Including public perception data in the evaluation of the consequences of sewerage derived urban flooding

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ABSTRACT

This text reports research which was undertaken to assess the failure consequences associated with sewerage systems. In an effort to move away from considering only flood volume, depth or extent, the text will focus on how a survey of public opinion was used to inform the development of a consequence scoring methodology. The failure consequences considered range from internal flooding of properties, to road closure, environmental damage and odour problems. The text reports the extent to which experience of flooding influences perceptions of failure consequence and sewerage system management. It is also outlined how this data was used, along with other data sources, to construct an objective scoring process that can be used to evaluate failure consequence and readily prioritise sewerage maintenance.

Key words | flooding consequence, public engagement, public perception, sewerage asset management, social cost

INTRODUCTION

Internationally, there has been a concerted move to use serviceability as a key performance indicator in sewerage provision (e.g. Beenen et al. 2005; Melo Baptista et al. 2005; Shepherd et al. 2005; Ertl et al. 2007). Serviceability covers not only general service provision, but also socio-economic factors and environmental impacts such as:

- Sewer blockages which lead to flooding
- Plant failures which lead to flooding
- Properties affected by restricted discharge to sewer
- Traffic disruption
- Health and safety issues
- CSO spills

In the UK, sewerage provision regulators categorise all sewerage derived flooding as being one of two types: those due to hydraulic overloading and those due to all other causes. Although the media tends to focus on hydraulic overloading problems, 84% of sewerage derived flooding incidents (>26,000 per year) in England and Wales fall into the latter of these categories and > 90% of these are due to blockages (Arthur et al. 2009). Considering the role of blockages is therefore a key research challenge; across the world they are probably the number one cause of losses in sewer serviceability in either dry or wet weather flow conditions (Ashley et al. 2004). At best, this can be inconvenient. At worst, blockages can lead to damage to property, stress, illness or possibly even death. A key challenge in this area is being able to identify how likely a pipe is to block and what the consequence of the failure is.

PROJECT DETAILS

This text reports a key part of a larger project which aims to create a technique to enable asset managers to determine where proactive maintenance of sewers is most viable, from a serviceability perspective, and therefore enable them to manage maintenance activities efficiently (e.g. Arthur & Crow 2007). It is recognised that in many countries critical assets (those with significant failure consequence) are
identified and receive appropriate levels of proactive maintenance. For this reason the proposed methodology is designed to identify pipes which just fail to meet this criteria (sub-critical) and may benefit from proactive maintenance. The focus is to produce a technique which can be instigated with little or no additional data collection beyond that which is already available to the majority of water companies. The process is based on risk analysis as a function of consequence and likelihood of failure occurring—Failure Modes, Effects and Criticality Analysis (FMECA) (e.g. Moss & Woodhouse 1998). Values for both consequence and likelihood are developed by considering a number of pipe flow and catchment characteristics which are readily available from a combination of local government and wastewater company reports. These values are then used to produce a rank of pipes which are at greatest ‘risk’ from flooding. To ensure that the methodology is as flexible as possible, and it can be used in the broadest range of catchments, it was divided into four key modules, namely:

1. Screening—to improve computational efficiency, this phase aims to remove any “low risk” elements from the analysis. A key research outcome in this module was successfully profiling “problems pipes” in a real network in a manner which is transferable and scaleable (Arthur et al. 2009).

2. Consequence scoring—this module focuses on assessing the consequence of a system failure. A substantial research challenge to be overcome in this phase was quantifying potential failure consequences, and then assigning validated relative weights to them.

3. Likelihood scoring—this key module focuses on assessing the perceived likelihood of a failure; in this case blockages (Arthur et al. 2008).

4. Score combination and ranking.

Specifically, this text reports research which was undertaken to assess failure consequence (Module 2). However, rather than simply considering flood volume, depth or extent, the text will focus on how a survey of public opinion was used to understand the human impact of flooding and inform the development of a broader consequence scoring methodology. Hence, the aim of this exercise is to produce an approach which is much more sensitive to the expectations of customers and, by incorporating other data streams, their resilience where sewerage derived flooding is concerned. This would then enable failure consequence to be considered fully when proactively maintaining sewerage assets. Furthermore, empowering the public by allowing it to influence the operational maintenance of the sewerage system in this way encourages it to understand its role in flood management (e.g. Newman et al. 2008; Pasche et al. 2008). The flood impacts considered range from internal flooding of properties, to road closure, environmental damage and odour problems.

**STUDY AREA**

The focus of this project is the Scottish city of Edinburgh. Located in the south-east of the country, Edinburgh lies on the east coast of Scotland’s highly urbanised “Central Belt” and has a population of approximately 448,642. Census data collected in 1991 (City of Edinburgh Council 2003) indicated that Edinburgh’s population structure is skewed towards the 16 to 44 age range when compared to the national average. This perhaps reflects the ability of Edinburgh’s strong economy to attract and retain workers. Indeed, Edinburgh’s population grew by 3% in the ten years to 2001; over the same period the population of Glasgow, Scotland’s largest city, dropped by 8%.

Edinburgh’s topography and location mean that it does not suffer from any acute flooding risk when compared to other cities in the UK and northern Europe. However, it was considered important to target areas (not specific households or individuals) in this study which had experienced flooding problems as well as those which had not. Areas which had experienced sewer flooding were identified using three sources of data:

- data provided by Scottish Water;
- reports in a local newspaper; and
- Edinburgh City Council’s Biennial Flooding Reports.

Most of the flooding incidents documented were highly localised in nature and none represented a significant risk to life.

**DATA COLLECTION**

Based on a knowledge of sewerage flooding events, a number of areas were highlighted in Edinburgh as being
suitable for sampling public opinion—this comprised both “flooded” and “non-flooded” areas. Using area-wide socio-economic and building type classifications, the highlighted areas were then further refined to a representative list of target streets—these ranged from areas of social housing, to newer private developments and affluent suburbs. The data was collected in these target streets using a simple questionnaire. The questionnaire comprised 11 multiple choice questions and, using the approach outlined by Gillham (2000), was initially trialled as prototype to ensure the questions were relevant, appropriate, clear, precise, unbiased and could be quickly completed in 10 minutes. Where a resident was at home, they were given the opportunity to complete the questionnaire face-to-face. Where the resident was not a home or was busy, the questionnaire was left behind with a pre-paid envelope, details of where the questionnaire could be completed electronically on the internet and an overview of how sewer systems operate. Residents were given an incentive to respond—they were assured that a single latrine would be built in a developing country for every 50 responses received (purchased via Oxfam.org). This effort resulted in 173 of the 478 questionnaires (36.2%) being returned (141 face-to-face, 31 via mail and 1 via the internet) between 12th May and 9th of June 2006 (and four latrines being built by Oxfam.org). Whilst this response rate may appear modest for a face-to-face survey, it is important to note that no return calls were made where the resident was not at home.

DATA ANALYSIS

As is was possible that certain factors may have influenced who completed the survey (e.g. the Oxfam.org offer), the customers who completed the questionnaires were assigned to demographic groups based on variables such as age, gender, marital status and household details, occupation, housing type, whether they were bill payers or not, and whether or not they were living in an area which had experienced flooding. Analysis of this data indicates that 52% of the respondents were male (the 2001 census reported 48% of the population to be male). As Figure 1 illustrates, the age profile of the respondents differed slightly from the Edinburgh and Scottish averages. To avoid any adverse impact on the results, opinions from underrepresented age categories were given an increased weighting. Ideally, a similar weighting exercise would have been undertaken for socio-economic parameters. However, it was felt that the direct questions required to obtain the data to undertake this would have had a significant impact on the questionnaire response rate. Within this context, the area-wide socio-economic and building type classifications previously explained were considered to be sufficient.

As Figure 2 illustrates, the policy of targeting areas which are known to have flooding problems meant that a substantial minority of respondents (29%) had some experience of flooding. On an area-by-area basis, this ranged from 10% to 45% of respondents. As shown in Figure 2, the impact areas ranged from public roads to inside public buildings. Although no attempt was made to verify the extent of these flooding incidents, respondents were encouraged to consider only events which related to the assets maintained by the sewerage service provider (e.g. fluvial flooding and domestic plumbing problems should not have been considered).
As the aim of this project is to inform asset management activities by targeting potential failures which have the greatest failure consequence, it is important to understand how the public consider different flood impacts. To accomplish this, the questionnaire encouraged respondents to score a variety of failure impacts on a range of 1 to 5 (with five being the highest score and allowing equal scores in separate categories). The respondents’ opinions are presented in Figure 3. It can be seen that, as would be expected, respondents are most concerned about the internal flooding of their own properties (i.e. 83% of respondents assign it the score of 5). Figure 4 presents the same data, but in the form of a separate score for the flooded and non-flooded respondents. Interestingly, it shows that there is very little difference between the two groups. Although it is only statistically significant at the 10% level, the only significant difference was that the flooded respondents are less concerned about failure impacts in areas outside their own property. In both Figures 3 and 4, the relatively high and low scores assigned to public buildings and public amenity areas (green space where families would be expected to spend time) respectively is noteworthy. Indeed, as Figure 5 illustrates, when asked to score how improvements to wastewater treatment works (WWTW), environmental pollution and flooding risk to domestic properties should be prioritised, the respondents were clear that protecting amenity areas was of least importance.

If public opinion is to be used as part of the basis upon which sewerage asset maintenance is prioritised, it is important to understand the knowledge upon which that information is based. Within this context, the questionnaire asked the respondents to rank the relevance of key factors which may increase the likelihood of failure—the results are shown in Figure 6. The key outcome presented in Figure 6 is that, by recognising the role of “household and business activities”, the respondents feel that the sewerage service provider’s customers must take some responsibility for network failures. This is particularly true of flooded respondents—this group scored this 25% higher than the non-flooded group. Additionally, the relatively low score given to “poor maintenance” would tend to suggest that the respondents were relatively happy with the service provided by their sewerage services provider. However, although additional questions indicated that the sewerage services provider gave better than average value for money, it also indicated that 37% (26% and 41% for flooded and non-flooded respondents respectively) felt that the sewerage services provider gave better than average value for money.
non-flooded respondents respectively) of respondents had no idea of how much they paid for water and sewerage services (much of the remainder underestimated the amount they paid). Despite this, 59% were willing to pay more for improvements (this rose to 72% where the improvements were more “environmentally friendly”!)

The issue of value for money was further explored by asking what was felt to be the basis of sewerage asset maintenance activity; proactive, reactive or both. In response, 60% of householders felt that maintenance was entirely reactive—78% for flooded respondents. Despite this view, only 8% of respondents thought that the sewerage service provider could do more to manage the flood risk associated with their assets. However, where proactive intervention was undertaken, only 38% of respondents felt that this was undertaken in a way which minimised disruption (e.g. it was felt that the utility operators could coordinate their operations better and that more work could be undertaken at weekends)—only 20% of flooded respondents agreed with that view. Indeed, as Figures 7 and 8 illustrate, when asked about a range of issues, levels of satisfaction are generally not as high as they could be amongst those who expressed an opinion—none are above 50%.

Although the range of opinions expressed by respondents may be of some concern, it is important to put these opinions within the context of a range of services and factors which impact on quality of life in urban areas. Within this context, the questionnaire asked how improvements to quality of life should be prioritised. As Figure 9 illustrates, it is clear that improvements to sewerage services are not considered an issue when compared to healthcare, crime and education. Indeed, even amongst those who had been previously flooded, investment in sewerage services is ranked behind everything other than transport improvements—one of Edinburgh’s strengths. The data in Figure 9 perhaps reflects the belief that customers must share the blame for blockages (Figure 4).

**FAILURE CONSEQUENCE MODEL**

Having gained an understanding of public opinion with regard to sewerage service provision, the next phase of
the project involved incorporating this understanding in a failure consequence model. The model aims to represent four key failure consequences;

- the nature of the land use in the area;
- the level of social deprivation in the area;
- the occurrence of repeat events; and
- the significance, or importance, of any roads which may be affected.

**Land use**

The vulnerability of an area to flooding impacts is highly dependent on the specific land use. For example,
the flooding of a recognised environmentally sensitive area such as a Site of Special Scientific Interest (SSSI) would have a more serious impact on the area than the flooding of a brownfield site which is not considered to be environmentally sensitive. Also, the impact of an event in an area of housing would be more serious than an event which has occurred in an industrial area. Building on this philosophy, it was possible to use the questionnaire data to inform how different failure impacts can be evaluated. Based on this, the framework illustrated in Table 1 was constructed based on the rankings derived from the questionnaire data.

**Level of deprivation**

The level of deprivation takes into account the vulnerability of individuals in the area to the impacts of sewer flooding. It is also interesting to note that although UK sewerage service regulators encourage companies to award ad hoc compensation (NAO 2004), the legal requirement for sewer flooding compensation is to simply refund the annual sewerage charges and is therefore not dependent on the cost of the damage caused. This approach by the regulator implies that householders are expected to have adequate insurance to cover the financial costs of the event; a factor which further highlights the need for considering social deprivation. An accessible measure of deprivation level in Scotland is the Scottish Index for Multiple Deprivation (SIMD) (Scottish Executive 2004), which is based on census data. Levels are assigned to specific zones dependent on a total of 31 indicators, including such factors as: income, employment, health, education skills and training, housing, geographic access and access to telecommunications.

<table>
<thead>
<tr>
<th>Flood location</th>
<th>Mean ranking (from questionnaires)</th>
<th>Weighting (from ranking)</th>
<th>Adjustment to fit 0–5 score range</th>
<th>Consequence score</th>
</tr>
</thead>
<tbody>
<tr>
<td>In your house</td>
<td>1.34</td>
<td>0.75</td>
<td>0.75 × (5/0.75)</td>
<td>5</td>
</tr>
<tr>
<td>In public buildings</td>
<td>1.85</td>
<td>0.54</td>
<td>0.54 × (5/0.75)</td>
<td>3.6</td>
</tr>
<tr>
<td>In a SSSI</td>
<td>–</td>
<td>0.43</td>
<td>0.43 × (5/0.75)</td>
<td>2.87</td>
</tr>
<tr>
<td>In public amenity areas</td>
<td>3.09</td>
<td>0.32</td>
<td>0.32 × (5/0.75)</td>
<td>2.13</td>
</tr>
<tr>
<td>In your garden</td>
<td>3.10</td>
<td>0.32</td>
<td>0.32 × (5/0.75)</td>
<td>2.13</td>
</tr>
<tr>
<td>+ a vulnerable land use</td>
<td>–</td>
<td>+0.2 (or as appropriate)</td>
<td>0.20 × (5/0.75)</td>
<td>+1.35</td>
</tr>
</tbody>
</table>
Each data zone or neighbourhood is assigned one of five levels of deprivation (A to E, A being most deprived). Using this data, the scores assigned to pipes are dependent on the area in which they are situated. Table 2, shows the recommended scoring categories.

### Occurrence of repeat events

The role of repeat events in affecting consequence is based on the stress individuals undergo when experiencing flooding. Flooding incidents cause stress to those affected by it, however, the occurrence of repeat events can exacerbate this stress significantly (Fenner et al. 2000). These stresses can include financial concerns, health and safety worries and the fear of further flooding. To determine whether repeat events have taken place in an area, four years of customer complaint data was interrogated. This data provides information as to the number of complaints which have been made from a specific postal code zone. In terms of assigning a consequence score, if an incident has occurred previously in the postal code area, a score of 1 is assigned, otherwise a score of zero is given.

### Road usage

As the questionnaire responses highlighted, the impact of flooding on road users is also an important consideration. The level of road usage is an obvious measure of the number of individuals affected by such flooding. In the UK, roads (including those in urban areas) are normally categorised to facilitate utility operations and reinstatement works. As these categories are primarily based on road usage levels, they were considered to be a suitable measure of failure impact (Table 3).

### APPLICATION

Having established the consequence scoring methodology, it is possible to incorporate it within the wider asset management tool. This has four distinct phases:

1. Screening—to improve computational efficiency, this phase removes any “low risk” pipes from the analysis which, if partially blocked will not result in surface flooding (Arthur & Crow 2007). The remaining pipes are labelled as “problem pipes”. A key research outcome in this module was successfully profiling “problem pipes” in a real sewer network in a manner which is both transferable and scalable. Although this tool was essentially developed to streamline the whole methodology, considered alone it may be viewed as groundbreaking as it allows bottlenecks in the system to be readily identified using only very basic data. The screening tool’s robust performance means that it should be well suited to identifying bottlenecks in sewerage systems in general.

2. Consequence scoring—this module focuses on assessing the consequence of a system failure. Throughout the duration of the project, significant advances have been

<table>
<thead>
<tr>
<th>SIMD category</th>
<th>Associated score</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>20% most deprived</td>
</tr>
<tr>
<td>B</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>20% least deprived</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Road category</th>
<th>Traffic capacity</th>
<th>Associated score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 0</td>
<td>Over 30 to 125 msa*</td>
<td>5</td>
</tr>
<tr>
<td>Type 1</td>
<td>10 to 30 msa</td>
<td>4</td>
</tr>
<tr>
<td>Type 2</td>
<td>2.5 to 10 msa</td>
<td>3</td>
</tr>
<tr>
<td>Type 3</td>
<td>0.5 to 2.5 msa</td>
<td>2</td>
</tr>
<tr>
<td>Type 4</td>
<td>Up to 0.5 msa</td>
<td>1</td>
</tr>
</tbody>
</table>

*msa—Million Standard Axles.

### Table 2 | SIMD categories and associated scores

### Table 3 | Road reinstatement categories with definitions and associated scores (Note: a score of 0.5 was given for cycle paths and walk ways)

### Table 4 | Weighting of consequence

<table>
<thead>
<tr>
<th>Consequence factor</th>
<th>Score range</th>
<th>Weighting</th>
<th>Weighted score range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level of deprivation</td>
<td>1–5</td>
<td>0.5</td>
<td>0.5–2.5</td>
</tr>
<tr>
<td>Occurrence of repeat events</td>
<td>0–1</td>
<td>0.75</td>
<td>0–0.75</td>
</tr>
<tr>
<td>Land use</td>
<td>0–5</td>
<td>1</td>
<td>0–5</td>
</tr>
<tr>
<td>Road usage</td>
<td>0–5</td>
<td>0.39</td>
<td>0–1.2</td>
</tr>
</tbody>
</table>
Table 5  | Factors which may indicate increased blockage likelihood

<table>
<thead>
<tr>
<th>Factor</th>
<th>Increased likelihood</th>
<th>Statistically significant?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined pipes are more likely to block</td>
<td>146%</td>
<td>Yes</td>
</tr>
<tr>
<td>Pipes which surcharge during a 5-year return period design storm</td>
<td>44%</td>
<td>No</td>
</tr>
<tr>
<td>Pipes which flood during a 5-year return period design storm</td>
<td>839%</td>
<td>Yes</td>
</tr>
<tr>
<td>Pipes which convey flows influenced by a backwater effect</td>
<td>55%</td>
<td>No</td>
</tr>
<tr>
<td>Proximity to flow confluence—pipes just upstream of a junction</td>
<td>38%</td>
<td>No</td>
</tr>
<tr>
<td>Pipes which failed to achieve a peak flow velocity of 1.0 m/s during a 2-year return period event (Arthur et al. 1999)</td>
<td>80%</td>
<td>Yes</td>
</tr>
<tr>
<td>Pipes laid at a gradient less than 1:pipe diameter</td>
<td>102%</td>
<td>Yes</td>
</tr>
<tr>
<td>Pipes with large direct inputs</td>
<td>167%</td>
<td>Yes</td>
</tr>
<tr>
<td>Pipe size—&lt; 225 mm in diameter</td>
<td>521%</td>
<td>NA</td>
</tr>
</tbody>
</table>

Figure 10  | Composition of likelihood and consequence scores for a sample of 24 pipes (adapted from Arthur et al. 2009). In both cases, the scores are factored so that the maximum possible score is 1.0. Pipes 1–23 are real assets from a case study catchment and Pipe 24 is a theoretical worst case scenario pipe which is presented to illustrate the maximum possible scores in each category.
made (e.g. Balmforth & Dibben 2005; Renouf et al. 2005) in assessing where flood flows may travel when they leave sewerage systems. As these approaches are still under development and rely on processing large amounts of high quality data, it was decided that this project would establish its own approach which was computationally efficient and accessible. Rather than modelling flood routing on the catchment surface, an attempt was made to establish the zone within which flooding was likely to occur. In order to determine the extent of this zone, data produced as a by-product of the screening exercise was used. The distance of each of the flooded nodes from the upstream node of the blocked pipe was then recorded. The zone within which 95% of these nodes occurred was defined as the “consequence zone” and used to evaluate failure impacts (Arthur & Crow 2007). Having established the consequence zone, a substantial research challenge to be overcome in this phase was quantifying potential failure consequences, and then assigning validated weights to them. Based on the public consultation exercise reported herein, it was possible to build a hierarchy of failure consequences which were primarily based on land use; development categorisation, road traffic levels and environmental considerations. However, it was also recognised that factors such as social deprivation and exposure to previous flooding events are also important. Based on the questionnaire data, social deprivation data and discussions with the sewerage service provider, the scores were combined using the weightings presented in Table 4.

3. Likelihood scoring—this key module focuses on assessing the perceived likelihood of a failure; in this case blockages. Clearly, as well as considering the consequence of failure, it is also important to balance this with an understanding of its likelihood. In order to do this in generic terms, a database of customer complaints obtained from the water services provider was interrogated. Key to this was the philosophy that with a relatively small catchment it should be possible to assess each blockage incident in isolation and reach a conclusion about its cause. Based on this, each blockage was assessed in turn together with related network characteristics (physical and hydraulic) using MapInfo and Infoworks CS. This analysis resulted in several features being highlighted as being possible factors which may indicate that an individual pipe has an increased propensity to block. To validate each of these hypotheses, the entire database was checked for

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**Figure 11** | Boston Diagram with indicative intervention levels illustrated (adapted from Arthur et al. 2009).
blockages which could be considered to have similar causes and a 5% confidence level Chi-Squared ($\chi^2$) Distribution test (e.g. Clarke & Cook 2005) was used to test the results. Table 5 outlines the parameters which were highlighted as being important. A full explanation of why these factors were selected is given elsewhere (Arthur et al. 2008).

4. Risk is a function of consequence and likelihood. Therefore, the total consequence and likelihood scores for each pipe must be considered together to produce a final ‘risk’ score which can be used to rank each problem pipe—score compositions for typical pipes are illustrated in Figure 10. In doing this, it is important to consider how failure consequence and likelihood should be combined to enable the assets to be ranked. It was concluded that a Boston diagram (Figure 11) was the most suitable reporting method as this allows each asset’s blockage likelihood and consequence to be considered separately (i.e. information should not be obscured by arithmetically combining them). The pipes most likely to block may then be highlighted on a GIS to enable staff to readily assess the output.

CONCLUSION

This text has reported the construction of a failure consequence model which is partly based on what the public feel are the most severe failure impacts. The model reflects the public perception that the most severe failures are those which result in the flooding of domestic properties and that public amenity areas are viewed as being significantly less important. In constructing the methodology, it was also recognised that it was important to incorporate factors such as social deprivation and exposure to previous flooding events. Using this information, it has been possible to construct a failure consequence model which reflects the needs of consumers. However, although the approach developed is robust, as this module relies heavily on site-specific data, it perhaps needs to be further developed using data from additional catchments. Despite this, the philosophy which underlies it (i.e. the economic, social and environmental dimensions) is adaptable for use in other catchments.

Furthermore, although it did not contribute to the consequence model, it was clear that many respondents were not completely happy with their sewerage service provision. Despite this, services such as education, health and law enforcement were considered as being more worthy of investment. The survey of public opinion also found that the public acknowledged that they had partial responsibility for blockage related failures—a key outcome when considering public engagement with the wider flood risk management and capacity building philosophies. Lastly, despite the efforts of sewerage service providers to develop proactive maintenance strategies, the respondents felt that a reactive strategy was acceptable.

ACKNOWLEDGEMENTS

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