35 return periods) is computationally demanding, so investigations were made as to whether EAD for the network could be approximated using a small subset of these events.

3.1.1. Appropriate matrix of events (selection of durations-return periods)

Various tests were made of subsets of return periods and durations. The tests appeared to show that it is relatively easy to approximate the catchment EAD using a combination of a few durations and return periods, and this is illustrated in Table 5.

Table 5 Catchment EAD using reduced matrix of events

Return periods (years)	Reference	5 – 50		5 -10 - 50		5 – 10 – 20 – 50 - 100
Duration (min)		60 - 240	90 - 240	60 - 240	90 - 240	90 - 240
EAD (£)	1428076	1404899	1420904	1206171	1216133	1281719
EAD (%)	100	98.2	99.5	84.5	85.2	89.8

However, if the EAD for the top 7 manholes that generate the highest damages are examined (Table 6) this approach shows that individual manholes' EAD are not well reproduced.

Table 6 Manholes EAD using reduced matrix of events

Return periods (years)	Reference	5-50		5-10-50		5-10-20-50-100
Duration (min)		60 240	90 240	60 240	90 240	90 240
Manhole ID	£ per year	%				
NS60649802	474718	79	82	82	84	89
NS60637916	306233	0	0	0	0	7
NS60643003	282697	225	225	210	210	213
NS60641102	89407	140	140	107	107	110
NS59649705	83847	143	143	67	67	78
NS60636902	61582	0	0	0	0	6
NS60655104	39592	148	154	70	73	73

As can be seen in Table 6, for some manholes (NS60637916 and NS60636902), the EAD is close to 0 and for others (like NS60643003), the damage expected each year using a few return periods and durations is badly overestimated compared to the reference matrix, even though the EAD at the catchment scale has been fortuitously (inadvertently) well reproduced.

a) Threshold of flooding of each manhole

As described in appendix 1, it is very important to capture the threshold of flooding of each manhole to avoid an overestimation of the damages. NS60643003 and NS60641102 are examples where this hasn't been achieved.

As Table 7 shows, these two manholes are already spilling at the lowest return period considered (5 years). Therefore, for the risk calculation, the 5 years damage calculation for this event will be applied to all more frequent events, which leads to severe overestimation of EAD.

Table 7 Critical duration and damage associate for the seventh critical manholes at each return period (using 20 Durations and 35 return periods)

	NS60641102		NS60643003		NS60649802		NS60655104		NS59649705		NS60637916		NS60636902	
Return period (years)	Duration (min)	Damage (£)	Duration (min)	Damage (£)	Duration (min)	Damage (£)	Duration (min)	Damage (£)	Duration (min)	Damage (£)	Duration (min)	Damage (£)	Duration (min)	Damage (£)
2	30	0	30	0	30	0	30	0	30	0	30	0	30	0
5	240	44012	270	564562	30	0	30	0	30	0	30	0	30	0
10	300	232880	600	781612	90	2674796	120	3656	30	0	30	0	30	0
20	450	822489	600	1991268	90	3354293	90	245061	240	759084	600	1367003	600	358582
30	390	1009309	450	2146631	90	4255682	150	545129	240	1342281	600	4438801	600	1012665
40	330	1050875	480	2156960	90	4641699	150	684132	240	1420744	600	5138525	600	1228807
50	270	1066611	330	2151805	150	4833445	150	783330	240	1488672	480	5370243	600	1382639
60	240	1083548	300	2149947	150	4929808	150	868662	240	1528853	480	5370243	600	1477930
70	210	1071291	270	2167386	150	4996568	240	915028	240	1557016	600	7065945	570	1481626
80	210	1088491	270	2162842	150	5037433	270	969368	240	1587095	600	8415411	510	1442450
90	180	1071523	270	2147298	180	5092644	300	978651	270	1606810	600	9093841	450	1408059
100	180	1063703	240	2136028	180	5136822	360	1012617	240	1626801	600	9395655	420	1396966
110	180	1049394	240	2141141	180	5205025	390	1040157	240	1641610	600	9619769	390	1400967
120	150	1051102	210	2094353	210	5297217	420	1048444	300	1660620	600	10118122	360	1358094
130	150	1060930	210	2105070	240	5371805	450	1071956	270	1674071	600	10504008	360	1414934
140	150	1079336	210	2088017	240	5421511	510	1094432	270	1686163	600	10685002	330	1349061
150	150	1057986	180	2121974	270	5443741	480	1107363	270	1701804	600	10785937	330	1419068
160	150	1035427	180	2089464	270	5494869	540	1112728	300	1715041	600	10851025	330	1447983
170	120	1030012	180	2017285	270	5516207	600	1126453	300	1726536	600	10900231	300	1385598
180	120	1037055	180	2020231	300	5557479	600	1148778	300	1739144	600	10927991	300	1449343
190	120	1037243	150	2036025	300	5597184	570	1157635	300	1749439	600	10946770	270	1362403
200	120	1049007	150	2050948	300	5625818	600	1161037	300	1758087	600	10955727	270	1406659
210	120	1057835	150	2063807	300	5637190	600	1152471	300	1764533	600	10967537	270	1427310
220	120	1057433	150	2066033	300	5660202	600	1163931	300	1774089	600	10971904	270	1447137
230	120	1050574	150	1996239	330	5684155	570	1156104	300	1781503	600	11046482	270	1445164
240	120	1042643	120	1929022	330	5715074	600	1168830	300	1789379	600	11065197	240	1388919
250	120	1035206	120	1937685	360	5731621	600	1171223	300	1796373	600	11076855	240	1411617
260	90	1028195	120	1947569	360	5766171	570	1164697	390	1803559	600	11090870	240	1454872
270	90	1034709	120	1951542	360	5796210	600	1175654	390	1809595	600	11095223	240	1468311
280	90	1038207	120	1960680	360	5812152	570	1154002	300	1815841	600	11108493	240	1479950
290	90	1046798	120	1968698	390	5843726	600	1169387	390	1823734	600	11108509	240	1456777
300	90	1055448	120	1969319	390	5876020	600	1165545	390	1830200	600	11118153	210	1364240
500	90	1124132	90	1829521	510	6127205	570	1111457	510	1935198	480	11104801	180	1442895
750	90	1096121	90	1679559	600	6281311	600	1070832	600	2018551	390	11002449	150	1442309
1000	60	1142505	60	1663187	600	6302454	570	1023552	600	2071613	600	11392009	120	1388312

To avoid this situation, the user has to make sure that every manhole does not generate any flooding for at least one of the return periods selected.

As can be seen in Table 8, if the matrix includes an event for which these two manholes are not generating flooding (2 year event), the EAD for these manholes is no longer overestimated.

Table 8 Improvement of manholes EAD using reduced matrix of events – Threshold of flooding of each manhole

Return periods (years)	Reference	5-50		5-10-50		5-10-20-50-100	2-5-10-20-50-100
Duration (min)		60 240	90 240	60 240	90 240	90 240	90 240
Manhole ID	£ per year	%					
NS60649802	474718	79	82	82	84	89	89
NS60637916	306233	0	0	0	0	7	7
NS60643003	282697	225	225	210	210	213	76
NS60641102	89407	140	140	107	107	110	75
NS59649705	83847	143	143	67	67	78	78
NS60636902	61582	0	0	0	0	6	6
NS60655104	39592	148	154	70	73	73	73

Notice that for some manholes several return periods were not generating flooding. This has no implication for an accurate assessment of damages, but only indicates a loss of analytical efficiency.

b) Capturing the critical duration

As described in appendix 1, it is very important to capture the critical duration of each manhole to avoid an underestimation of the damages. NS60637916 and NS60636902 are examples when this hasn't been achieved.

As can be seen in Figure 39, by considering either 60 and 240 or 90 and 240 minutes durations, damages for any given return period are much smaller than with longer durations (especially 600 minutes).

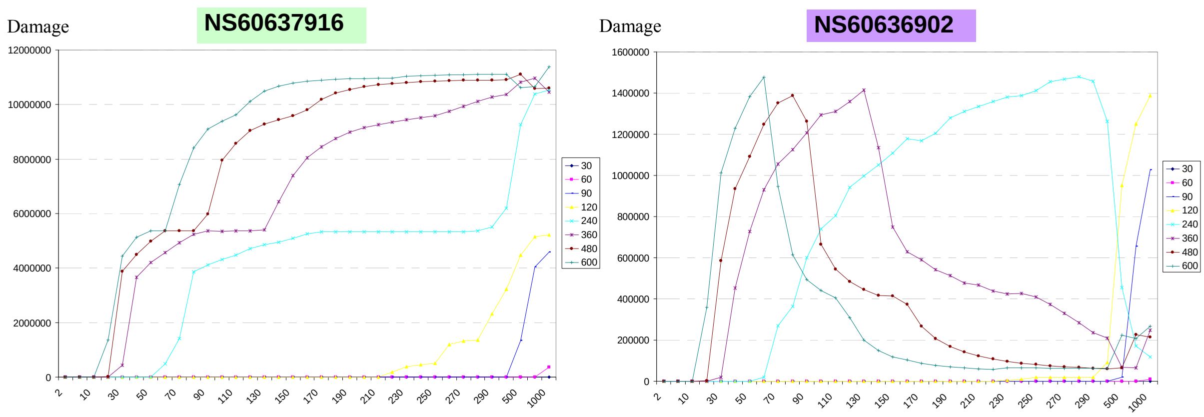


Figure 39 Damages at 2 manholes for different durations for a range of return periods

Therefore, if 600 minutes is included in the matrix of event durations for which these two manholes are generating flooding/damages, the EAD as these manholes is no longer underestimated.

Table 9 Improvement of manholes EAD using reduced matrix of events – Capturing the critical duration of each manhole

Return periods (years)	Reference	5-50		5-10-50		5-10-20-50-100	2-5-10-20-50-100	2-5-10-20-50-100
Duration (min)		60 240	90 240	60 240	90 240	90 240	90 240	90 240 600
Manhole ID	£ per year	%						
NS60649802	474718	79	82	82	84	89	89	89
NS60637916	306233	0	0	0	0	7	7	66
NS60643003	282697	225	225	210	210	213	76	90
NS60641102	89407	140	140	107	107	110	75	80
NS59649705	83847	143	143	67	67	78	78	78
NS60636902	61582	0	0	0	0	6	6	71
NS60655104	39592	148	154	70	73	73	73	73

The lesson learnt from this assessment into running a reduced matrix of events suggests that:

1. A high level of resolution is needed in terms of frequency at low return periods, but a coarse selection can be applied for events above 20 years.
2. The range of critical duration events should be assessed for a catchment and this cannot be significantly reduced.
3. That following these two rules, the estimated value of EAD will be under-estimated in the region of 10% to 20%.

3.2. TIME SERIES RAINFALL

3.2.1. Rainfall events identification

As an alternative to the use of design storm events, the hydraulic failure risk tool (SAM-Risk I) enables the use of time series rainfall. In this case, the matrix of durations/return periods has to be replaced by a set of events extracted from a time series.

The pilot study used a continuous spatial series generated by Newcastle University, an output from a different task of this project.

Using this dataset and a rainfall processing tool also developed by the project, processing of the rainfall series identified 14286 rainfall events from a 70 years time series.

Most of these events would not generate flooding (without a structural failure event occurring), so these events were filtered to select those which might cause flooding assuming the system was operating normally.

3.2.2. Catchment flooding threshold – Extremes identification

To be able to identify the relevant extreme events, a flooding duration curve of the catchment was produced.

To do this, the IWCS model was run using a range of uniform constant intensity events for a range of conditions and checked for flooding. If no flooding occurred, the intensity was increased for the same duration until flooding took place. This defined an intensity-duration threshold curve above which network flooding could be expected.

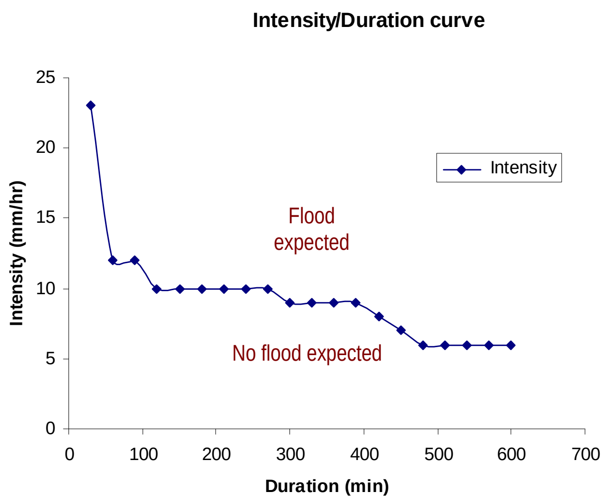


Figure 40 Dalmarnock catchment flooding threshold

It can be seen that when the duration increases the threshold intensity defining the transition between flooding and no flooding, decreases.

Using this threshold intensity curve and the intensity duration curve of each event (which is a direct output from the rainfall processing tool), **97** events were identified as extreme events for the 70 years time series.

3.2.3. Results

Performing the hydraulic failure risk analysis with the 97 events which were identified as potentially causing flooding, it was observed that only **41 events** actually generated flooding (Figure 41).

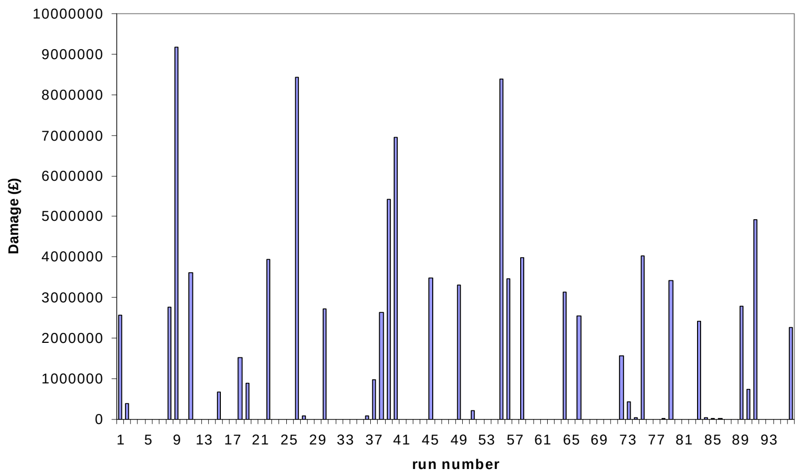


Figure 41 Damages due to the selected 97 extreme events

This is due to the fact that using a uniform intensity over the whole catchment is an extremely conservative assumption because the spatial rainfall series was checked against the intensity/duration relationship at each cell (1 km^2) of the model. No doubt further improvements might be made in reducing the number of events as 50% redundancy leads to a doubling of the run time for this analysis.

The average annual damage expected for the catchment is shown in Figure 42.

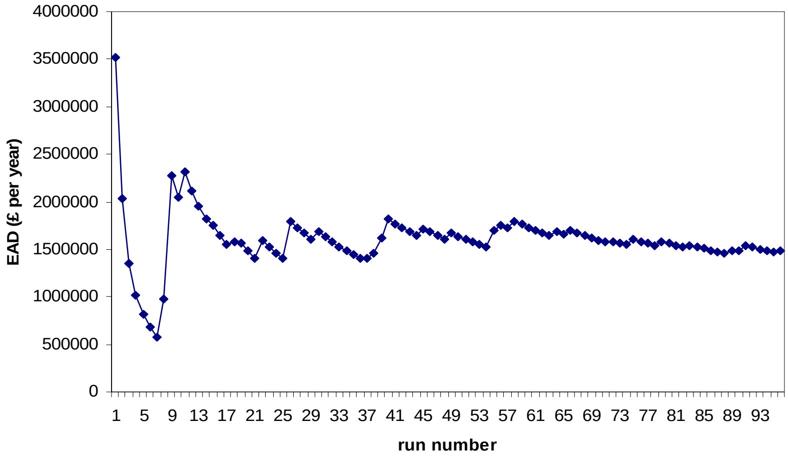


Figure 42 Dalmarnock Expected Annual Damages using Time series events

As can be seen from Figure 42, even if the value of damage between events fluctuates widely (Figure 41), at the catchment scale a quick convergence of the total EAD is obtained.

However, if we again look at the Expected Annual Damage for the top five manholes, we can see that, the EAD for the whole catchment is largely driven by the EAD of one manhole, but in addition that for some manholes (especially number 4) the convergence would not have been considered as having been reached yet.

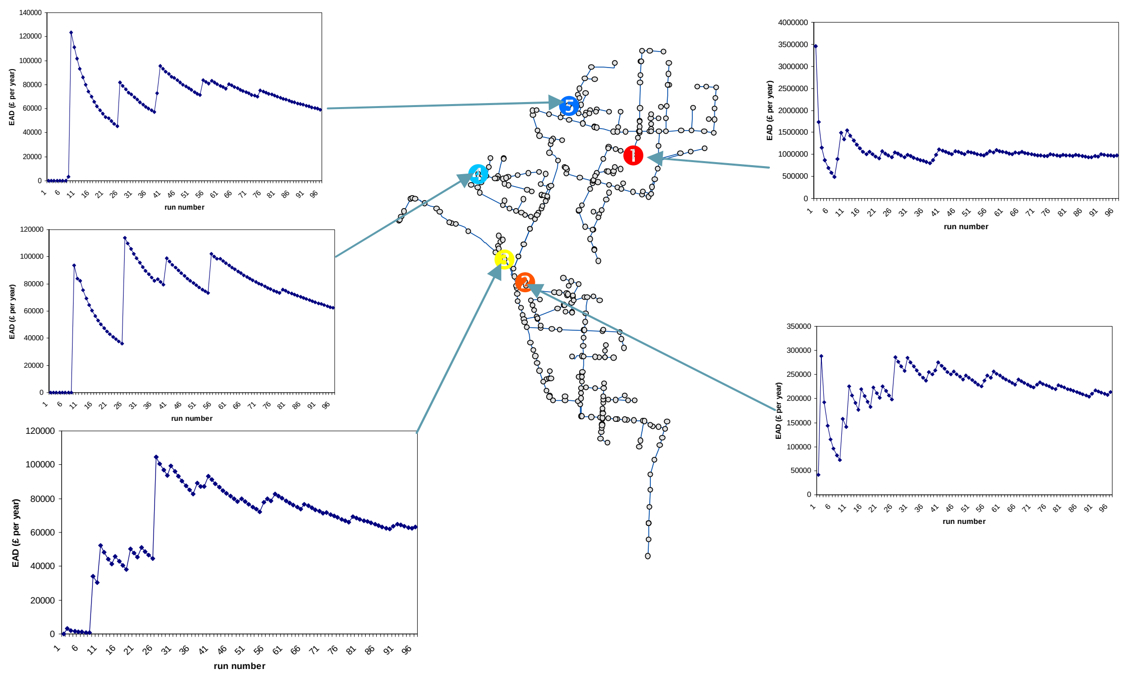
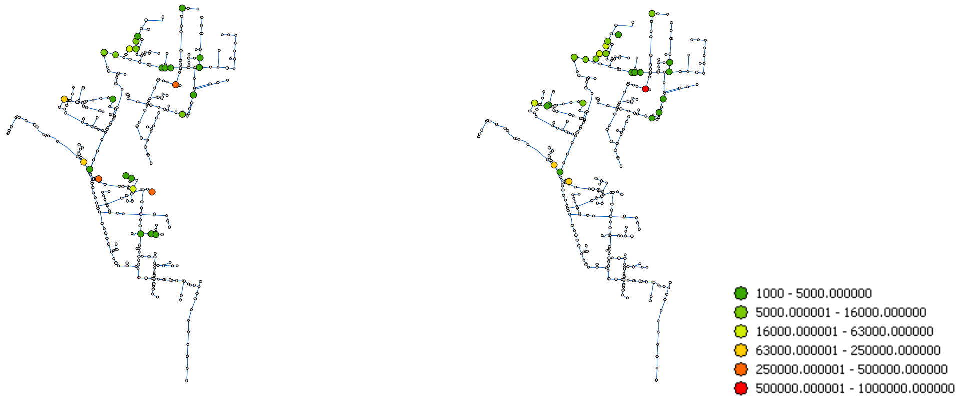


Figure 43 Convergence of manholes Expected Annual Damages

As a consequence, a longer time series may be needed for some nodes compared to others to obtain an accurate assessment of EAD.

If a comparison is made of the EAD obtained at the manholes using the design storm and the time series approach, we can see that the spatial distribution of EAD is different (Figure 44). This suggests that the time series may not reflect the same hydrological properties as those assumed in design storms. Which is more correct would require detailed investigation, but it should be noted that the assumption of uniform rainfall across the catchment when using design events is not true and will also be affecting the results.



Design storms Time series Rainfall

Figure 44 Comparison of Dalmarnock EAD using design storm or time series rainfall

3.3. IMPACT ZONE OUTPUTS

In addition to the calculation of Expected Annual Damage at each manhole, the risk based analysis tool provides information at the receptor location (Impact Zones).

3.3.1. Manholes EAD distribution

As can be seen in Figure 45 the tool allows identification of the Impact Zones that are flooded by flood water for every manhole.

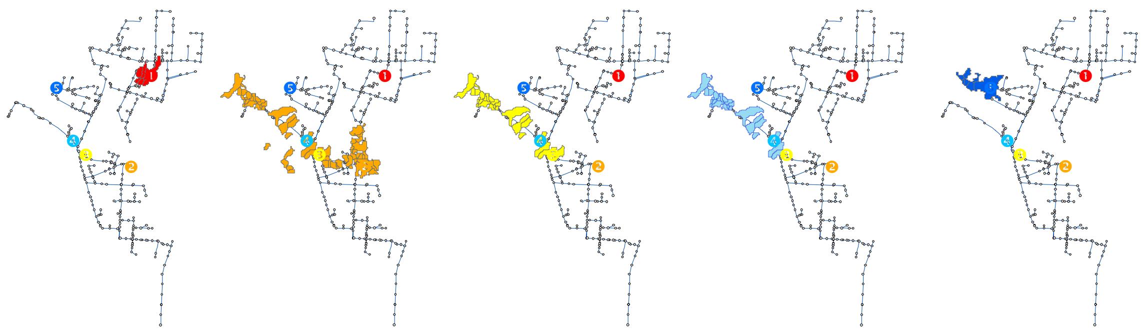


Figure 45 Example of damage locations identification (Impact Zones)

The tool calculates the damage costs for each Impact Zone associated with the flooding volume from all manholes. The tool then makes a proportional calculation in attributing the damage costs in each Impact Zone back to each manhole which contributed to the flood damage by proportion based on the tracked volume of water from each manhole.

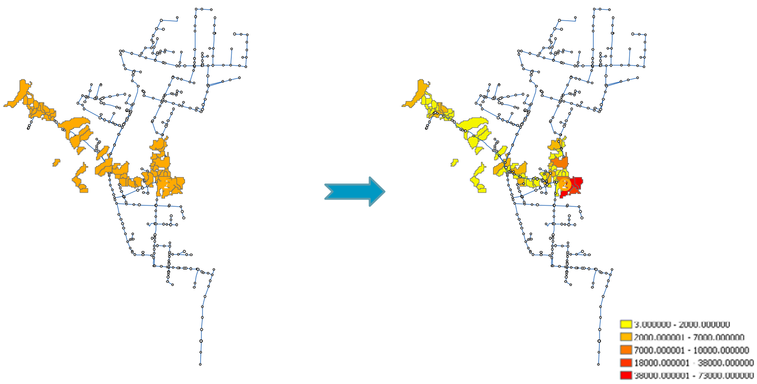


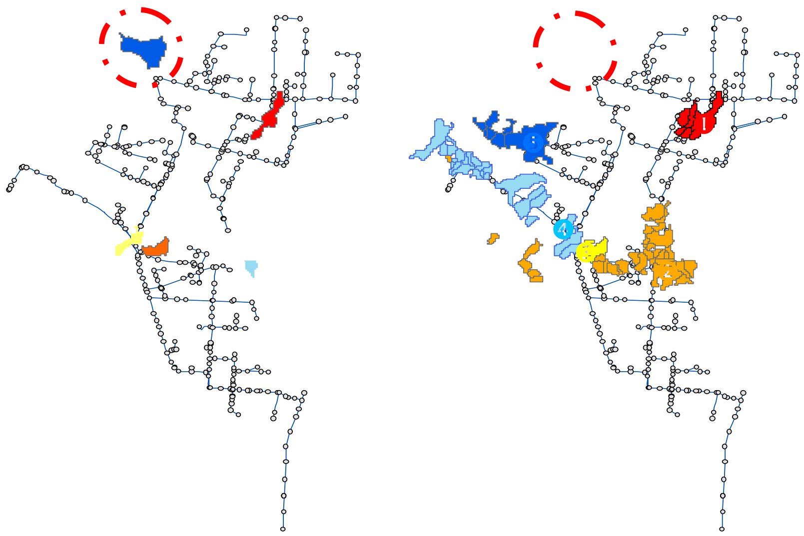
Figure 46 Distribution of damages due to a manhole across impact zones

3.3.2. Impact zone EAD

For every impact zone, the risk based analysis tool also outputs the total damage due to all manholes that are contributing to it and therefore the EAD value is also obtained for each impact zone.

Figure 47 Catchment map of Expected Annual Damages

However, as we can see on Figure 48 which represents the five impact zones with the highest amount of damage (left) and compare this with the 5 top manholes in terms of attributed EAD, it can be seen that one impact zone (circled in red) is not related:



Top 5 impact zones Top 5 manholes

Figure 48 Illustration of the difference in focussing manholes and impact zones

This is due to the fact that some Impact Zones may received flood damage contribution from a large number of manholes and therefore suffer a high level of damage with each manhole contributing a fairly small proportion of the damage (see Figure 49).

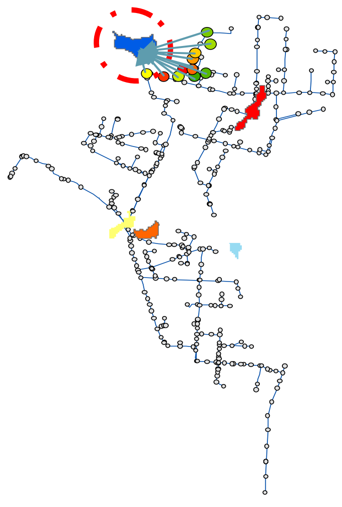


Figure 49 Manholes contributions to one of the top 5 impact zones.

3.3.3. *Flood frequency*

When performing a risk analysis using design events, the SAM-Risk I tool also provides flood frequency of every Impact Zone (Figure 50). This is not strictly a risk based approach, but it is considered that the concept of a minimum level of service is still relevant even if a risk based approach is applied to assessing a network and its management needs.

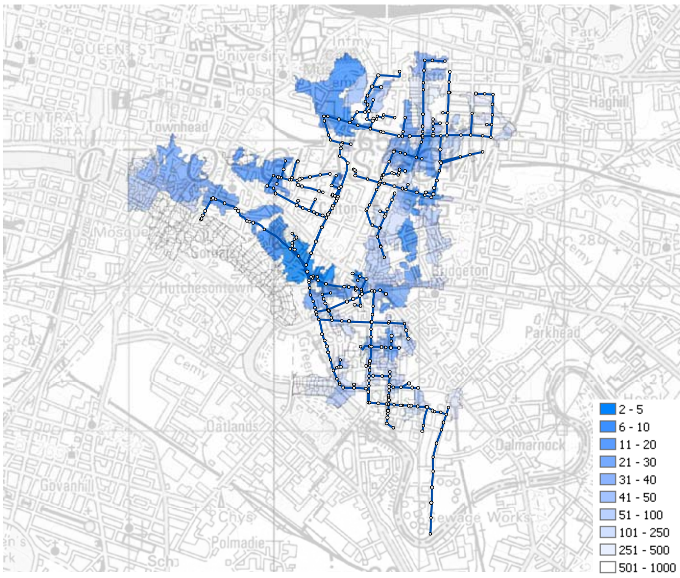


Figure 50 Impact zones flood frequency map (all return periods)

The tool can therefore generate flood maps for any or all the return periods that have been run, such as the 50 years event flood map (Figure 51):

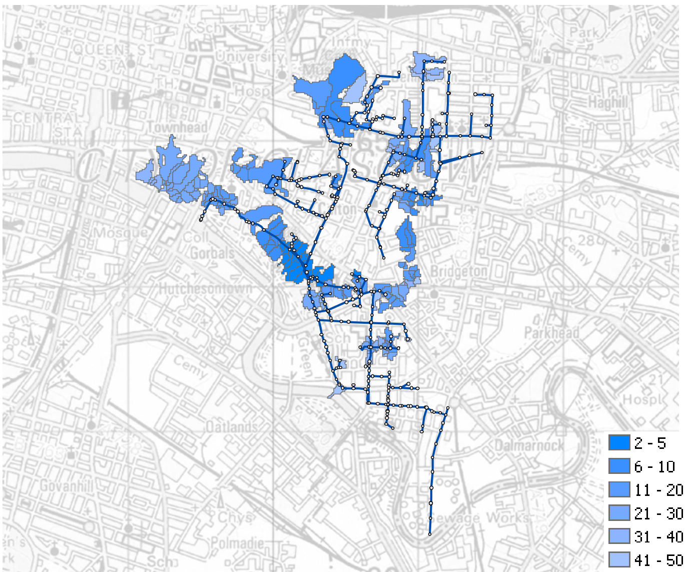


Figure 51 Impact Zones flooded by events up to a 50 years return period

It is important to notice that showing the flooding of impact zones instead of cells, shows the entire impact zone identified as flooded as soon as any cell within it has flood damage. For more detailed flood analysis it is more appropriate to show flooding at the cell level. It should be noted that the cost basis is only applied at the cell level and the values aggregated to report information at the level of the impact zone.

4. Assets failure evaluation

4.1. PIPES' PROBABILITIES OF COLLAPSE AND BLOCKAGE.

The risk based approach based on the assumption that the network is considered to operate normally (in the sense that no collapse or blockage of any pipe takes place) is strictly incorrect. It is important to recognise that other systems states involving assets failure exist where each pipe has the possibility to "fail" (collapse or block). The probabilities of failure of each asset are difficult to predict and are unique for each pipe and piece of equipment.

For the purpose of the Dalmarnock pilot study, correlation equations have been used based on the pipe length, the diameter, the age, the traffic load, the number of connected properties and the gradient to predict the frequency of blockage or collapse. These are similar to existing equations that have recently been produced by research carried out by the water industry:

$$\text{Likelihood of blockage} = \frac{7.5618 \times 10^{-12} \sqrt{Ncon \times L}}{G^2 \times D^2}$$

$$\text{Likelihood of collapse} = \frac{7.5618 \times 10^{-12} \times Tr \times \sqrt{A \times D \times L}}{D}$$

Equation 1 Equations of likelihood of blockage - collapse

With L : pipe Length (m)
D : Diameter (m)
A : Age (yr)
Tr : Traffic Load (vehs/hr)
Nconn : Number of connected properties
G : Gradient

These equations reflect the fact that small diameter long pipes with low gradients and many properties connected will tend to block more often than others, and that old, long pipes with high traffic loading will tend to collapse more often.

Because the InfoWorks model does not contain information on age, number of connected properties nor traffic load, and because the purpose of the pilot study was to demonstrate the applicability of a risk based calculation and not to provide answers which were necessarily correct, relationships to available information were used to generate these variables in order to obtain plausible probabilities of collapse and blockage (Table 10).

$$\text{Age(years)} = \text{diameter(m)} \times 100$$

$$\text{Traffic Load} = \text{diameter(m)} \times 25000$$

$$\text{Number of connected properties} = \frac{\text{pipe length(m)}}{5} \text{ if pipe diameter} \leq 450\text{mm or } \frac{\text{pipe length(m)}}{15} \text{ if pipe diameter} > 450\text{mm}$$

Equation 2 Equations used to evaluate age, traffic load and number of connected properties

These relationships are acknowledge as being arbitrary and based on simple logic. For instance, it was assumed that big diameter pipes will probably be old with higher traffic loads, and that small diameter pipes will be connected to more proprieties.

The probabilities generated (Table 10) are fairly realistic when compared to industry information.

Table 10 Example of probabilities of collapses and blockages

us_node_id	link_ suffix	Age (years)	width (m)	length (m)	Tr	Ncon	Gradient	Blockage	Collapse
new mh11	1	160	1.6	102.7	40000	6.85	0.00438	4.08E-06	3.07E-05
newmh1	2	105	1.05	105.8	26250	7.05	0.00232	3.48E-05	2.04E-05
newmh10	1	160	1.6	106.4	40000	7.09	0.00438	4.23E-06	3.12E-05
newmh12	1	160	1.6	109.2	40000	7.28	0.00437	4.36E-06	3.16E-05
newmh14	1	60	0.6	47.3	15000	3.15	0.00131	0.000149	7.8E-06
newmh2	1	105	1.05	106.4	26250	7.09	0.00233	3.47E-05	2.05E-05
newmh3	2	105	1.05	86.2	26250	5.75	0.00232	2.84E-05	1.84E-05
newmh4	1	105	1.05	87	26250	5.80	0.00234	2.81E-05	1.85E-05
newmh5	2	105	1.05	87.9	26250	5.86	0.00279	2E-05	1.86E-05
newmh6	1	67.5	0.675	85.7	16875	5.71	0.0028	4.68E-05	1.18E-05
newmh7	1	160	1.6	98.5	40000	6.57	0.00115	5.68E-05	3E-05
newmh8	1	160	1.6	97.1	40000	6.47	0.00115	5.6E-05	2.98E-05
newmh9	1	160	1.6	111.2	40000	7.41	0.01294	5.06E-07	3.19E-05

4.2. DRY WEATHER FLOW CALCULATION (IWCS INITIALISATION PHASE PROBLEM)

Because the SAM-UMC tool developed as part of the project to enable the large number of simulations to be set-up and run automatically cannot add or remove any component to a network but only change parameters, representation of blocked and collapsed pipes are achieved by sizing the selected ‘failed’ pipe size to a diameter of 20mm. However, because every InfoWorks CS simulation is composed of two phases: an initialisation phase prior to simulation, a dry weather flow calculation is performed to set up the initial state of the sewer network, and this is used for the simulation phase during which the rainfall event is run. This is because the pipe size reduction will result in an initialisation failure if there is a dry weather flow in the model.

Two options were therefore available; the first is to ignore all dry weather flow, or to reconfigure the model to include the dry weather flow as part of the event based information.

4.2.1. *Assuming zero dry weather flow*

The easiest solution is to simply remove all forms of dry weather flow from the model. As no water is applied to the network during the initialisation phase, initialisation is achieved. But doing so, underestimates the flood damage as some water is removed that should have been included.

Modifying the model to remove dry weather flow, a hydraulic failure analysis using both updated and original networks was carried out to evaluate how important the underestimation would be for Dalmarnock. Results are reported below:

Table 11 Example of the impact of dry weather flows on EAD

Return Period	5 - 10 – 20 – 50 – 100	
Durations	90 – 240	
Network	Original Network	dry weather flows removed
EAD (£)	1281719	1084458
%	100	85

As can be seen from Table 11, removing all forms of dry weather flows reduces the damage by 15%. It is therefore quite important to represent the dry weather flows in the model through a first pass analysis would justify this approach for most systems.

4.2.2. *Conversion of all forms of dry weather flows into an inflow file*

To enable the model to run, the model has to be modified to convert the base flow and waste water flow for each subcatchment into an inflow to apply at the receiving manhole; and allocate the first minute of flow to zero to enable the initialisation phase to converge.

Figure 52 represents pipe flow examples using both original and updated networks for an InfoWorksCS simulation without any rainfall. As can be seen, the results are identical which means that the dry weather flow modification approach has been implemented correctly.

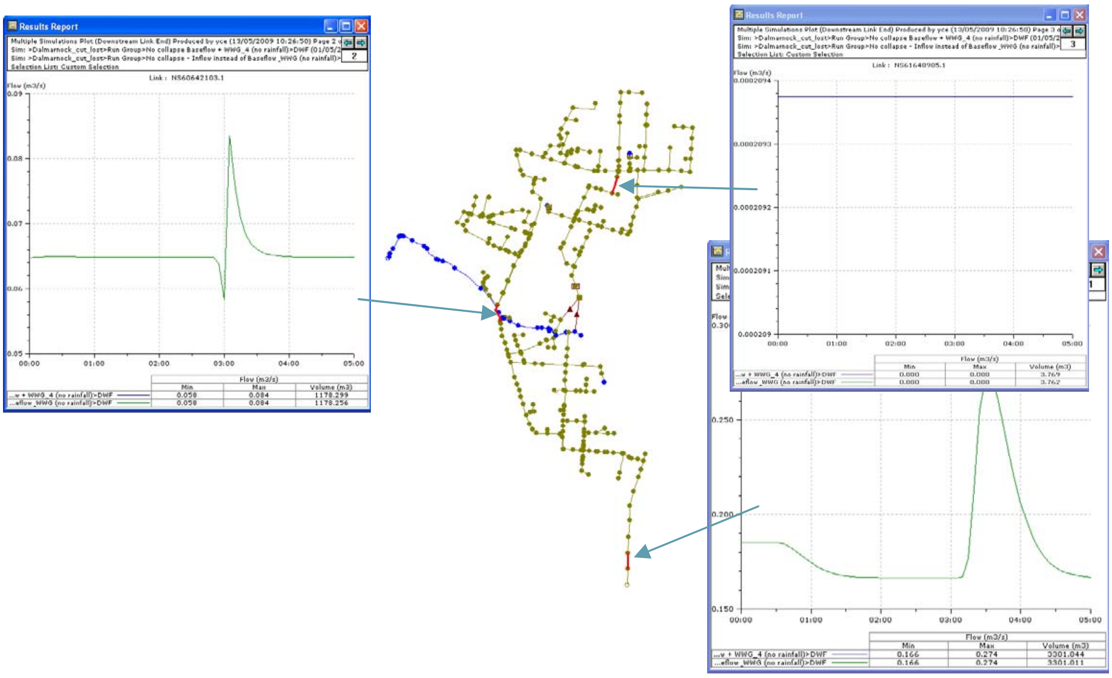


Figure 52 Validation of the conversion of dry weather flows into inflow file

To check that the models behave in the same way a hydraulic analysis between the improved updated network and the original network was carried out to evaluate the difference. Results are reported below:

Table 12 Validation of inflow file utilisation in EAD evaluation

Return Period	5 - 10 – 20 – 50 – 100	
Durations	90 – 240	
Network	Original Network	dry weather flows converted into inflow file
EAD (£)	1281719	1280963
%	100	99.94

As can be seen in Table 12, the use of an inflow file has reproduced the same value for EAD to better than 0.1%.

4.3. ASSETS FAILURE RESULTS

Because it was decided at an early stage to develop in parallel two different tools to study the so called hydraulic only failure or single system state (SAM-Risk I) and the assets failure or multiple system states (SAM-Risk II) a check was carried out of the second tool by using a zero percent probability of collapse or blockage, to check that the results (Table 13) were the same for both tools.

Table 13 Validation of structural failure analysis with 0% probability of failure (using hydraulic failure tool)

Hydraulic Failure analysis tool		Assets failure analysis tool (with 0% probability of collapse or blockage)	
Dry weather flow removed	Dry weather flows converted into inflow file	Dry weather flow removed	Dry weather flows converted into inflow file
£ 1084458	£ 1280963	£ 1084458	£ 1280963

As can be seen in Table 13, the assets failure tool provides exactly the same output as the hydraulic tool, which demonstrates that the assets failure analysis tool is working correctly.

An assets failure analysis was carried out using realistic probabilities of collapse or blockage described in 3.1, to see the influence of the assets failure component compared to the hydraulic failure only case.

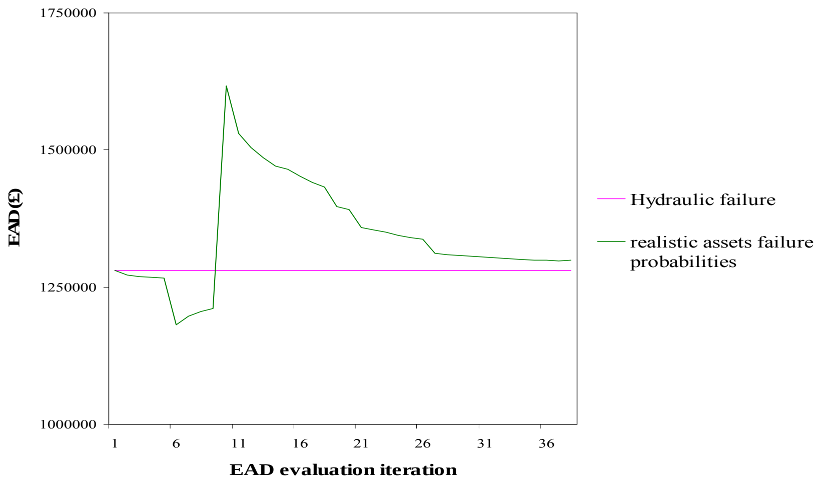


Figure 53 Catchment assets failure EAD comparing to Hydraulic failure EAD

The Expected Annual Damage values obtained whether structural failure was assumed or not, were reasonably similar. This suggests that the influence of the collapses/bockages on the value of Expected Annual Damage is very small.

To be able to illustrate the difference in EAD between hydraulic failure only and with assets failure, unrealistically high probabilities of failure were used (Figure 54).

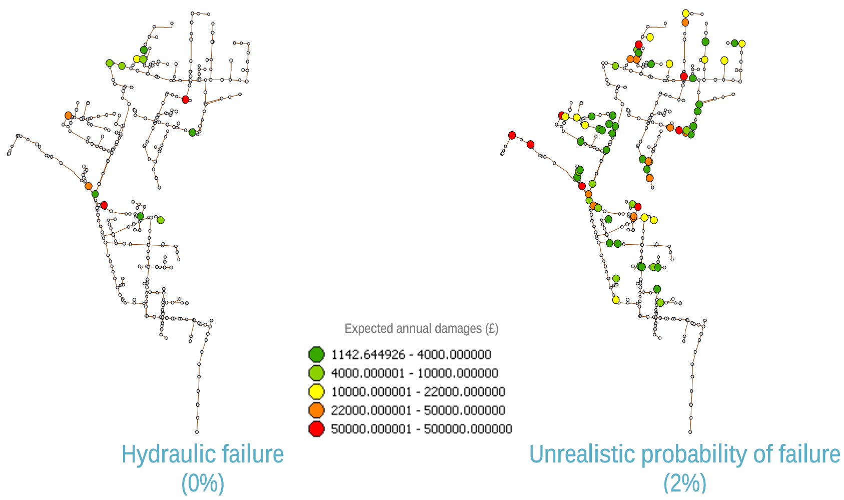


Figure 54 Influence of the blockages and collapses on the manholes EAD (using very high probabilities of failure)

As can be seen in Figure 54, by using very high probabilities of failure, some manholes that were not surcharged during an hydraulic failure risk calculation, had flooding due to a blockage or collapse. As a result, the Expected Annual Damage become unrealistically high, but does demonstrate the potential of the tool for assessing various asset states.

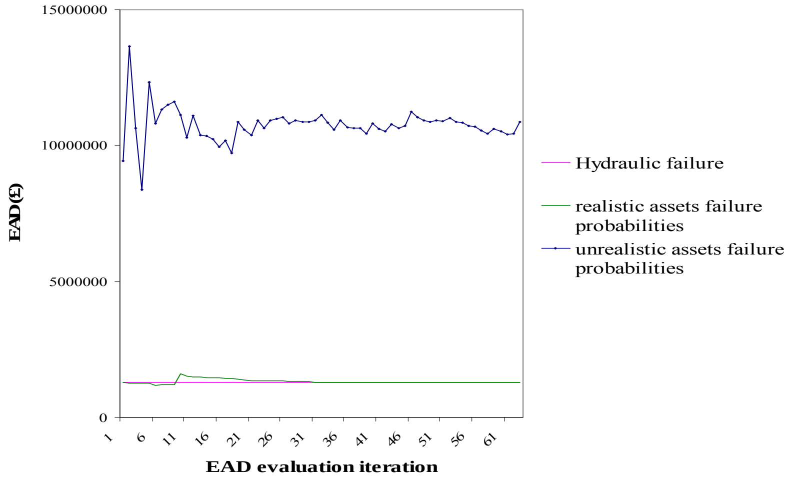


Figure 55 Influence of the blockages and collapses on the catchment EAD (using unrealistic probabilities of failure)

5. Conclusion

The DTI SAM project has developed a new procedure and tools for an integrated analysis of drainage systems using a risk based approach. The Dalmarnock pilot study has helped to demonstrate that these tools are now available to perform a systematic risk-based approach that enables strategic decision-making to be made on the basis of consequences instead of performance.

It also provides recommendations on how to apply the procedure (like selection of rainfall events and dry weather flow integration) along with typical outputs at catchment level, manhole level and impact zones level.

Finally, although more tests are needed to confirm that the level of impact of asset failures is small, it suggests that asset failure should not be the focus of a risk based approach to urban drainage management. There is definitely a need for applying a risk based approach to multiple system states, but considering the additional computational demand and the limited contribution to EAD for 'failed' states, it is proposed that these two assessments are made separately as the needs requires.

Appendix 3 SAM-Risk tool

1. Introduction

The SAM-Risk tool was designed as probabilistic risk tool for integrated urban drainage and surface flooding. While the SAM-UMC tool enables one scenario to be run each time, SAM-Risk manages the preparation of the scenarios and performs the probabilistic analysis that is needed for the calculation of risk.

In brief, SAM-Risk:

- Initialises IWCS;
- builds the first scenario:
  - selects rainfall to input;
  - selects the network and the network condition;
  - prepares the SAM-UMC input file for the single scenario;
- launches the SAM-UMC;
- extracts the results for this single SAM-UMC run;
- uses these results as input for the Risk calculation;
- determines the next scenario according to the results and the probabilistic criteria;
- manages the outputs;
- calculates the convergence and uses this and other parameters as ‘stop criteria’.

2. SAM-Risk I and SAM-Risk II: differences between the two parts of the SAM-Risk tool

The SAM-Risk tool was designed to receive inputs from both design storms and time-series rainfall. The choice between the two inputs depends on the data availability; although the time-series rainfall can be more accurate, the design storms are usually most widely available to the user. Both SAM-Risk and SAM-Risk II can receive inputs from either designed storms or time-series rainfall.

SAM-Risk was designed to study the two cases where the network is assumed to either operate ‘normally’, or to consider all possible system states (including blockage and structural failure). The choice between the two methods depend on the availability of data concerning the pipes’ probability of failure or the assumption that system failure is not a likely or relevant scenario.

Therefore, SAM-Risk tool has been designed as two separate sub-tools: **SAM-Risk I**, that calculates the risk associated with normal network operation, while **SAM-Risk II** calculates the risk taking into account the probability of failure due to potential collapse and blockage.

3. 'SAM-UMC': general overview

The SAM-UMC software supports a linked InfoWorks CS / RFSM model. In principle, this tool can support multiple runs, however SAM-UMC only allows to define 'a priori' the number and scenarios to be run. Therefore the SAM-Risk tool needed to be developed to enable runs to be made which took into account the result of previous model runs.

The SAM-UMC first calls the IWCS model. An IWCS model run consists of:

- Making changes to the attributes of some nodes and/or conduits.
- Specifying the set of rainfall data and wastewater data
- Specifying other run parameters such as duration
- Running the simulation
- Extracting the results from the simulation – volume lost from manhole nodes.

The SAM-UMC then takes the flood volumes from the IWCS run and calls the RFSM (Rapid Flood Spreading Model), which distributes the volume over the catchment area and calculates the depth of water in individual Impact Zones and/or Cells. The software can also calculate estimates of the damage caused.

CSV (comma-separated variables) results files are produced. File names consist of a fixed stem followed by the run name:

- IWCS results named IWCS_RunName.csv, contains the flooding volume for each node.
- RFSM cell results named RFSMCell_RunName.csv, that is produced after a successful RFSM run which has produced cell-based results. Contains Cell ID, depth and damage for each cell in the RFSM model which has produced a non-zero depth.
- RFSM Impact Zone results named RFSMIZ_RunName.csv. Contains the value of depth and damage for each Impact Zone in the RFSM model which has produced a non-zero depth. The damage value is the associated estimate of damage.
- RFSM Impact Zone source results named RFSMIZSource_RunName.csv. Contains IZ, node id, 'ratio' and damage for each Impact Zone in the RFSM model which has produced a non-zero depth. There is one line for each IWCS node that has contributed to the flooding in that Impact Zone. The 'ratio' value (> 0 and ≤ 1) is the proportion of the volume in the Impact Zone which has been contributed by the IWCS flooding node.

4. 'SAMRisk I'

The 'SAM-Risk I' tool is provided with a graphic user interface (Figure 56) for loading the required data and parameter values. This section describes all the required inputs.

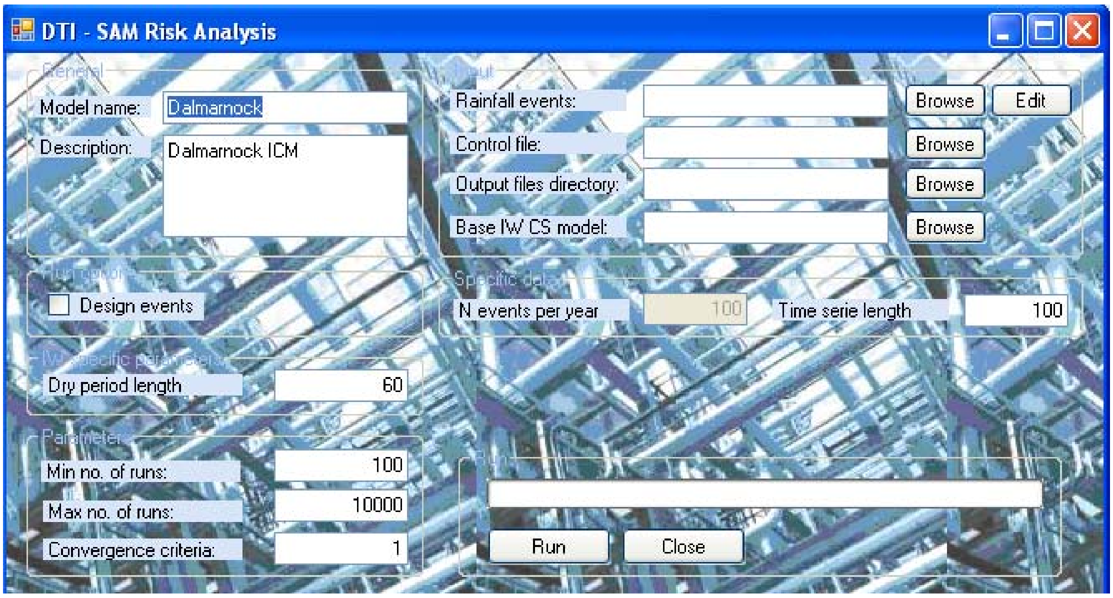


Figure 56 SAMRisk I user interface

4.1. INPUT DESCRIPTION

4.1.1. 'Model name'

The name of the model. This name will be used only to name the output files.

4.1.2. 'Description'

An arbitrary description of the model.

4.1.3. 'Rainfall events'

This field contains the path to the CSV input file containing the information regarding the rainfalls. When the 'Design events' box is ticked, this CSV file contains:

Rain file (path+name)	Return time	Duration

Otherwhise, this file will need to contain:

Rain file (path+name)	Severity	Duration	Year	Month	Day	Hours	Minutes

Where the year, month, day, hour, minutes fields refers to the event start date.

4.1.4. 'Control file'

This file is a standard SAM-UMC control file. The 'Field 4' after the Rainfall Group and the Duration are arbitrary, as they will be updated reading the rainfall file, as well as the 'Field 3' in the Rainfile. The 'Field 3' in the MasterDB line will be updated with the path given in the 'Base IW CS model' input field (see below), while the Catchment and the Network names need to be the correct ones.

*BATCHDATA START			
IWCS	MasterDB	S:\11.0 Hydraulic model\Dalmarnock.iwm	
IWCS	Catchment	Dalmarnock_cut_lost	
IWCS	Network	ICM_BASE_008#1	
IWCS	Rain	Rainfall Group	
IWCS	Waste	WWG	WWG_2
IWCS	Inflow	Inflow	Inflow
RFSM	DBServer	BARNOCK	
RFSM	Dbname	MwDalmarnock2	
OPTION	ResultsFolder	d:\work\DTISAM\Risk\model\Results	
OPTION	RunRFSM	TRUE	
OPTION	SaveDB	TRUE	
OPTION	SaveCsv	TRUE	
*BATCHDATA END			
*RUN START	No Changes		
IWCS	Rain	Rainfall Group	hallo
IWCS	Run	Duration	200
IWCS	Run	TimeStep	30
IWCS	Rainfile		
*RUN END			

4.1.5. *'Output files directory'*

This field contains the directory where the output files will be stored

4.1.6. *'Base IW CS Model'*

This field points to the IWCS model that contains the base network.

4.1.7. *'Number of Events per Year'*

This parameter is used only in the case where design storms are used (and therefore the 'Design events' box is ticked), and it is used in the formula of the Expected Annual Damage. The default value is 100.

4.1.8. *'Time Series Length (years)'*

This parameter is used only in the case where time-series rainfall are used (and therefore the 'Design events' box is not ticked), and represent the whole length (in years) of the rainfall time-series that is used as input. This parameter is used in the formula for calculating the Expected Annual Damage.

4.1.9. *'Dry period length'*

This parameter refers to a hypothetical duration that is added at the end of each rainfall event to ensure all flooding volume that can spill from the network after the rainfall event is ended is accounted for. The default value is 120 minutes.

4.1.10. 'Min. no. of runs'

This parameter is the minimum number of events that have to be run before the convergence is checked, and therefore the minimum number of run in the simulation. The default value is 100.

4.1.11. 'Max. no. of runs'

This parameter is the maximum number of events that are to be run. The actual number of runs will be always bounded between the Min. no. of runs and the Max. no. of runs. The default value is 10,000.

4.1.12. Convergence criteria

The convergence test is based on the percentage difference between two subsequent results in terms of EAD for a specified IZ/node or group of IZ/nodes, or the system as a whole. The default value is 1%.

4.1.13. Dry event probability

This parameter is the probability of a dry event.

4.2. OUTPUT DESCRIPTION

4.2.1. Dalmarnock_ExpectedAnnualDamage.csv

Contains the EAD calculated for each run.

N	EAD

4.2.2. ModelName_FinalSummaryNodes.csv

This file contains the final results for each node, including the Expected Annual volume spilled by the node, the EAD associated to the node, and the number of times the node fails.

It is important to emphasise that the nodes that are in this output file are not all the nodes of the network, but only the ones which fail. Therefore, if some nodes are not present in this file, no flooding has occurred at these locations. Furthermore, if a node is present, but the EAD is 0, it means that the node failed, but without causing any damage. This can be possible if the flow depth is below to the minimum threshold in the depth-damage curve or if there is nothing of value being flooded.

Node_ID	Total_Volume_out	Total_Damage	N_times_failed

4.2.3. ModelName_DamagePerNodePerDurations.csv

This file is only created when design storms are used and contains the total damage associated with each RP and each duration node by node.

Rp	Duration	N1	...	Nn	TotalDamageperRP

4.2.4. ModelName _VolumePerNodePerDurations.csv

This file is only created when design storms are used and contains the total damage associated to each RP and each duration node by node.

Rp	Duration	N1	...	Nn	TotalVolumeperRP

4.2.5. ModelName _IZDamageTotal.csv

If design storms are used, this file contains:
IZID , minimum RP that caused damage in this IZ , EADamage for IZ , Node 1 (damage caused by) , Node 2 , .. , Node n

If time-series rainfall is used, this file contains:
IZID , number of time that this IZ has been flooded , EADamage for IZ , Node 1 (damage caused by) , Node 2 , .. , Node n

4.2.6. ModelName _IZDamagePerRP.csv

This file is only created when design storms are used, and contains the damage obtained for IZ for RP:

IZID	RP	damage

5. 'SAMRisk II'

As with the 'Sam Risk I', the 'SAM-Risk II' tool is provided with a graphic user interface (Figure 57) that is used to load the required parameters.

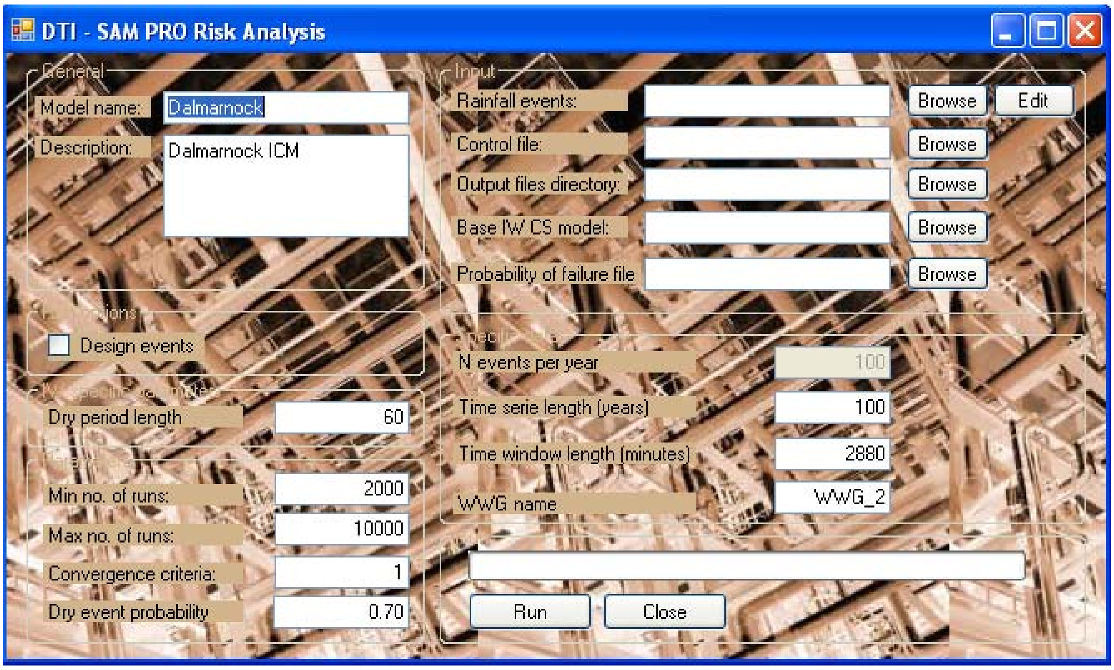


Figure 57 SAMRisk II user interface

5.1. INPUT DESCRIPTION

5.1.1. *'Model name'*

The name of the model. This name will be used only to name the output files.

5.1.2. *'Description'*

This field contains an arbitrary description of the model.

5.1.3. *'Rainfall events'*

This field contains the path to the CSV input file containing the information regarding the rainfalls. When the 'Design event' box is ticked, this CSV file contains:

Rain file (path+name)	Return time	Duration

Otherwise, this file will need to contain:

Rain file (path+name)	Severity	Duration	Year	Month	Day	Hours	Minutes

Where the year, month, day, hour, minutes fields refers to the event start date.

5.1.4. *'Control file'*

This file is a standard SAM-UMC control file. The 'Field 4' after the Rainfall Group and the Duration are arbitrary, as they will be updated reading the rainfall file, as well as the 'Field 3' in the Rainfile. The 'Field 3' in the MasterDB line will be updated with the path given in the 'Base IW CS model' input field (see below), while the Catchment and the Network names need to be the correct ones.

*BATCHDATA START			
IWCS	MasterDB	S:\11.0 Hydraulic model\Dalmarnock.iwm	
IWCS	Catchment	Dalmarnock_cut_lost	
IWCS	Network	ICM_BASE_008#1	
IWCS	Rain	Rainfall Group	
IWCS	Waste	WWG	WWG_2
IWCS	Inflow	Inflow	Inflow
RFSM	DBServer	BARNOCK	
RFSM	Dbname	MwDalmarnock2	
OPTION	ResultsFolder	d:\work\DTISAM\Risk\model\Results	
OPTION	RunRFSM	TRUE	
OPTION	SaveDB	TRUE	
OPTION	SaveCsv	TRUE	
*BATCHDATA END			
*RUN START	No Changes		
IWCS	Rain	Rainfall Group	hallo
IWCS	Run	Duration	200
IWCS	Run	TimeStep	30
IWCS	Rainfile		
*RUN END			

5.1.5. ‘Output files directory’

This filed points to the directory where the output files will be stored.

5.1.6. ‘Base IW CS Model’

This field needs to point to the IWCS model that contains the base network.

5.1.7. ‘Probability of failure file’

File containing the probabilities of failure for each pipe. The file is in .csv format and is structured as:

us node id	link suffix	AGE	conduit_width (in m)	conduit length	Tr	Ncon	gradient	Blockage	Collapse

Where:

“us node id” is the ID of the upstream node of the pipe;
“link suffix” is the suffix of the pipe as defined in IWCS;
“AGE” is the age of the pipe;
“conduit_width (in m)” is the width of the conduit in meters;
“conduit length” is the length of the conduit in meters;
“Tr” is the traffic load;
“Ncon” is the number of properties connected to the pipe;
“gradient” is the gradient of the pipe;
“Blockage” is the probability of blockage of the given pipe;
“Collapse” is the probability of collapse of the pipe;

The probability of blockage and collapse varies with location and information on this should be sought from appropriate authorities or experts.

5.1.8. ‘Number of Events per Year’

This parameter is used only in the case where design storms are used (and therefore the ‘Design events’ box is ticked), and it is used in the formula of the Expected Annual Damage. The default value is 100.

5.1.9. ‘Time Series Length (years)’

This parameter is used only in the case where time-series rainfall are used (and therefore the ‘Design events’ box is not ticked), and represent the whole length (in years) of the rainfall time-series that is used as input. This parameter is used in the formula for calculating the Expected Annual Damage.

5.1.10. ‘Time window length’

This parameter is used only in the case time-series rainfall is used (and therefore the ‘Design events’ box is not ticked), and represent the length (in minutes) of the “window” of events to be analysed (appendix I).

5.1.11. 'WWG name'

Waste water group to be used for the dry event (appendix 2).

5.1.12. 'Dry period length'

This parameter refers to a hypothetical duration that is added at the end of each rainfall event to ensure all flooding volume that can spill from the network after the rainfall event is ended is accounted for. The default value is 120 minutes.

5.1.13. 'Min. no. of runs'

This parameter is the minimum number of time EAD is calculated before the convergence is checked. The default value is 100.

5.1.14. Max. no. of runs'

This parameter is the maximum number of events that are to be run. The actual number of runs will be always bounded between the Min. no. of runs and the Max. no. of runs. The default value is 10,000.

5.1.15. 'Convergence criteria'

The convergence test is based on the percentage difference between two subsequent results in terms of EAD for a specified IZ/node or group of IZ/nodes, or the system as a whole. The default value is 1%.

5.1.16. Dry event probability

This parameter represents the probability of the dry event.

5.2. OUTPUT DESCRIPTION

5.2.1. ModelName _ExpectedAnnualDamage.csv

This file contains the EAD calculated for each run:

N	EAD

5.2.2. ModelName _FinalSummaryNodes.csv

This file contains the final results for each node, including the Expected Annual volume spilled by the node, the EAD associated to the node, the number of times the node is failed (both hydraulically and due to blockage/collapse) and the Expected Annual Damage associate to each possible failure:

- EA damage due to blockage/collapse in dry weather,
- global EA damage due to extreme event,
- EA damage due to blockage/collapse in extreme event,
- global EA damage due to failure,
- EA damage due to blockage/collapse failure,
- global EA damage due to hydraulic failure (field called 'Weigh Damage NFAIL').

It is important to emphasise that the nodes that are in this output file are not all the nodes of the network, but only the ones who fail. Therefore, if some nodes are not present in this file, no flooding has occurred at these locations. Furthermore, if a node is present but the EAD is 0, value means that the node failed, but without causing any damage. That can be possible if the outflow volume is below to the minimum threshold in the depth-damage curve or if there is nothing of value being flooded.

The structure of the file is shown below:

Node ID	E_A Volume out	E_A Damage	N times failed	Weigh Damage Dry_block	Weigh Damage Dry_coll

Weigh Damage Ex	Weigh Damage Ex_block	Weigh Damage Ex_coll	Weigh Damage FAIL	Weigh Damage Freq_block	Weigh Damage Freq_coll	Weigh Damage NFAIL

5.2.3. *ModelName _IZDamageTotal.csv*

If design storms are used, this file contains:
IZID , minimum RP that caused damage in this IZ , EADamage for IZ , Node 1 (damage caused by) , Node 2 , .. , Node n

If time-series rainfall is used, this file contains:
IZID , number of time that this IZ has been flooded , EADamage for IZ , Node 1 (damage caused by) , Node 2 , .. , Node n