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Reducing the Occurrence of Flooding through the Effective Management of Sewer Blockages

Submitted by Trefor Tamblyn Hillas to the University of Exeter
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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

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Abstract

Sewer blockages are responsible for the majority of sewer flooding incidents. They cause the discharge of raw sewage effluent into homes and into natural watercourses and are immensely expensive to the water industry. The number of sewer blockages suffered on public sewer networks is steadily increasing. This trend is likely to continue with deteriorating sewer networks and increased water efficiency both likely to contribute to an increased numbers of reported blockages.

Previous research examining the potential for reducing blockage numbers has primarily been concerned with interrogating historical sewer blockage records, and scheduling proactive sewer cleansing to target the worst performing parts of the network. Whilst this approach has represented some success in reducing the rate at which blockages are increasing, a new approach is required to deliver further reduction.

The aim of this project is to enable sewerage undertakers to reduce the number of sewer blockages in small bore (i.e. < 225mm) sewers. To achieve this aim, an improved approach based on active identification and management of potential blockages is proposed. Sewer blockages data records and the existing blockage management practices of five water service providers have been analysed. The resulting evidence base has been used to develop a conceptual decision support tool to predict blockage potential and the impact of blockage management interventions. The tool includes a framework that not only takes into account a range of causal factors contributing to blockage formation, but also systematically integrates expert views in the overall assessment of blockage likelihood. The tool also identifies the relative importance of each variable in influencing blockage formation. The tool has been calibrated using data from four case study catchments. The calibrated model has been subjected to a validation exercise, and the model predictions on blockage rates are broadly in agreement with the available data.

This thesis outlines an approach which attempts to a) deliver improvements to the way in which sewer blockages are managed reactively and b) provide a decision support tool for sewerage undertakers to undertake proactive removal and prevention of sewer blockages. It is anticipated that through applying the approaches

outlined in this thesis, sewerage undertakers will be able to deliver a reduction in the number of blockages suffered on public sewer networks.

Table of Contents

Table of Figures

List of Tables

1 INTRODUCTION

1.1 Background

1.2 Scope of Research

1.3 Industry Involvement in the Project

1.4 Aims and Objectives

1.5 Novelty and Benefits of Research

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1.1 Background

The remit of the modern sewer system is to provide safe and effective removal of wastewater from the urban environment. This service reduces public health risks and helps reduce the occurrence of flooding. Part of this functional requirement is the removal of solid material contained within wastewater. Historically the onus of drainage system design has been placed on preventing the accumulation of sediment and grit deposits found in combined and surface water sewers. This has led to the development of codified guidance which requires sewers to be constructed to a specification which reduces sediment accumulation. However this guidance does not explicitly consider the transport of large solids, defined as measuring > 6 mm in any direction (Davies *et al.,* 1998). In order to improve the performance of the current system a greater consideration of large solids in wastewater is required.

The past century has seen a change in the nature of large solid material discharged into the sewer system. An example of this is the reduced disposal of coal and coke into the sewer following the increased use of gas and historically oil central heating systems. More recently the emergence and increased use of hygienic sanitary products has seen an increase in the number of large solid items being disposed of into the sewer. Unlike toilet tissue, these items are durable to the mechanical action of the flow and maintain a physical presence through the sewer system, eventually being removed from inlet screens at treatment works.

The issues associated with large solids are particularly relevant to small sewers and this has formed the basis of several studies (Brown *et al.,* 1996; Littlewood & Butler 2003; Walski *et al.,* 2011). At the head of the network, flow within sewers is comprised of a series of intermittent pulses resulting in discontinuous flow. Under these conditions solid movement is also discontinuous and large solids are continually deposited. Once a stoppage has occurred if subsequent flush waves are unable to re-entrain the solid and generate subsequent movement the deposition of material becomes permanent and the sewer will become blocked.

Sewer blockages pose several problems to the functionality of the drainage system. This can include the loss of WC facilities which are unable to discharge into the sewer. The prevention of wastewater removal because of a blockage can result in the emission of foul odours from surcharged manholes and yard gullies. The continued hydraulic loading of a blocked sewer can result in the escape of sewage

from manholes, inspection chambers or yard gullies and cause external flooding. This may result in contamination of garden or road areas which will require cleaning and disinfection following the event. External flooding can also result in pollution of natural watercourses if an adequate pathway for sewage ingress into a watercourse exists. In the more extreme cases, sewer blockages can cause internal flooding of property. Aside from the distress and inconvenience caused to the householder, this can also pose significant health risks through contamination by disease spreading pathogens.

1.2 Scope of Research

This is a study of the occurrence of sewer blockages in small bore foul and combined sewers. These sewers are situated at the head of the sewer network and are characterised by intermittent flow conditions. Specifically, this investigation focuses on solid movement and the causes of sewer blockages along with their removal and management.

1.3 Industry Involvement in the Project

This project is a joint funded partnership through the EPSRC and the Water Research Centre (WRc) through the STREAM IDC. During the project inception the support of each of the 11 UK water and sewerage companies was sought. A presentation was given to a group of sewerage managers from each of the UK water companies at a meeting in Edinburgh in August 2010. A subsequent work proposal was issued to each company. A total of 6 water and sewerage companies agreed to provide support to develop the project deliverables. The companies included in the project include;

- Anglian Water PLC;

- Northern Ireland Water PLC;

- Scottish Water PLC;

- Severn Trent Water PLC;

- Southern Water PLC; and

- United Utilities PLC.

Following the inclusion of the 6 companies in the project, an initial steering group meeting was held. This meeting was held to allow the project objectives to be discussed and decided, based on the requirements of each of the participants. This led to the agreement of the project aims of objectives outlined below.

1.4 Aims and Objectives

The aim of this project is to enable sewerage undertakers to reduce the number of sewer blockages that occur on public sewer networks.

This aim will be carried out through the following objectives:

- conduct a state-of-the-art literature review;
- review current reactive sewer blockage management and make recommendations for improvement;
- based on an understanding of sewer blockage mechanisms, develop a predictive sewer blockages model to help support decisions in proactive maintenance; and
- develop a capability within the model which allows the effect of a sewer intervention to be understood.

An outline of the methodology used in fulfilling each of the objectives is provided at the start of each corresponding chapter.

1.5 Novelty and Benefits of Research

In comparison to the extent of work that has been undertaken regarding flooding from hydraulic overload of sewers, there has been comparatively little research into the other causes of sewer flooding, including sewer blockages.

Previous sewer blockage research has concentrated on developing methodology to support sewerage undertakers in planning proactive intervention, thereby reducing blockages. In contrast there has been a limited amount of coverage of the issues associated with repeat blockages resulting from poor reactive blockage management. This emphasis on proactive maintenance is surprising considering reactive maintenance currently accounts for 75% of blockage maintenance in the UK.

The previous research pertaining to proactive blockage management has explored the use of data driven approaches whereby historic blockage and asset data is used

to predict future failures. Due to the limited availability of such data for small bore sewers, the application of such techniques is mostly limited to > 225 mm sewers. However, the majority of blockages occur within smaller < 225 mm sewers. The approach adopted in this study is specifically targeted at small bore (< 225 mm) sewers, where the lack of data prohibits a data driven approach from being adopted.

The novel nature of the research will deliver several benefits, specifically;

- improved blockage clearance practices which will lead to a reduction in the number of recurrent blockages;
- improved data collection by operations crews facilitating planning of future intervention;
- increased scope for undertaking sewer maintenance on a proactive basis and reducing the number of blockages; and
- improved understanding of the mechanisms by which a sewer blocks and what sewer features are implicated in those mechanisms.

It is anticipated that through delivery of these benefits sewerage undertakers will be equipped with the necessary tools and knowledge to deliver a reduction in the number of sewer blockages suffered.

2 LITERATURE REVIEW

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2.1 Introduction

2.2 Solid Transport in Sewers

2.3 Sewer Blockages

2.4 Management of Sewer Blockages

2.5 Summary

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2.1 Introduction

In accordance with Objective 1 of this thesis set out in the introduction, a critical review of the previous literature relevant to sewer blockages has been undertaken.

The literature review carries the following objectives;

1. Establish what factors are related to solid transport in sewers
2. Establish what factors are related to the formation of sewer blockages
3. Review the current approaches for managing sewer blockages

The structure of the literature review has been developed around meeting each of the above objectives.

2.2 Solid Transport in Sewers

2.2.1 Background

An important consideration for future sewer performance is the reduced flow in sewers resulting from increasing water efficient practices. Large solids are reliant on flow as a vehicle for movement through the system. Therefore a reduction in flow may reduce the ability of a sewer to efficiently remove large solid material.

In the UK until the introduction of 6 l flush system in 1999, a 9 l flush was the norm. Prior to a reduction in flush volumes, water use from WC flushing accounted for 1/3 of all domestic water use (McDougal & Wakelin, 2009). Since the introduction of 6 l flush devices this figure is likely to have reduced. However, WC flushing remains a target for further water use reductions with ultra-low flush toilets < 4 l now beginning to emerge onto the market.

The adoption of such technologies has not thus far been met with any adaptations to the current sewer system; much of which was designed based on the technology of a century ago when flushes as high as 16 l were used. Therefore, if the benefits of water reduction are to be fully realised, consideration must be given to how sewer design can be updated to accommodate reduced sewer flows. To achieve this, an understanding of how solid material behaves in intermittent flow is required. This requirement has prompted a series of practical studies which have examined the transport of solid material through use of physical sewer models such as that shown in *fig 2-1*.

Figure 2-1 Photograph of the physical sewer model - image courtesy of WRc

A typical methodology, described by Littlewood (2000), sees the release of a sequence of flush waves from a header tank into a pipe at a defined gradient. This release of flush waves simulates the flow pulses in small sewers generated by the connecting water use appliances. A solid is placed into the head of the pipe and its behaviour observed and recorded. The maximum distance a solid can travel for a particular test configuration is referred to as the Limiting Solid Transport Distance (LSTD). A solid is said to have reached its LSTD if it fails to move for three consecutive flush waves (Littlewood, 2000).

In order to represent the range of solid material discharged to the sewer, several different large solids have been tested. Swaffield & Galowin (1992) refer to the use a small cylindrical solid referred to as the US National Bureau of Standards (NBS) solid. It was observed however that the NBS solid showed a tendency to become lodged at pipe joints prompting a subsequent version of the solid to be developed. The modified 'Westminster' solid as described by Littlewood (2000) averted the problem by chamfering the edges of the solid (*fig 2-2*). Along with the NBS and

Westminster solid, the transport of other solid materials such as sanitary towels, wet-wipes and nappies have been tested (Littlewood & Butler, 2002; Walski *et al.,* 2011).
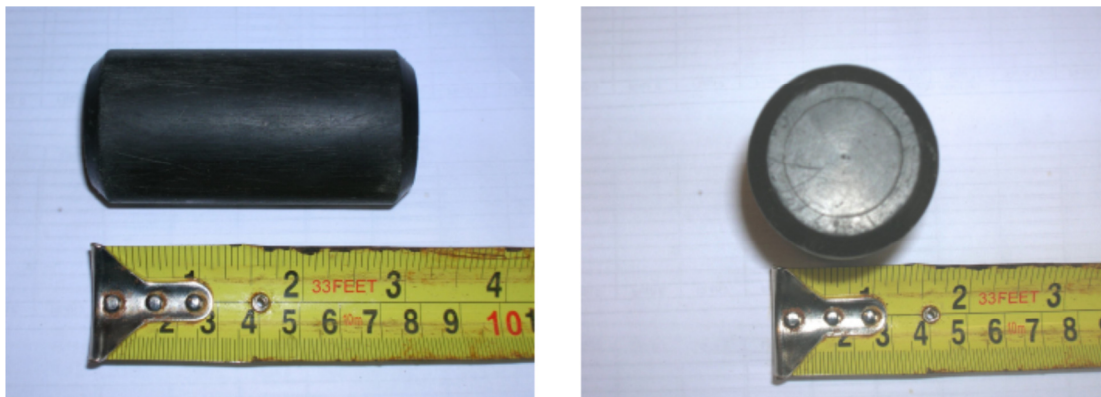
Figure 2-2 The Westminster solid - image courtesy of WRc

2.2.2 Forces Affecting Large Solid Transport

The forces acting on large solids in the sewer have been studied by Butler *et al.,* (2005) and Walski *et al.,* (2011). When a large solid enters the sewer, its movement is a function of the various opposing forces which act on it. The flush wave provides the horizontal force with the opposing frictional force being provided by the contact between the pipe and the solid. In order for movement of the solid to be achieved, the horizontal forces providing energy for solid movement must exceed the frictional resistance.

As the flush wave and the solid move through the sewer, the flush wave attenuates and dissipates energy (Swaffield & Galowin, 1992). The transport potential of the wave is therefore reduced the further down the sewer it travels. The point at which the energy of the flow is no longer sufficient to overcome the frictional of the pipe is the point at which the solid will be deposited. Any further movement of the solid will then require a subsequent flush wave to continue its movement downstream.

2.2.3 Factors Affecting Large Solid Transport

Littlewood & Butler (2003) observed two separate mechanisms by which large solids are transported (*fig 2-3*). Mechanism A occurs when the solid is small in relation to the pipe cross sectional area. The solid is entrained by the front of the flush wave and then deposited once the peak of the wave has moved past the solid (Swaffield & Galowin, 1992). The solid moves at a proportion of the wave velocity and as a result,

the majority of the energy contained by the wave is not utilised by the solid for movement.

Flow morphology unaltered by solid

Solid small in relation to pipe

Flow retained behind the solid

Solid large in relation to pipe
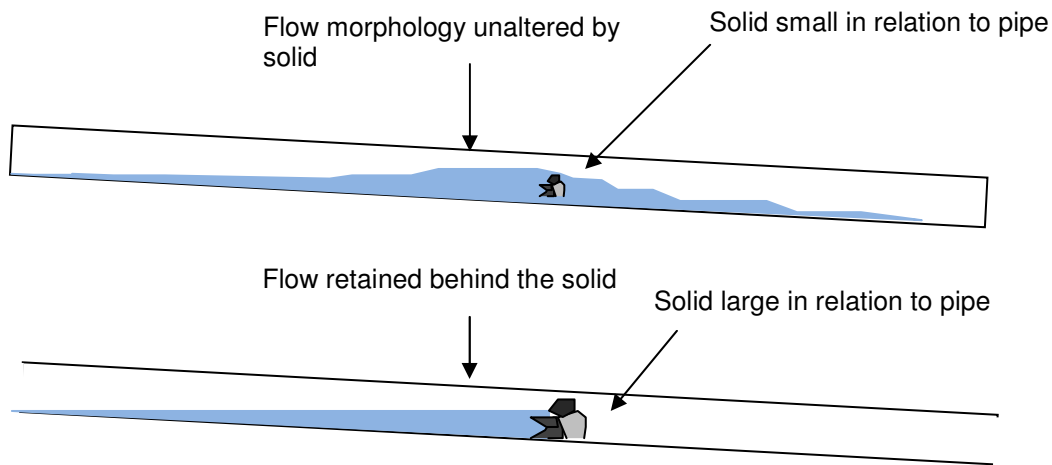
Figure 2-3 The floating movement mechanism (above) and the sliding dam movement mechanism (below)

Mechanism B occurs if the solid is large in relation to the pipe. Through this mechanism, the solid will act as a 'dam' and retain the flow behind itself. The solid is pushed along the pipe invert by the hydrostatic head of the wave retained behind the solid. With mechanism B, a greater proportion of the energy of the wave is translated into solid movement when compared to mechanism A and this in turn increases the LSTD. The cross sectional area of the flow occupied by the solid (which determines which mechanism will prevail) is described by Littlewood (2000) and Littlewood *et al.,* (2007) as the 'shape factor'.

WRc (2007) observed that the shape factor of a Westminster solid can be improved with the addition of toilet tissue. This improved the efficiency of the solid in acting as a dam and improved the movement of the solid (*fig 2-4*). A reduction in the pipe diameter also has the effect of improving the shape factor, and therefore the LSTD. Littlewood & Butler (2002) observed that a 50 mm pipe would 'outperform' a 100 mm and 150 mm pipe, generating an additional 9 m of movement compared to the 150 mm pipe (*fig 2-5*).
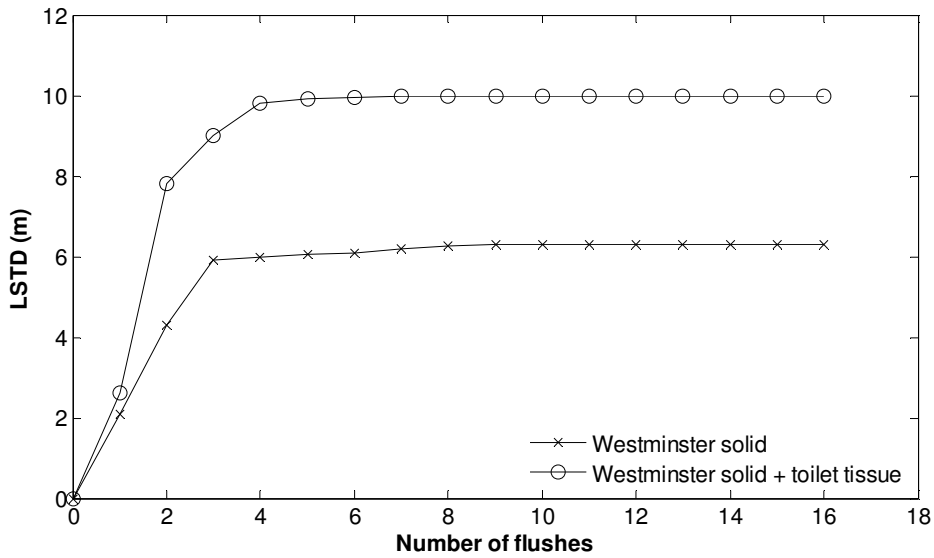
Figure 2-4 Effect of toilet tissue on Westminster solid movement for a 150 mm pipe, a 1:100 gradient and 3 L flush (courtesy of WRc)
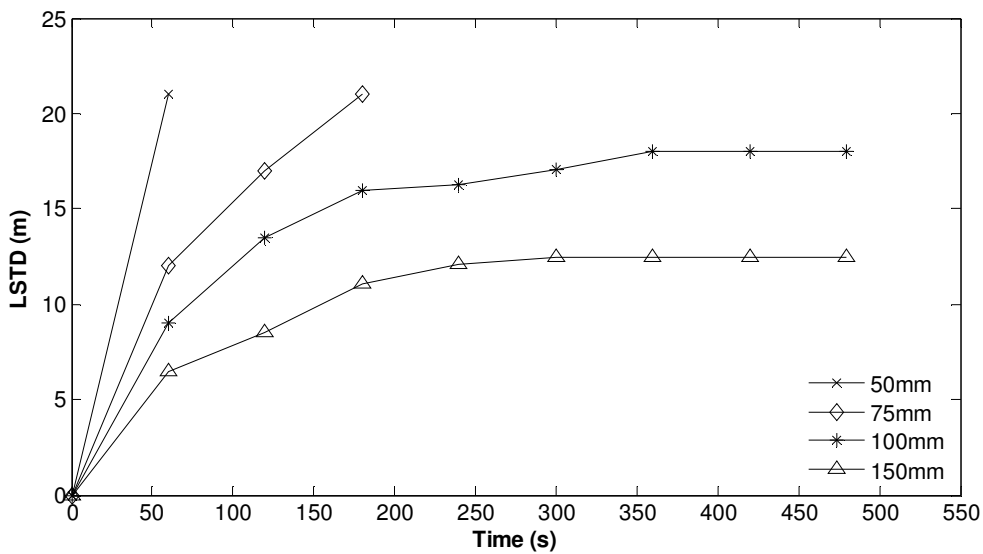
Figure 2-5 Effect of pipe diameter on Westminster solid movement for a 3 L flush and 1:100 gradient (Littlewood & Butler, 2002)

The observations made by Littlewood & Butler (2002) suggest there is scope to improve sewer performance, and therefore accommodate reduced WC discharges by amending design guidance to advocate the use of smaller pipe diameters. However whilst a reduction of pipe diameter has been demonstrated to improve the

LSTD for an artificial solid, consideration of the transport of larger solid items is required. Littlewood & Butler (2002) observed that a sanitary towel would readily move through 100 mm and 150 mm diameter pipes with a 3 l flush. However, in a 75 mm diameter pipe the sanitary towel would show only minimal movement, even with a full bore of flow behind it. The sanitary towel showed no movement in a 50 mm pipe (*Table 2-1*).

Table 2-1 Comparison of Westminster solid and sanitary towel movement (Data from Littlewood & Butler, 2003)

Pipe Diameter (mm)	Artificial Test Solid LSTD (m)	Sanitary Towel LSTD (m)
150	12	11
100	18	14
75	21.9	Minimal movement
50	23	No movement

Increasing the LSTD of a flush wave can also be achieved by increasing pipe gradient. Memon *et al.,* (2007) observed that for a 100 mm pipe and   flush, a LSTD of > 20 m could be achieved if a 1:150 gradient used. This produces the same transport distance as the 50 mm pipe used by Littlewood & Butler (2002) at a gradient of 1:100. The use of a 100 mm pipe at a steeper gradient rather than a 50 mm pipe has the advantage of being less susceptible to blocking should a large solid be discharged into the sewer.

2.3   Sewer Blockages

2.3.1   Background

The design of sewer systems has developed over a considerable period of time, stretching back to the Victorian era. Until relatively recently purely empirical rules were formulated and used. These have gradually been codified in successive national and international norms. However a more fundamental understanding of how these systems actually work (and therefore how they sometimes fail) is much more recent. An understanding of the causes of blockages has been facilitated by a steady improvement in the quality of both sewer asset data and blockage incident data. By identifying the factors implicated in sewer blockages, it is possible to develop an understanding of the mechanisms through which a sewer may suffer a blockage.

2.3.2 From Stoppage to Blockage

Lillwhite & Webster (1978) suggest a process by which a stoppage can lead to the formation of a blockage. This was based on a study of CCTV surveys of sewers with recurrent blockages. Once a stoppage has occurred, a subsequent flush wave is required to generate further movement of the solid. If a subsequent wave is unable to re-entrain the solid the stoppage will act as an obstacle to other solids and the mass of deposited material will begin to increase in size. Initially water will flow around and permeate through the stoppage. However as more solid material accumulates, less of the flow will be able to move past the deposited material and a dam will begin to form.

The hydraulic head behind the stoppage will increase as the depth increases and the continued build-up of hydraulic pressure may be sufficient to remove the solid material. This process of stoppage, build-up of hydraulic head and eventual dispersal may occur several times. If material continues to accumulate with no further movement a mass of material large enough to occupy the cross section of the pipe may develop, causing a complete blockage.

Hafskjold *et al.,* (2004) suggested three mechanisms by which a blockage may occur. A 'chronic' blockage can occur when the capacity of the pipe is reduced over time due to the accumulation of sediment. Under this mechanism a complete blockage of the pipe is unlikely but the hydraulic capacity of the sewer is gradually reduced. An 'acute' blockage occurs when a large object entering the sewer causes a total obstruction in the pipe, for example after a partial collapse or entry of a large foreign object. Thirdly, a combination of the two mechanisms may occur, where sediment accumulation and reduced capacity of the pipe may cause large objects to become deposited and cause an obstruction.

2.3.3 Factors Affecting Sewer Blockage

The hydraulic regime within a sewer is a function of several design parameters including pipe material, sewer function, diameter and gradient. Current design guidance specified in BS EN 752 suggests a minimum gradient should be achieved for a specific diameter. This has been demonstrated to ensure that a self–cleansing velocity of 0.7 m/s is achieved at least once per day (Butler & Davies, 2011). Prior to this guidance, sewer construction was undertaken on an ad hoc basis and design

standards were more localised. As a result some older sewers do not meet the modern requirements for self-cleansing.

Fenner *et al.,* (2000) reports that slack gradients (preventing self-cleansing velocity) are one of the pipe characteristics common to high blockage numbers. Arthur *et al.,* (2008) observed from a study in South-East England that of the sewers which were constructed to self-cleansing specification, 16 of 422 (7%) were blocked compared to 24 of the 198 (12%) that were not laid to self-cleansing design. Hafskjold *et al.,* (2004) observed that 10% of blockages that occurred in Trondheim, Norway were associated with slack sewer gradients.

Before the benefits of separate foul and storm sewers were realised, both types of wastewater were carried in a single pipe. In the UK, separate systems began to emerge in the 1920's and were gradually adopted up until the 1960's when national guidance recommended all new systems be installed with separate foul and surface water components. As such combined sewers represent the older element of the sewer network, with approximately 50% of properties being served by a combined system. Along with large solids from foul sewers, the inclusion of stormwater results in the entry of particulate material from catchment surfaces such as grit/sand/silt, litter and decaying flora into combined sewers. If self-cleansing is not achieved, such material can become deposited over long periods on the pipe invert forming a grit and sediment bed (*fig 2-6*).

Figure 2-6 Sediment and grit deposited on the pipe invert (image courtesy of WRc)

During transportation through the sewer, large solids will encounter a greater degree of friction from a sediment bed than would normally be encountered from the comparatively smooth surface of the pipe. This increased friction increases the likelihood of large solids becoming deposited and forming a stoppage (WRc, 2007). Arthur *et al.,* (2008) report that combined systems are 2.5 times as likely to become blocked as separate sewers. A study of a small sewer catchment (733 pipes) revealed that the 295 foul sewers suffered 11 blockages (4%) whilst the 438 combined sewers suffered 40 blockages (9%) over a 3 year period.

Hafskjold *et al.,* (2004) observed a similar relationship based on a study in Norway. Ugarelli *et al.,* (2010) however observed that combined sewers had a lower rate of blockage (*Table 2.2*).

Table 2-2 Comparison of blockage rates for two Norwegian cities

Study	Location	Length of Network Analysed (km)	Foul Sewer Blockage Rate (per km/yr)	Combined Sewer Blockage Rate (per km/yr)
Hafskjold et al., (2004)	Trondheim	1,006,137	0.086	0.096
Ugarelli et al., (2010)	Oslo	2,253	0.176	0.146

The blockage rates reported by Hafskjold *et al.,* (2004) and Ugarelli *et al.,* (2010) are significantly lower than the corresponding rates reported in the UK, which in 2008/9 ranged from 0.3 – 1.4/km/yr (OFWAT 2009; WICS 2009; NIUR 2009). One factor in this may be the use of hygienic sanitary products in the UK. The manufacturers' trade associations EDANA and INDA report that the UK is one of the largest consumers of such products.

Blanksby *et al.,* (2003) report that pipe defects are the biggest perceived cause of blockages by sewerage operators. Lillywhite & Webster (1979) describe a pipe defect as any discontinuity in the longitudinal profile of the drain and include displaced and open joints, pipe deformation/broken pipes, backfalls and deposits such as sediment or scale. The term 'defect' also covers the presence of any non-sewer items such as tree roots or poorly fitting intruding lateral connections which can cause an obstruction.

Fenner *et al.,* (2000) argue that many older sewers remain in good condition. This is supported by Hafskjold *et al.,* (2004) whose study concluded that age of pipe and blockage rate could not be correlated. This implies other factors such as soil type, sewer depth, pipe material and quality of construction may be important factors affecting sewer condition. Ugarelli *et al.,* (2010) substantiate this by reporting that sewers in Oslo constructed during the 1950-60 period were in poor condition, due to the housing boom of this period resulting in poor bedding practices and inferior workmanship.

Due to the number of factors involved, accurately estimating sewer condition can be difficult without the use of CCTV survey. Based on a study of CCTV and blockage

occurrence, Lillywhite & Webster (1978) concluded that defective pipe joints are one of the factors most commonly implicated in blockages. Blanskby *et al.,* (2003) however found no correlation between pipe defects and blockages and concluded that a wider range of factors including the hydraulic regime are responsible. Hafskjold *et al.,* (2004) also reports that for 75% of blockages in a study, a clear cause could not be identified and that only 20% of blockages could be attributed to a sewer defect.

Blanksby *et al.,* (2003) however suggest that rather than a blockage being attributable to a single defect, a combination of defects may be associated with a blockage. One example of this could be the effect of several successive displaced joints. The cumulative effect of each joint on reducing solid movement may cause the accumulation of solids and eventual formation of a blockage. It is also possible that solid material may be deposited downstream of a defect which would make identification of a causative factor more difficult. For example, the effect of pipe defects on blockage likelihood can increase when large sanitary items are discharged into the sewer. Large solids can become caught on rough or displaced pipe work and form a stoppage either at the defect itself or shortly downstream.

Another factor in blockage cause is the interceptor trap (*fig 2-7*) which is considered by several water companies to be the principal cause of sewer blockages (Ridgers, 2010; Challenor, 2010) Interceptor traps were a requirement of UK building legislation from the mid-nineteenth century until the mid-twentieth century. They were installed to provide a water trap between the property and the main sewer in order to prevent the ingress of sewer gases into buildings. The design of the interceptor trap is such that solids are frequently deposited in the sump of the trap. This is particularly true in the case of large solids (WRc, 2007).
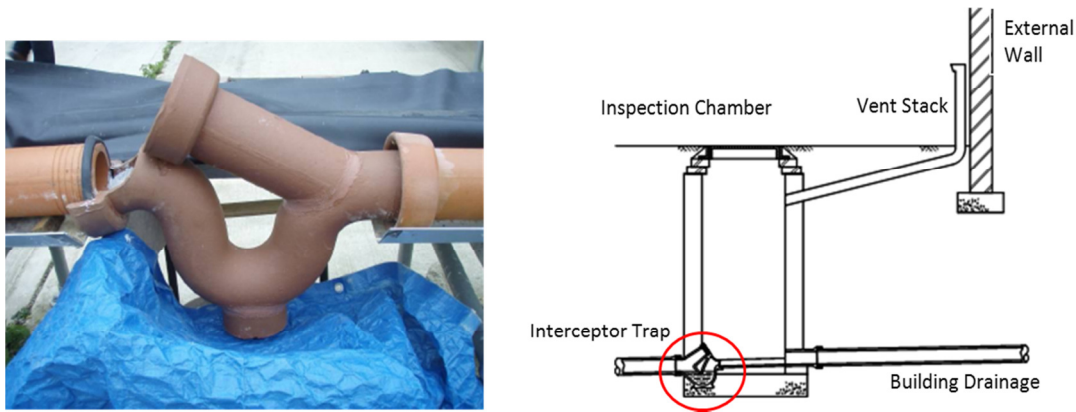
**Figure 2-7 An interceptor trap (Winser type) located within an inspection chamber –
Image courtesy of WRc**

The issue with large solid items extends beyond interceptor traps. Though not widely discussed in the literature, empirical evidence collated from sewer operators suggests that large solids are a highly causative factor in sewer blockages.

Though the exact mechanism is unknown, the large accumulations of coalesced sanitary material removed by sewerage operators suggest a process occurs by which the material becomes tangled, forming a large mass of solids (*fig 2-8*). The resistant nature of some of these materials increases cohesion of the blockage, making break up and dispersal of the material by mechanical means such as jetting or rodding more difficult.

Figure 2-8 Coalesced sanitary wipes removed from a blocked sewer

In the absence of a pipe defect, the likelihood of solid material being deposited and forming a stoppage in a sewer is a function of the ability of the sewer flow to generate frequent movement of the solid. Lilywhite & Webster (1978) state that whilst continuous movement of solids is not essential, regular movement is. If a solid is to remain deposited for an extended period of time, there is more chance the solid will adhere to the pipe wall and act as an obstacle for subsequent solids. Enfinger (2009) states that a diurnal or seasonal lack of flow in sewer lines can prevent self-cleansing and as a result is conducive to the accumulation of solid material. This principle is one explanation for why small sewers with intermittent flow suffer a greater number of blockages than larger sewers with near continuous flow.

Aside from flow conditions, Arthur *et al.,* (2007) suggest that large solids are more likely to become snagged and deposited in small diameter pipes compared to larger diameter pipes. Arthur *et al.,* (2008) observed the majority of pipes which had suffered a blockage were
< 225 mm in diameter. Blanskby *et al.,* (2003); Hafskjold *et al.,* (2004) and Ugarelli *et al.,* (2010) also report blockage frequency to be higher in small diameter sewers. It was however not specified whether this was believed to be a result of the flow conditions or the increased likelihood of obstruction forming from a large solid, as suggested by Arthur *et al.,* (2007).

Hafskjold *et al.,* (2004) observed that 20% of blockages occur within manholes or inspection chambers. This is significant when considering that the total proportion of the network represented by the length of sewer located within manholes and inspection chambers is likely to be very low. Lilywhite *et al.,* (1978) suggest that blockages in manholes could be the result of poor detailing where two opposite connections can cause a flow obstruction and the deposition of solids.

Where a manhole has been installed on a bend in the sewer, solid deposition either in or downstream of a manhole can occur. Lilywhite & Webster (1978) report this to be especially prevalent in sharp angle bends (90°). The deposition is caused by the increased amount of friction acting on a solid as it is transported around the bend.

2.4 Management of Sewer Blockages

2.4.1 Extent of Sewer Blockages

There were over 200,000 reported sewer blockages on public sewers in the UK in 2008/9 (OFWAT 2009, WICS 2009, and NIUR 2009). This represents a rate of 517 blockages per 1000 kilometres of sewer per year (blockages/1000km/yr). Across all UK water and sewerage companies, the highest rate reported was 1936 blockages/1000km/yr. The other companies were in the range 214 to 803 blockages/1000km/yr.

Of these blockages, approximately 2% caused internal flooding of properties and approximately 23% caused external flooding. Although the total number of pollution incidents associated with CSO and foul sewers are reported to the regulators, the number of incidents caused by blockages is not specified.

On 1st October 2011 responsibility for existing private sewers and lateral drains in England and Wales was transferred to the water and sewerage companies. It is estimated that this has increased the length of public sewers maintained by these companies by at least 70%. These sewers are expected to be predominantly smaller sewers (< 225 mm) which have high blockage rates. Consequently, the number of blockages that are the responsibility of the water and sewerage companies in England and Wales is expected to rise significantly.

2.4.2 Approaches to Management

The removal of sewer blockages can be undertaken on a reactive or a proactive basis. A reactive approach involves the undertaking of a corrective measure based

on a serviceability failure being reported by the customer i.e. internal flooding, restricted toilet use or odour (WRc, 2012). Proactive maintenance is the pre-emptive implementation of a corrective measure prior to a serviceability failure being reported (WRc, 2012). Cutting and Muggeridge (2010) report the ratio between reactive and proactive sewer blockage management in the UK to be 75% reactive to 25% proactive. Discussion with water company sewerage managers indicates that this figure varies significantly between each company, and that defining a precise ratio is difficult. Not only are there significant variations between companies, there is also a very significant seasonal and spatial variation within water company regions. Furthermore, it was reported that schedules of proactive maintenance would typically run for a set period of time, for example if a programme of interceptor trap removal was being undertaken.

2.4.3 Reactive Sewer Maintenance

Of the research undertaken examining sewer blockages, a very small percentage of the work has been concerned with achieving blockage reduction through improving reactive maintenance. Bratby (2000) describes the use of a methodology for managing blockages in former Section 24 sewers[1]. The operational issues asscoaited with former Section 24 sewers are significant. UK sewerage managers involved with this project report that most blockages, up to 50% in some catchments, occur within former Section 24 sewers. WRc (1995) & WRc (2005) also identified that the majority of blockages occur in these sewers, and can represent between 30 and 50% of blockages that occur.

Bratby (2000) stated that in order for blockages on former Section 24 sewers to be effectively managed, there are operational difficulties that need to be overcome. This includes problems with consistent data, which can lead to difficulties in establishing asset ownership, and therefore the responsibility for removing the blockage. Bratby (2000) also states that building over of sewers is a much more common occurrence in former Section 24 sewers, due to their proximity to the property. This not only increases the likelihood of sewer collapses, but also increases the chance of operatives encountering access issues when attempting to undertake sewer maintenance. Interceptor traps, which are exclusively located on former Section 24 sewers, were also identified as commonly being difficult to clear. This was reported

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[1] A former Section 24 Sewer is a drain which serves more one Property which was in existence pre 1st January 1937 and is the responsibility of the Sewage Undertaker

particularly common in instances where the trap had suffered structural damage in some way.

Muggeridge and Cutting (2010) state that improving the quality of reactive maintenance is required alongside increasing proactive maintenance to achieve a reduction in blockage numbers. The study suggests novel techniques such as real time monitoring and improved blockage removal techniques could be used to improve the effectiveness of reactive work.

2.4.4 Proactive Sewer Maintenance

Fenner *et al.,* (2000) suggest that proactive maintenance should target small diameter non-critical sewers which a) account for the largest percentage of the sewer network by length and b) are where the largest numbers of blockage occur. It is further suggest that sewers which possess certain criteria, i.e. slack gradients, poor condition or are located at critical flooding nodes should be used to select locations where proactive maintenance may be most effective. Similarly, Arthur *et al.,* (2007) describe part of a study in which historical blockage records were examined to understand where the majority of sewer blockages occur. It was concluded that the methodology cannot be applied to parts of the network where data availability is low i.e. historic blockage incidents cannot be attributed to an individual asset. This suggests that a method is required whereby smaller sewer can be targeted without relying on the presence of complete and accurate blockage and asset data.

Blanksby *et al.,* (2003) attempted to establish a link between structural pipe condition and blockage frequency. The rationale behind this approach was that if a strong correlation were found to exist, then proactive intervention could be planned based on an estimation of sewer condition. The study however concluded that no link could be made between condition and blockage occurrence, and that a wider range of factors such as flow conditions would need to be considered in planning proactive maintenance.

A commonality within each of these studies is that no method allows an indication of the impact on sewer performance to be understood, i.e. how much will the intervention reduce blockage numbers, and at what cost. The limitation of each of the methods therefore lies in the inability of a sewerage manager to economically

justify undertaking proactive maintenance, rather than simply continue on a reactive schedule.

2.5 Summary

The literature review of solid transport in small sewers has identified a number of factors which significantly influence the transport distance of a solid. The majority of publications however were concerned with solid transport in the context of new build sewers, and as such did not explore the effect of factors such as pipe condition or the presence of sediment.

A range of techniques has been applied to understanding the cause of sewer blockages. This has identified a number of factors which are associated with increased blockage likelihood. However there is a still a requirement for a better understanding of the mechanism by which a number of stoppages in a sewer aggregate to form a complete blockage, and in particular the timescale over which this process occurs. Both the findings from the solid transport work and sewer blockage cause work can be applied to identifying a mechanism by which a sewer may become blocked, which in turn can provide a basis for modelling the occurrence of blockages.

With respect to the management of blockages, the focus of previous research has been on increasing the extent of removal which is undertaken proactively. However, availability of data is a significant obstacle to planning proactive maintenance in small bore sewers. There is also no acknowledgement of the operational difficulties that can be encountered when undertaking reactive maintenance, and how overcoming these difficulties may improve the quality of work undertaken and in turn reduce blockage numbers.

The following work within this thesis will adopt an approach which will attempt to address the perceived gap in research, specifically:

- examine how the practical difficulties in undertaking sewer maintenance may be overcome to improve the overall quality of maintenance, reducing repeat occurrences;

- identify the mechanisms through which sewer blockages occur, relating them to the understanding of blockage cause and improving management; and

- develop a method whereby the effect of a sewer intervention can be understood, so that decisions regarding sewer intervention can be supported.

3 REDUCING THE OCCURRENCE OF REPEAT BLOCKAGES

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3.1 Introduction

3.2 Results

3.3 Analysis

3.4 Discussion

3.5 Summary & Recommendations

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3.1 Introduction

In accordance with Objective 2 of this thesis, the following chapter conducts a review of current reactive sewer blockage management and makes recommendations for improvement.

This chapter carries the following objectives:

1. Review the practical method through which blockage removal is undertaken
2. Review the current Code of Practice to assess its suitability for use
3. Review the effectiveness of the data reporting system currently in use
4. Identify how the current method and data reporting system could be improved

A large number of sewer blockages are repeat incidents, defined as the recurrence of a sewer blockage at the same locality within a specified length of time. The 'specified' length of time varies between water companies and can be anything from 3 days and 1 year. The inconsistent approach to defining a repeat blockage makes it difficult to estimate the number of repeat blockages that occur. Correspondence with the participating water companies indicate that repeat blockages can vary from 10 to 50% of the total number of blockages reported.

Previous research on repeat blockages undertaken by WRc (2004) suggested a high number of repeat blockage incidents are associated with ineffective blockage clearance practices. This includes the blockage and associated debris not being properly cleared from the sewer, causing the blockage to recur within a short period of time. It was also identified that poor reporting of blockages does not allow water companies to properly establish the blockage cause. This in turn prevents operations managers from properly assessing the causes of blockages, which in turn prevents the planning of interventions to remove/repair the cause of the blockage.

In order to assess the effectiveness of blockage removal currently undertaken, the blockage removal practices of 5 UK water companies were observed. Each of the 5 site visits took place over 3 day periods between February 2010 and April 2010. In line with the objectives specified, the following methodology was followed:

- **Review the practical method through which blockage removal is undertaken**

A qualitative assessment of the blockage practices of operations crews has been made. Observations were recorded based on the extent to which the work was being

undertaken in accordance with the operational best practice outlined in WRc Technical Report 6490: Sewer Jetting to Reduce Flooding – Best Practice Manual (WRc 2005). The assessment aimed to establish;

- to what extent operational best practice was being observed; and

- what job specific circumstances led to operational best practice not being observed;

Best practice was adjudged against five criteria each representing one element of practical blockage removal. These criteria are outlined in Section 3.2.

- **Review the current Code of Practice to assess its suitability for use**

A critical assessment of the current guidance document WRc Technical Report 6490: Sewer Jetting to Reduce Flooding – Best Practice Manual has been made. Observations on-site have been used to assess the suitability of the document in providing guidance to sewer operation crews.

- **Review the effectiveness of the data reporting system currently in use**

A critical assessment of the data reporting systems currently in use has been undertaken. The data reported on-site by the operatives has been reviewed and compared to the information recorded during the site visit. This aimed to establish:

- whether the correct fault was being recorded when reporting a blockage; and

- whether or not the information could be retrieved in order to be used to investigate the cause of repeat blockages;

The quality of reporting was assessed based on the ability of the sewer operations manager to review the blockage reports, and identify where follow up work may ensure that the blockage does not recur.

- **Identify how the current method and reporting system could be improved**

A series of recommendations have been made. The findings from objectives 1 & 2 of the chapter have been collated to provide:

- a list of practical recommendations as to increase the extent to which operational best practice is observed; and

- a data specification outlining how blockage incidents can be recorded to improve the diagnosis of sewer faults at repeat blockage locations;

3.2 Results

This section contains an overview of the results and observations obtained from the site visits. The results recorded from each site are included in Table 3-1 to 3-5.

The literature review did not identify any studies which present results similar to those presented here. As a result it has not been possible to undertake a comparison of the results outlined here, to those from similar studies.

3.2.1 Blockage Clearance Practices

The results are presented based on the findings from each individual work schedule of blockage removal for each company. The criteria used to assess best practice are summarised as:

- **Undertaking of appropriate initial investigation**

This indicator is used to assess whether the operative made an initial attempt to understand the location of the blockage and the connectivity of the system.

The initial aim of the operative is to establish the location of the blockage. Once the blockage has been located the operative can then review the sewer layout plans to determine if the blockage is the responsibility of the water authority or if the blockage is located on a private sewer. This initial investigation prevents blockage removal being undertaken on an asset for which the water authority is not responsible.

- **Work action used to remove the blockage**

This indicator is used to assess the action(s) undertaken by the operative in order to clear the sewer blockage.

Blockage crews were normally equipped with both sewer jetting equipment and sewer rods. Once the operative has identified the location where the work is to be undertaken, it is necessary to select the appropriate equipment to remove the blockage. The Code of Practice specifies that all blockage clearance should be undertaken with jetting equipment.

- **Work location**

This indicator is used to assess the location from which the operative attempted the blockage removal, i.e. upstream manhole or downstream manhole.

The Code of Practice specifies that blockage clearance should be undertaken from the downstream manhole. This helps to ensure that the majority of the blockage material is broken up and will not cause a blockage to form downstream. This also reduces the chance of internal flooding of a customer as a result of the blockage clearance.

– **Removal of blockage material from sewer**

This indicator is used to assess whether or not the blockage material was removed from the system.

The blockage removal undertaken by the operative should be sufficient to dislodge the blockage material and restore the flow. This will normally cause the blockage material to be dispersed downstream, being transported by the escaping flow. In order to prevent a repeat blockage, it is necessary to ensure that the blockage does not reform downstream. This can be achieved by removing the blockage material as it passes the downstream manhole with a 'gully grab' (*fig 3-3*).

– **Operational best practice**

This indicator is used to assess the overall quality of the blockage removal, based on the indicators above. In order to be considered 'best practice', the operative must carry out the work to the correct specification for each of the factors above.

Blockage Clearance Practice							Data Reporting		
Location Ref	Private Sewer	Initial Investigation	Action	Work Location	Blockage Material Removed	Best Practice*	Impact	Cause	Follow Up Recommended
AW/A	No	No	Rodding[1]	u/s	No	No	RTU[2]	NRV	No
AW/B	No	No	Rodding[1]	u/s d/s	No	No	RTU	Gradient Sanitary	No
AW/C	No	No	Rodding[1]	u/s	No[3]	No	RTU Ext Flood[4]	Interceptor	No
AW/D	Yes	No	Rodding	d/s	No	No	RTU	Tree Roots	No
AW/E	No	No	Rodding	u/s	No	No	RTU	Interceptor	New MH Cover
AW/F	No	No	Rodding[5] Jetting	u/s d/s[6]	No	Yes	Ext Flood	Sanitary	Tanker Jetter[7]
AW/G	No	Yes	Rodding Jetting	d/s u/s	Yes	Yes	Ext Flood	Partial Collapse	Uncover Buried MH Chamber

* Best practice was judged by comparison with WRc Code of Practice for sewer jetting (WRc 2005)

1. Operator was not equipped with jetting unit.

2. Restricted Toilet Use

3. Operative sufficiently broke up blockage material with rod.

4. External Flooding

5. The initial use of rodding was for investigation purposes only.

6. Unable to access manhole immediately downstream as cover was stuck; tried next manhole downstream but jetter could not reach blockage.

7. Initial jetter had insufficient pressure/water volume to remove significant accumulations of silt and debris in large diameter pipe.

Table 3-1 Anglian Water Site Observations

Blockage Clearance Practice							Data Reporting		
Location Ref	Private Sewer	Initial Investigation[1]	Action	Work Location	Blockage Material Removed	Best Practice*	Impact	Cause	Follow Up Recommended
NIW/A	No	No	Rodding Jetting	u/s d/s	Yes	Yes	RTU	Tree roots	No
NIW/B	No	No	Rodding Jetting	u/s	No[2]	No	RTU	Unknown	CCTV
NIW/C	No	No	Jetting	d/s	Yes	Yes	Ext Flood	Wipes	Clear up
NIW/D	Yes	No	Rodding	u/s	Yes	Yes[3]	RTU	Sanitary	No
NIW/E	Yes	No	Jetting	u/s	No	No	RTU	Unknown	No
NIW/F	Yes	Yes	N/A[4]	N/A	N/A	N/A	Odour	Unknown	No
NIW/G	No	No	Rodding	u/s	No	No	RTU	Unknown	No
NIW/H	No	No	Jetting	d/s	No	Yes	RTU	Unknown	No
NIW/I	No	Yes	Jetting	d/s	Yes	Yes	RTU	Wipes	CCTV
NIW/J	Yes	No	Rodding Jetting	u/s	N/A[5]	N/A	RTU	Partial Collapse	Excavation

* Best practice was judged by comparison with WRc Code of Practice for sewer jetting (WRc 2005)

1. Blockage crews were not provided with sewer layout plans

2. The operations crew were not able to clear the blockage

3. Could not access downstream chamber, used rods but removed blockage material

4. No blockage was located

5. Sewer had suffered a partial collapse

Table 3-2 Northern Ireland Water Site Observations

Blockage Clearance Practice							Data Reporting		
Location Ref	Private Sewer	Initial Investigation	Action	Work Location	Blockage Material Removed	Best Practice*	Impact	Cause	Follow Up Recommended
STW/A	No	Yes	Jetting Rodding	u/s d/s	Yes	Yes	RTU	Sanitary	No
STW/B	No	No	Jetting	d/s	No	Yes	Ext Flood	Unknown	No
STW/C	No	No	Jetting[1]	u/s[2]	No	No	RTU	FOG Sanitary	No
STW/D	No	Yes	Rodding	u/s	No	No	RTU	Gradient	No
STW/E	No	No	Rodding	d/s	No	No	Pollution	Unknown	Tanker[3]
STW/F	No	No	Jetting	u/s[4]	No	No	Sewage Escape	Tree Roots	No
STW/G	No	Yes	Jetting	d/s	No[5]	Yes	Sewage Escape	FOG	No
STW/H	No	No	Jetting	u/s	N/A[6]	N/A[6]	Ext Flood	Interceptor	Interceptor Removal

* Best practice was judged by comparison with WRc Code of Practice for sewer jetting (WRc 2005)
1. Action of jetting from upstream caused internal flooding of a customer
2. Operative could not gain access to downstream manhole in private garden
3. Jetter could not remove blockage
4. Operatives could not locate downstream manhole
5. Blockage material sufficiently broken up
6. Blockage could not be removed

Table 3-3 Severn Trent Water Site Observations

Blockage Clearance Practice							Data Reporting		
Location Ref	Private Sewer	Initial Investigation	Action	Work Location	Blockage Material Removed	Best Practice*	Impact	Cause	Follow Up Recommended
SW/A	Yes	Yes	Rodding	Upstream[1]	No	No	Ext Flood	Manhole Detail	No
SW/B	No	Yes	Rodding	Upstream	No	No	RTU	Manhole Detail	List as Private[2]
SW/C	No	Yes	Rodding	Upstream[1]	No	No	RTU	Interceptor	No
SW/D	No	Yes	Rodding	Downstream	No	No	RTU Odour	Gradient Condition[3]	No
SW/E	Yes	No	Jetting	Upstream	No	No	Ext Flood	Unknown	List as Private[2]

* Best practice was judged by comparison with WRc Code of Practice for sewer jetting (WRc 2005)
1. Operative could not locate downstream manhole; not indicated on sewer plans
2. Repeat blockage awaiting CCTV inspection; suspected poor pipe condition
3. Note attached to blockage report form to indicate private status

Table 3-4 Scottish Water Site Observations

Blockage Clearance Practice							Data Reporting		
Location Ref	Private Sewer	Initial Investigation	Action	Work Location	Blockage Material Removed	Best Practice*	Impact	Cause	Follow Up Recommended
UU/A	Yes[1]	Yes	Rodding Jetting	Upstream Downstream	Yes	Yes	Ext Flood	Foreign[2] Object	No
UU/B	No	Yes	Jetting	Upstream	No	Yes	Int Flood	NRV	Install Access Chamber[3]
UU/C	No	No	Jetting	Upstream	No	Yes	RTU	Unknown	Mapping[4]
UU/D	Yes[1]	No	Jetting	Upstream Downstream	No	No	Int Flood	Interceptor	No
UU/E	No	Yes	Jetting	Downstream[5]	No	Yes	RTU	Sediment	De-silt

* Best practice was judged by comparison with WRc Code of Practice for sewer jetting (WRc 2005)

1. Established after blockage had been removed through manhole and CCTV inspection
2. Large piece of wood from manhole chamber
3. To allow access to the NRV which had caused the blockage
4. Location of sewer and blockage was unclear, mapping exercise required to determine sewer layout and blockage location
5. Operative required to contact city council for access to alley way at rear of properties

Table 3-5 United Utilities Site Observations

3.3 Analysis

3.3.1 Data Reporting

The information recorded by each of the operatives was requested as part of the study. This was to enable a comparison to be made of the information recorded by the operative to the observations which had been made on-site. The data returned from each company is summarised below:

− **Anglian Water**

Anglian Water was able to supply copies of the information recorded on their information systems for the blockages AW/B to D described in Table 3-1. The reports for the remaining two incidents (locations AW/A and AW/F) could not be identified on Anglian Water's systems.

For each of the 5 blockages the impact of the blockage and the clearance method used had been correctly recorded. However, Anglian Water's records did not record significant details of the incidents, such as specific causes and in particular whether the blockage occurred at an interceptor trap.

− **Northern Ireland Water**

Northern Ireland Water supplied copies of the information recorded on their information systems for the blockages observed on-site NIW/A to D and G to J described in Table 3-2. The blockages at locations NIW/E and NIW/F could not be retrieved, possibly due to the indeterminate ownership of the assets on which the blockage removal took place.

For location NIW/A, tree roots and rags were identified on site as the specific problem. However, the report recorded 'no reason stated'.

The blockage at location NIW/B was correctly recorded but the follow up work requested (tanker and CCTV) was not included in the report.

The blockage at location NIW/C was recorded but not as a flooding incident despite significant highway flooding. The blockage material, a mass of wipes, was recorded as 'inappropriate materials'. The location of the incident at the entrance to the estate was recorded as the address of the caller, over 100 m from the blockage.

At location NIW/G a blockage was recorded as 'no reason stated' despite the crew identifying wet wipes and removing accumulations from the sewer. The record also did not record the deposited granular material, similar to the type used as granular backfill which may have indicated an open joint or partial collapse. However, a CCTV follow up was recommended to investigate this.

- **Severn Trent Water**

Severn Trent Water were able to supply copies of the information recorded on their information systems for all the blockages observed on-site, described in Table 3-3.

A review of the reports as entered on the Severn Trent Water system for four of the blockages identified that, where a number of different actions had been taken (e.g. rodding followed by jetting), only the last action carried out was reported. The causes entered on the system did not agree with the site observations. At locations STW/E and STW/G the report listed the cause as sanitary products; however no obvious sanitary products were observed at these locations.

- **Scottish Water**

Scottish Water were able to supply copies of the information recorded on their information systems for all the blockages observed on-site, described in Table 3-4.

For the reports made available, the single external flooding source, (location SW/A) was correctly reported by the operative. However it was noted that for all incidents attended, the 'Cause of Flooding' field was used to report the cause of the incident regardless of whether flooding had occurred.

The nature of the blockage was reported on all reports as 'sanitary products' and although these products were observed in the backed up flow at sites observed, structural features of the sewer were considered to be the primary reason for the blockage. Sanitary products were considered a contributing factor.

At Locality SW/A, poor detailing of the benching had resulted in debris lodging in the channel leading to a blockage. The report does not clearly identify the cause or the position of the blockage at the outlet from the manhole. The method of clearance was incorrectly recorded as 'jetting' when the clearance was affected by rodding and wash down with the hose without the nozzle.

At Locatlity SW/C the incident was a blockage at an interceptor trap, but the report recorded a 'Cause of Flooding' as Blockage/Defect. It is likely that the blockage was directly attributable to the interceptor trap and fats deposited in it. The trap was only reported in the free text part of the report.

At Locality SW/D the 'Cause of flooding' was reported as collapse from a CCTV survey carried out following a previous blockage. No follow up tasks were requested on the report and no reference to multiple previous incidents was noted.

‒ **United Utilities**

United Utilities were able to supply copies of the information recorded on their information systems for all the blockages observed on-site, described in Table 3-5.

Two of the reports related to incidents identified as United Utilities responsibility (Locations UU/A and UU/B in Table 3-5). Two reports related to incidents observed on private drains. Data entered for both the public and private jobs were equally comprehensive.

The incident codes were only used to identify that the incident was caused by the blockage rather than giving the cause of the blockage. No code for an interceptor trap was available which was the perceived cause of the blockage at Locality UU/B. The causes of blockages were therefore not fully reported.

The causes of the incident, (blockage, collapse, equipment failure, hydraulic, flooding other causes), were adequately identified, but details regarding the cause of the blockage (e.g. FOG, wipes, roots etc., exact position of blockage, pipe size, asset condition etc.) were not recorded despite this being positively identified by the crews on site.

3.4 Discussion

3.4.1 Initial Investigation

Of the 29 blockages observed whilst on-site, initial investigation to establish the responsibility of the blockage was undertaken at 7 locations. For the 22 locations where initial investigation was not undertaken, 6 of these resulted in blockage removal being undertaken on a private sewer for which the water company was not responsible.

In order to establish whether a blockage is the responsibility of the water company or the homeowner it is necessary to establish a) the location of the blockage and b) the ownership of the asset on which the blockage is located. It was observed that locating the blockage was straightforward for most of the blockage jobs witnessed and this was confirmed through discussions with the operatives. Establishing ownership of the sewer however was much more difficult, and this was observed to be the primary cause of blockage removal being undertaken on private assets.

When trying to establish ownership of an asset the common protocol was for the operative to review the plans for the sewer catchment. These were provided to operatives through 'toughbook' field computers. The operatives reported significant difference in the accuracy and completeness of the sewer plans between different catchments. Sewer catchment plans were often reported to be inaccurate, incomplete or misleading and prevented the operative from determining asset ownership through this method. It was reported that such data issues were more frequent in former Section 24 catchments. It was on former Section 24 sewers where the majority of the blockages observed on-site occurred.

In the event of sewer plans not being suitable for establishing asset ownership, the operative would be required to establish the system connectivity through identifying incoming connections in manholes. As a rule of thumb, if the operative identified connections from two or more different properties then the sewer located downstream is the responsibility of the water company. However, this procedure could only be undertaken after the blockage had been removed, and the manhole chamber was no longer surcharged. An example of this was observed at Locality UU/A. Following the removal of a blockage, the operative was able to determine that connections from only one property discharged into the manhole (*fig 3-1*). The blockage had therefore been removed from a private asset. At several further localities it was observed that establishing the ownership of the sewer, and therefore a blockage could only be done retrospectively.

Figure 3-1 Location UU/A - Manhole before and after blockage removal; operative was able to subsequently identify blockage was removed from a private asset

It is anticipated that through improving the sewer record plans provided to operatives, more effective identification of asset ownership could be achieved. This in turn would reduce the number of blockages removed from private assets.

Guidance on establishing asset ownership is not included in the current Code of Practice. There is therefore potential for an addendum to be made, which would give full guidance on establishing sewer ownership before undertaking blockage removal. This would include guidance when using sewer plans, and guidance where sewer plans were not available or could not be used.

3.4.2 Blockage Clearance Practice

Of the 29 blockage jobs observed, operational best practice described in the Code of Practice manual was observed at 12 localities. Scottish Water had the highest proportion of jobs which did not adhere to best practice, as every one of the jobs witnessed demonstrated some practice which did not meet the Code of Practice specification. Northern Ireland Water had the lowest proportion of jobs which did not meet specification.

The job localities where Code of Practice was not followed has been summarised in Table 3-6. The results indicate that if one element of best practice was not followed, this tended to occur concurrently with the other elements not following best practice. This correlation may suggest that there is a tendency for one factor to be implicated in another.

Evidence of this was observed on-site. It was observed that upstream working tended to necessitate the use of rods rather than jetting equipment. Several operatives explained that due to the associated flood risk with using jetting equipment in an upstream work location, they would favour the use of rods when working from upstream. Upstream working was also observed to prevent blockage material being removed from the sewer.

Upstream working acts as a catalyst for the other two elements of best practice not being observed. It could therefore be reasoned that if operatives were encouraged to undertake work from a downstream location, this would improve the overall quality of the blockage clearance undertaken, which in turn would reduce the number of repeat occurrences.

Table 3-6 Summary of blockage jobs not following best practice

Location REF	Action	Work Location	Material Removed
AW/A	Rodding	Upstream	No
AW/B	Rodding	Upstream/Downstream	No
AW/C	Rodding	Upstream	No
AW/D	Rodding	Downstream	No
NIW/B	Rodding/Jetting	Upstream	No
NIW/E	Jetting	Upstream	No
NIW/G	Rodding	Upstream	No
STW/C	Jetting	Upstream	No
STW/D	Rodding	Downstream	No
STW/E	Rodding	Downstream	No
STW/F	Jetting	Upstream	No
SW/A	Jetting	Downstream	No
SW/B	Rodding	Upstream	No
SW/C	Rodding	Upstream	No
SW/D	Rodding	Downstream	No
SW/E	Jetting	Upstream	No
UU/D	Jetting	Upstream/Downstream	No

Part of the review reactive sewer operation is to examine why the operational guidance in the Code of Practice was not being observed. In order to investigate the tendency of operatives to remove blockages from upstream locations, operatives that chose an upstream work location were questioned about the selection.

The majority of operatives were able to appreciate the importance of working from downstream. However, a number explained that a) locating a downstream manhole and b) gaining access to a downstream manhole prevented blockage removal from being undertaken from downstream. This is consistent with observations made on-site. At STW/5 for example, the operative was not able to locate a downstream manhole, and the sewer records did not indicate its location. The operative was therefore unable to attempt the work from a downstream location.

It was observed that the downstream manhole was more difficult at localities where the manhole was located in a private garden. This was a common occurrence with blockages on former Section 24 sewers where the drainage was often located to the rear of the property. At Locality STW/5 for example, access could not be gained to a manhole which was located in a neighbouring garden (*fig 3-2*).

Furthermore if a manhole was located in a private garden, it was common for access to the manhole to obstructed by garden furniture or decking. This would require the permission of the householder to remove the obstruction. Based on the site observations however, operatives would tend to undertake the blockage removal from upstream, rather than seek to address the access issues.
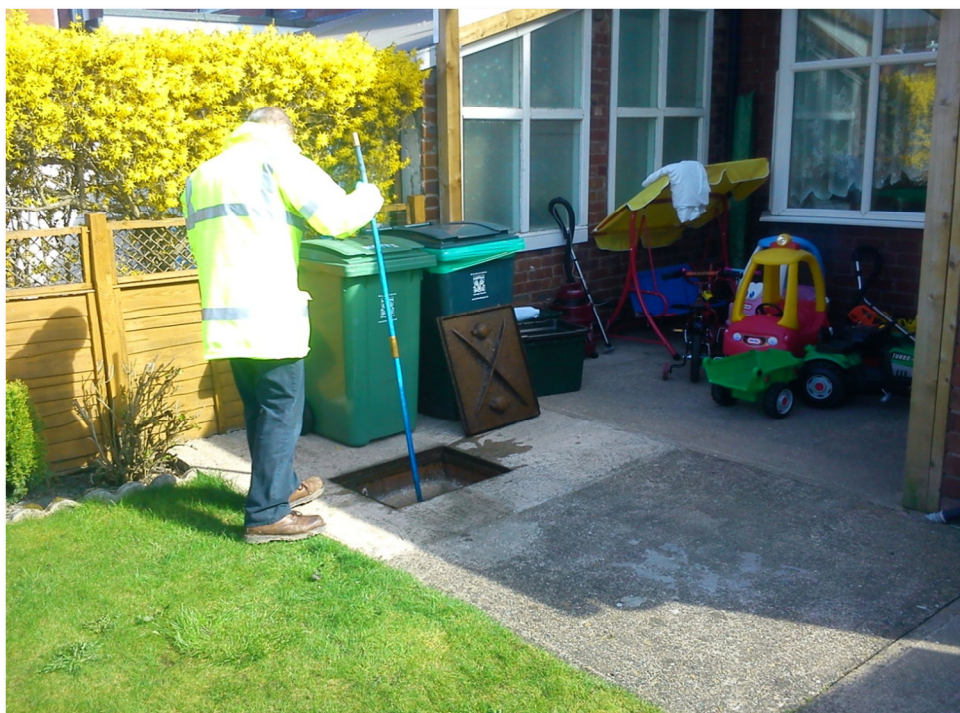
Figure 3-2 Location STW/3 - Work being undertaken from the upstream manhole, the downstream manhole (located in the garden to the left of the operative) could not be accessed

The Code recognises that in some circumstances working from an upstream location may be necessary, and the several observations made on-site reinforce the need for this concession. The Code outlines the flood risk associated with using jetting equipment in a fully surcharged sewer, and the necessary precautions that should be taken. This includes attempting to restore the flow and provide hydraulic relief of the sewer before attempting to fully remove the blockage. This guidance was not followed on-site at Locality STW/3, and the blockage removal caused a customer to be internally flooded.

Working from an upstream location not only increases the chance of internal flooding of customers, but also impairs the ability of the operative to remove the blockage material from the system. The Code specifies that debris from the blockage should be broken up into small pieces and/or removed from the system at the downstream chamber. However, no guidance is given if removal is being undertaken from upstream and/or the downstream manhole cannot be accessed.

When undertaking blockage removal from the upstream manhole, special rod attachments exist which enable the operative to pull the blockage material out of the system. This then allows the operative to remove the blockage material with a gully grab (*fig 3-3*). The use of the specialist rod attachment was only observed at NIW/A. Other operatives indicated they had not been provided with the attachment, or if they had were only inclined to use it if the blockage could not be cleared otherwise.

Figure 3-3 Location NIW/A - A 'gully grab' used to remove blockage material from the sewer

However, at a number of localities it was observed that the removal of material was not necessary. At Locality STW/5, the blockage material consisted of dewatered particulate toilet tissue and solid human waste which had disintegrated in the flow (*fig 3-4*). It was observed that this type of blockage material was mobile in the flow of effluent and would therefore have not posed a blockage risk downstream. In such cases, the operative can sufficiently break up the material with a sewer rod to ensure it is able to be transported downstream without causing a subsequent stoppage.

Removal of the material however is required when large non-degradable items such as wet wipes and sanitary products (*fig 3-4*) are present in large quantities in the blockage material.

Figure 3-4 (Left) Location NIW/C - Gross non-degradable solids which would be likely to cause a blockage downstream. (Right) Location STW/E - Degradable solids which can be removed with the flow and so do not require removal from the system

The observations on-site suggest that there is potential to update the current Code of Practice to give guidance under what circumstances blockage material should be removed from the system. This may increase the propensity of operatives to remove material and will clarify the requirement for removal of material from the system. This in turn may increase the amount of non-degradable material being removed from the system, which may otherwise cause a repeat blockage.

The study of repeat blockage locations along with the observations made on-site indicate that operatives would preferentially use rods as a method of removal when the blockage was located on a Section 24 sewer at the rear of a property. Blockages located to the rear of the property would often prevent the operative using a jetter, mainly due to practical issues in locating the van close to the location of the blockage (*fig 3-5*). The study of repeat blockage locations indicate that several blockage jobs for which rodding was used, the blockage reports often included comments such as 'could not access blockage with jetter'.

**Figure 3-5 Location AW/2 - Blockage on a section 24 sewer to rear of property;
cleared with rods as could not access with jetter**

The Code indicates that where there is restricted access for jetters, it may be appropriate to run the jetter through the property of a customer. However several incident report forms included comments such as 'customer did not allow the running of the jetter hose hrough the property'.

With respect to reducing repeat blockages, the evidence from on-site and blockage reports has indicated in some circumstances the use of rods is unavoidable. However, if a blockage is cleared with rods there should be a greater onus on the operative to a) ensure that all the blockage material has been dispersed from the site of the blockage and b) the blockage material from the sewer is removed or adequately broken up to prevent a repeat occurrence. The latter could be increased by including material removal as part of the on-site data reporting requirements.

Ensuring proper clearance of the blockage material can be achieved through use of a CCTV camera, and was observed at several localities. Locality UU/3 for example used a 'look see' CCTV camara to inspect the pipe after completing the work. The quick survey allowed the operatives to confirm that no debris that could cause a repeat blockage remained in the pipe. This could also be included as part of a data reporting requirement.

The current Code does not advocate, or give guidance on the use of rods in any situation. In order to improve the quality of blockage work undertaken, it may be necessary to include a guidance section on using rods, and what additional measures should be used to ensure the blockage removal is undertaken properly. This would ensure that where rods are used as a method of removal, further actions are taken to reduce the chances of a repeat incident.

3.4.3 Data Reporting

Of the 29 blockages, 25 work records were retrieved from each company database. Of the 4 that could not be identified, 2 were from Anglian Water whilst 2 were from Northern Ireland Water. In the case of Northern Ireland Water, it is possible the jobs which could not be retrieved were those where there was indeterminate ownership of the asset, i.e. the blockage was located on a private sewer. In contrast, the blockages which occurred on private sewers cleared by United Utilities were both recorded onto the system. This recording of private jobs may allow repeat blockages at the same location to be easily identified as a private problem, and thereby reducing the chance of United Utilities undertaking removal work on these assets.

The majority of the blockage reports correctly identified the work which was undertaken. This is important as it can allow an analysis of repeat blockage locations and the removal method used.

A review of the blockage reports however highlights that recording of the cause of the blockage was low. For example, a number of blockages were observed to have occurred at interceptor traps, specifically AW/3 (*fig 3-6*).

Figure 3-6 Location AW/3 - Blockage removed from an interceptor trap, recorded as 'no cause'

No mention of interceptor traps however was included in the blockage report. Similarly at Locality NIW/1, tree roots and sanitary items were identified by the operative as the cause of the blockage. However the report retrieved stated 'no reason given' as the cause.

The lack of information regarding the cause of the blockage significantly reduces the chances of sewerage managers identifying areas where follow up maintenance may reduce the chances of a repeat blockage. This is particularly true where a defective feature of the sewer was the cause of the blockage. This may have been the result of tendency of operatives to include such information in the same part of the report as follow up work requests.

The free text comments box from the blockage report forms could only be retrieved from the Scottish Water record database. Discussions with sewerage managers indicated that a lot of the information regarding a blockage (often including the cause) was recorded in the free text comments box at the bottom of the form. It is likely that this in part is responsible for the information not being recorded on correct area of the form.

Overall it is concluded that the data retrieval from the blockage report forms is low. The reason for this is the amount of information which is recorded in the free text box which is subsequently not included in further analysis. There is therefore the potential for the reports to be redesigned in order to extract the information from the operatives rather than this information being entered in the free text box.

3.5 Summary and Recommendations

3.5.1 Overview

The literature review outlined the lack current lack of understanding of how operational difficulties regarding reactive sewer blockage removal can impact on the quality of blockage removal undertaken. In order to improve the understanding of the effectiveness of blockage removal, this chapter describes a field study examining how operational difficulties on-site can reduce the quality of sewer blockage removal, and cause an increase of repeat blockages.

3.5.2 Initial Investigation

The observations made on-site indicate that a significant number of private blockages are cleared by sewer operatives. The main cause for this was poor quality sewer plans that did not allow the operatives to identify the ownership of the sewer. It is therefore anticipated that if improvements are made to the accuracy and completeness of sewer records, this will reduce the number of private blockages removed by operatives.

The issue of sewer records was discussed with sewer managers during the project. It was stated that a proactive exercise of plotting unmapped areas of the network was considered to unfeasible, both practically and economically. A method is therefore required through which unmapped sewers can be updated onto the system following the occurrence of a blockage at a particular catchment location.

This approach has been adopted by Southern Water in recent years as reported by Challenor, (2010). When recording the blockage particulars on the incident report form, the operatives can mark up any previously un-recorded assets on a digital "red line drawing". Following confirmation by a sewerage manager this was entered onto the GIS sewer record system. The measure was reported to be very successful, especially useful in repeat blockage locations such as Section 24 sewers. It is anticipated that if a similar system is introduced to other water companies, this will allow a gradual increase in the quality of sewer records provided to operatives. This in turn may reduce the number of private blockages being removed from the system.

In order to implement a procedure to allow asset resolution to be improved, the following recommendations are made in Table 3-7.

Recommendation	Description/Benefit
Introduce facility for incremental mapping of sewers	It is anticipated the measure will deliver these primary improvements: • Mapping of sewers improves without a costly investment • Improved ability of operatives to determine private blockages • Reduced working time • Improved clarity of information provided to customers These benefits will be subsequent to those described above: • Better understanding of blockage occurrence and location • Improved recording of blockages to correct asset
Introduce training for use of mapping facility	• Operatives are able to undertake mapping properly and consistently • Operatives appreciate the importance of undertaking the mapping seriously; and is not regarded as simply additional work
Introduce a data reporting facility that will allow inaccurate sewer plans to be flagged	• Reduction in the number of private blockages removed • Reduced confusion and the time spent on-site by operatives

Table 3-7 Recommendations for Improvements to Operational Practice

With respect to the current Code of Practice, there is potential for an addendum to be included which would give guidance in establishing asset ownership, both with and without the use of reliable sewer plans. Currently the code of Practice describes the potential issues which may be associated with certain sewer catchments, namely former Section 24 sewers. However there is no guidance on a procedure for identifying private assets.

Based on the findings from the study, the following recommendations are made for the update of the current Code of Practice document in Table 3-8.

Recommendation	Description/Benefits
Provide guidance on establishing sewer ownership	• Better establishment of private sewers • A reduction in the number of private blockages removed
Provide guidance on mapping sewer plans; to be introduced alongside the appropriate training	• Operatives are able to undertake mapping properly and consistently • Operatives appreciate the importance of undertaking the mapping seriously; and is not seen as additional work

Table 3-8 Recommendations for Improvements to Code of Practice

3.5.3 Blockage Clearance Practices

The quality of blockage removal in accordance with the Code of Practice was assessed against 3 criteria. It was observed that if one aspect of best practice was not followed, this tended to occur concurrently with other aspects not being followed. Of each of the components used to assess best practice, it was established that upstream working was the catalyst for the other two aspects of best practice not being followed.

In order to improve the quality of blockage clearance undertaken, the following recommendations to the operational practice are made in Table 3-9.

Recommendation	Description/Benefits
Facility for Disposal of Blockage Material	• Increased removal of blockage material from sewers
Better guidance on Access Issues; a protocol whereby guidance specifies that if the blockage cannot be removed properly without access, follow up work is scheduled subject to obtaining necessary access.	It is anticipated the measure will deliver the following specific improvements: • Reduce the occurrence of upstream working This will in turn lead to: • Fewer occurrences of internal flooding due to upstream working • Fewer blockage removals with rods • Improved blockage clearance • Increased material removal from the system

Table 3-9 Recommendations for Improvements to Clearance Practices

The observations on-site indicate that the current Code of Practice does not adequately reflect the complexity and variation in the types of blockage jobs encountered. For example the Code of Practice does not give any guidance on the use of sewer rods for blockage removal. It was however observed that, in some instances, blockage removal with rods was unavoidable.

Based on the findings, a series of potential amendments to the current Code of Practice are suggested in Table 3-10.

Recommendation	Description/Benefits
Guidance on use of rods; including a stipulation that the use of rods should be considered if jetting cannot be undertaken safely	• Improved blockage clearance when the use of rods is completely necessary This will include: • Improved break up/removal of material when using rods • Improved blockage clearance; based on protocol for ensuring blockage is fully removed when rods are the clearance method.
Guidance on upstream working	• Improved blockage clearance when working from upstream This will include: • Guidance for use of safe jetting • Procedure for removing blockage material
Guidance on removal/ break up of blockage material from sewer; a protocol for what circumstances material removal is important	• Increased tendency of operatives to removal blockage material (if required) • Increased tendency of operatives to break up of blockage material (if required) • Improved data reporting of blockage material; operatives encouraged to give a better account of the work undertaken, what blockage material was etc. • Increased tendency for blockage crews to flag up subsequent work (if required)

Table 3-10 Recommendations for Improvements to Removal Code of Practice

3.5.4 Data Reporting

The study has indicated that the information reported following a blockage was insufficient to allow sewerage managers to properly assess repeat blockage causes. This was due to the majority of information regarding the blockage being recorded in

the free text box. This information was subsequently not transferred onto the system. To this end, a data specification has been developed. The specification outlined in Table 3-11 aims to give guidance on what information should be requested as part of the blockage incident report form.

Work Details	
Job Reference	<Insert reference>
Postcode	<Insert postcode>
House/Building No.	<Insert house number>
What caused the blockage to be reported? (if not already supplied)	The following options should be included as a dropdown selection: • Restricted Toilet Use • Internal Flooding • External Flooding • Pollution Incident • CSO Overflow • Odour • Surcharged manhole • Other (specify)
How was the blockage cleared?	The following options should be included as a dropdown selection: • Jetted from Downstream MH • Rodded from Downstream MH • Jetted from Upstream MH • Rodded from Upstream MH • No Work Required
Which manhole was used for access	<manhole reference>
What happened to the blockage material?	Operative should select 1 field from the following • Deliberately broken up and flushed down sewer • Removed • Accidentally flushed away before being broken up or removed
Was a CCTV survey undertaken?	Operative should select 1 field from the following • Yes – "look-see" camera • Yes – full survey • No

Blockage Details	
Location of blockage	<insert coordinates>
What is the main material present in the blockage?	Operatives should be able to select multiple fields: • FOG • Rags/Wet-Wipes • Sanitary Items • Dewatered Sewage • Tree Roots • Silt/Sediment • Other - See Comments • Unknown
Is there any obvious reason why the blockage occurred where it did in the sewer?	Operatives should be able to select multiple fields: • Joint defect • Intruding connection • Broken/fractured pipe • Cross flows • Excessive bends in manholes • Tree root intrusion • Interceptor trap • Large volume of silt/debris • Collapsed pipe • Sharp bend in sewer line • Slack gradient
Are there any difficulties with access to manholes? If yes please specify	No Yes (specify) :
Asset Details	
If the asset is mapped, what is the pipe reference number?	<Insert reference>
What is the pipe material?	Opetive should select 1 field from the following • Clay • Plastic • Concrete • Brick • Pitch fibre
What is the pipe	Operative should select 1 field from the following

diameter?	• 100 mm • 150 mm • 225 mm • 300 mm or greater

Table 3-11 Data Specification for Blockage Report Form

4 SEWER BLOCKAGES MODEL DEVELOPMENT

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4.1 Introduction

4.1.1 Background

In order to reduce the number of blockages suffered by public sewer networks, there is a requirement to undertake more sewer maintenance on a proactive basis. In order to meet this demand, a method is required through which the decisions regarding proactive intervention can be supported. One of the major obstacles to proactive blockage removal is accurately estimating where a proactive schedule of work should be prioritised. To meet this need, a predictive sewer blockages model has been developed.

The objective of the model is to allow sewerage operators to identify which sewers in their network are most susceptible to suffering blockages, and what factors characterise this susceptibility. Once an understanding of the factors and mechanisms implicated in blockage formation has been achieved, the effect of various types of proactive intervention on blockage rate can be estimated. This can then allow proactive maintenance to be scheduled on an economic basis, i.e. will the cost of an intervention will be economic in terms of what effect the intervention has on the occurrence of future blockages.

In accordance with Objective 3 of this thesis, the following chapter describes the development of a tool to help support decisions in proactive maintenance. Unlike previous sewer blockage models which have been developed through statistical analysis of previous blockage occurrence, the approach adopted is based on an empirical understanding of the mechanisms through which a sewer can become blocked.

This chapter carries the following objectives:

1. Based on empirical evidence, provide an account of the mechanisms through which a sewer can become blocked, and what factors are implicated in those mechanisms

2. Based on an understanding of sewer blockage mechanisms, develop a conceptual blockage model which describes the formation of a sewer blockage

3. Based on the conceptual model, develop an arbitrary scoring system which designates a score of risk for a certain sewer parameter based on an understanding of its contribution to a blockage mechanism

4. Calibrate the scoring system with observed sewer blockage data

5. Develop a number of potential sewer interventions and, based on an understanding of sewer blockage mechanisms, quantify the effect of each intervention on blockage rate

6. Review the model performance and discuss the current model limitations.

4.1.2 Specification

The majority of sewer blockages occur in the intermittent flow zone in small 100-225 mm sewers at the head of the sewer network. The model has therefore been developed to be representative of the processes which occur in this part of the sewer network.

Chapter 3 outlines the extent of the blockage and asset data currently held by water authorities for a sewer catchment. The data requirements must be reflective of the data availability and must not require extensive additional data collection. Notwithstanding this, based on the current data availability the model must be robust enough to give accurate enough predictions on which to plan proactive sewer maintenance. The model must also be flexible to be applied to range of sewer catchment scenarios.

4.1.3 Approach

In order to model the process of blockage occurrence there is first a requirement for the process of blockage formation to be established. This will include developing an understanding of the factors involved in blockages. Based on an understanding of the factors implicated in blockage mechanisms, an assessment of sewer vulnerability can be made for a given length of sewer. This can then allow the effect of various interventions on blockage rate to be estimated.

Establishing the blockage mechanisms will be based on empirical evidence gathered during the site work described in Chapter 3, previous experimental work on solid

transport, and previous literature examining the occurrence of sewer blockages. Expert judgement will also be used, specifically from sewer flooding specialists at WRc along with sewer managers from each of the water companies participating in the project.

4.2 Development of Conceptual Model

4.2.1 Sewer Blockage Mechanisms

The literature review summarises the previous work that has examined the mechanisms of solid transport in intermittent flow conditions. These intermittent flow conditions occur in small diameter sewers (< 225 mm) at the upstream section of the system. Further down the system in sewers larger > 300 mm in diameter, the number of connections increases and this generates a continuous flow regime. Most sewer blockages occur in these smaller sewers in the intermittent flow zone where the flow conditions result in the stoppage of solid material.

When a solid is discharged into the system, the flush wave from an appliance will carry a solid a certain distance before it becomes stranded. A subsequent wave will then be required to generate subsequent movement of the solid, either from the same or a different appliance that connects into the system. However, since the waves become more attenuated and have less carrying capacity as they move further downstream, there is a limiting distance that the flows from a single appliance can transport solids (Littlewood, 2000; Littlewood & Butler, 2003)

In normal operation it should therefore be expected that there will be stranded solids at intervals along any pipe in the intermittent flow zone. Individually these are not likely to be large enough to cause a blockage. The question therefore is how these stranded solids come together to form a blockage. Two possible mechanisms are proposed:

1. As a solid from the appliance is moved downstream by successive waves it merges with other solids. The mass of solid material becomes larger causing the friction between the solid and the pipe wall to increase. Eventually this frictional force will be greater than the force generated by the flow and the material will become permanently deposited. It is possible that a wave of surface water during rainfall events may contribute to the amassing of solid

material, and that this process is quicker than under the action of successive waves from appliances.

2. The solid transport experiments observed that if the invert of the pipe is smooth, solids are observed to slide along the base of the pipe (Littlewood, 2000). However, if the friction between the solid and the invert is high, for example due to sediment in the invert, the solids roll and tumble along through the pipe. In this case solid material would tumble over each other and become entangled, forming a large mass of coalesced solids. This may explain the mass of solids observed at inlets to sewage treatment works.

Currently there is no experimental data to confirm either theory. It is also possible that these mechanisms occur concurrently in the build-up to a sewer blockage. In either instance however the factors that contribute to solid deposition, and therefore also blockage formation are the same. These can be summarsied as:

- hydraulic conditions;

- pipe friction; and

- nature of the solid.

The factors contributing to each are described in more detail below.

- **Hydraulic conditions**

Solid transport through a sewer system is dependent on the hydraulic conditions therein. Movement of solids requires there to be a sufficient flow rate to maintain the necessary depth and velocity to overcome the friction between the pipe and the solid.

In foul sewers (and combined sewers during periods of dry weather), the flow in the sewer is generated entirely by water use appliances in the buildings upstream which the drainage serves. Littlewood (2000) observed that only discharges from WC's have a sufficient depth of flow to transport gross solids. These discharges will attenuate as the distance from the appliance increases, reducing the depth of flow. The solid transport capacity of the flow therefore depends on the frequency of the discharges, and there proximity to the appliance. In high density housing therefore where sewer lengths tend to be shorter permanent deposition of solids is therefore less likely when compared to lower density housing with longer sewers.

Lilywhite and Webster (1969) stated that the detailing of the sewer system can create poor hydraulic conditions. Not only in the case of housing density and length of sewers described above, but also at manholes or inspection chambers.

It is reported that sewer blockages can often be associated with heavy rainfall events where the sewer is prone to surcharging. Arthur *et al.,* (2008) suggested that pipes which are prone to surcharging may be at increased risk of blockage. There is no previous research to suggest why this correlation may occur, or what the mechanism may be. However, surcharging of pipes creates an additional backwater effect. This in turn would reduce the velocity of the flow through the pipe, making deposition of solid material and formation of a blockage more likely.

– **Friction between pipe and solid**

When the depth of flow is insufficient for solids to float clear of the invert of the pipe (mechanism A as described in Chapter 2), the movement of the solid along the pipe is influenced by the friction between the solid and the invert of the pipe. Higher pipe friction will reduce the movement of a solid. As a result, any feature which increases this friction will reduce the distance a solids travels with a wave, and this will cause an increased number of deposited solids within the pipe length. The more solids that accumulate, the greater the likelihood of a blockage occurring.

Any feature therefore that increases the friction will reduce solid mobility will in turn increases the likelihood of a blockage. This is particularly true in smaller sewers with intermittent flow as lower result in a greater degree of contact between the solid and the pipe invert. Features that contribute to the friction can be summarised as:

- sediment (fine silt, grit or debris);

- displaced, open or broken joints;

- pipe bends;

- interceptor traps;

The Sewer Risk Management (SRM) report (WRc, 2008) describes a system for quantifying the extent of friction of a pipe. The system is described as the 'serviceability grading' and is based on a grading system of 1 to 5. These grades are derived from designating a score to certain features that increase the friction of the pipe, which are normally identified through a CCTV inspection. The allocation of

scores in the SRM for each type of defect is subjective as it is based on the expert judgement of the operative examining the CCTV report.

Where CCTV information is not available, the likelihood that there is a sediment bed can be estimated using the criteria for the design of sewers to achieve self-cleansing conditions. Modern design guidance such as Sewers for Adoption – A design and construction guide for developers (WRc, 2006) recommends a minimum gradient for a given diameter to ensure that self-cleansing conditions are achieved. Prior to the existence of national design guidance, design standards were more localised. As a result, some older sewers do not meet the current requirements for self-cleansing conditions. This is particularly common in areas with a predominantly flat topography where the slope of the sewers represents that of the surface.

Self-cleansing conditions for pipes are determined by:

- gradient

- diameter

The flux of sediment carried in a pipe is determined by the function of sewer, more specifically the inclusion of surface water. Grit and other sediment is largely derived from surface water runoff so will generally not occur in foul sewers, but will common in combined sewers.

- **Solid entry**

As identified in the literature review, the type of solid deposited into the sewer will have an influence on blockage formation as it is this material that is responsible for the causing obstruction to the flow. The disposal of non-'large solids' such as non-degradable materials, non-woven fabrics (*fig 4-3*) etc. is reported to significantly increase the likelihood of a blockage.

The disposal of inappropriate materials into the sewer system that are large in comparison to the size of the pipe, when combined with poor hydraulic conditions and/or high serviceability grading, can make certain locations more susceptible to blockage formation. These factors are considered to be related to social economic and demographic factors.

4.2.2 Conceptual Blockage Model

Based on an understanding of the mechanisms through which a sewer can become blocked, a conceptual blockages model has been developed which describes the factors involved in determining the formation of a blockage. The concept model (*fig 4-1*) has been developed to assess the likelihood of a sewer blockage of a particular length of sewer based on the presence of factors identified to increase blockage likelihood.
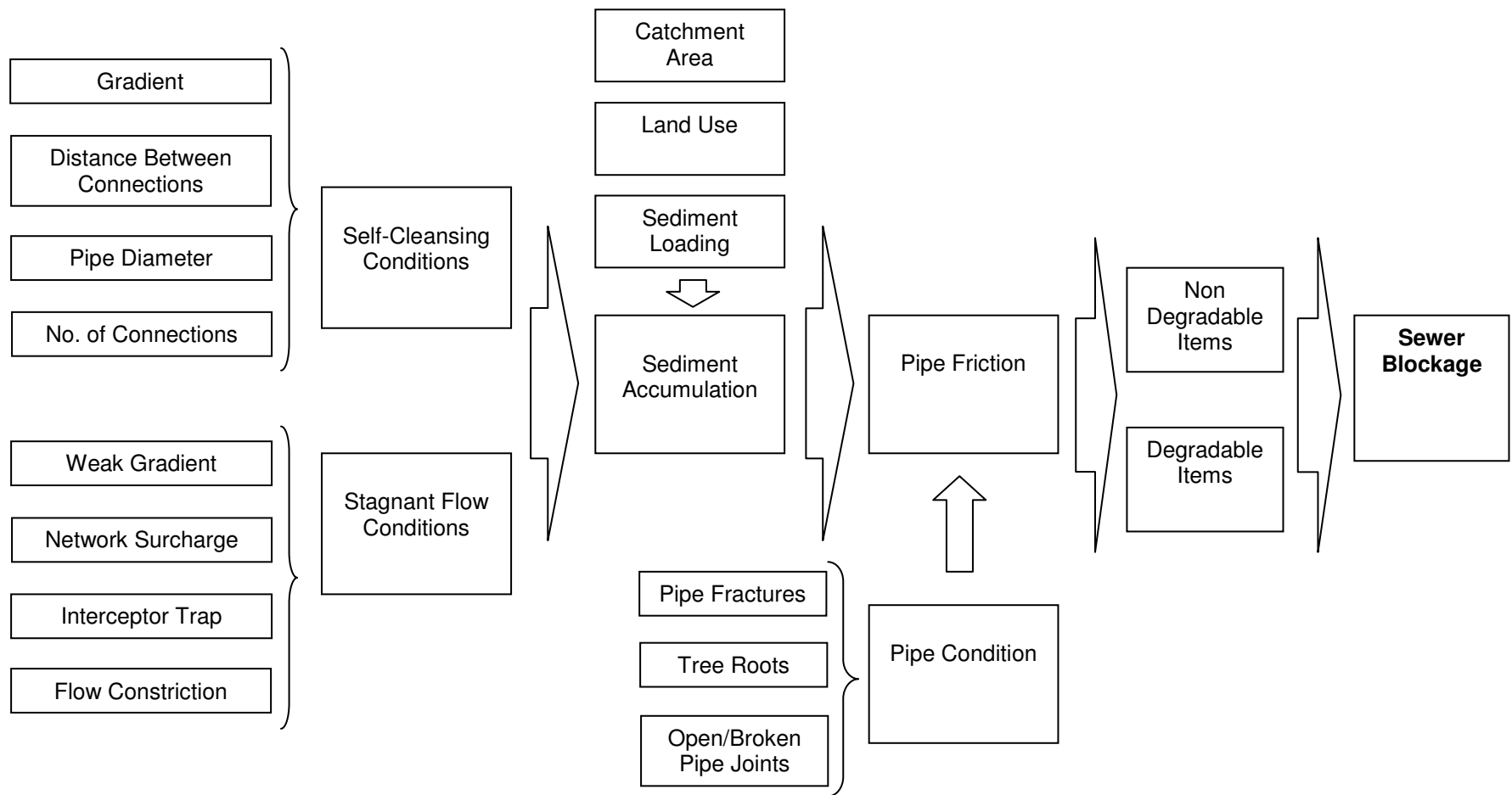
Figure 4-1 Conceptual Sewer Blockages Model

The conceptual model provides an indication of all the factors that can combine to determine blockage likelihood. However in order to predict the blockage rate for a given sewer, the individual effect of each factor on the blockage rate of a sewer is required.

4.3 Development of Scoring System

In order to allow the conceptual model to be developed to predict the likelihood of blockage, the individual effect of each model parameter needs to be quantified. This has been achieved through assigning each parameter a coefficient value. This value will reflect the relative importance of the parameter in determining blockage likelihood. The coefficient values for each parameter will be incorporated into a scoring system, whereby the sum of the coefficient values will be calculated. The sum of the coefficient values will reflect the likelihood of the given length of sewer to become blocked.

The parameters included in the model are summarised as follows:

- the flow characteristics and the likelihood of a sediment bed being present on the invert of the sewer. Scores are allocated for the number of upstream connections, the ratio between the gradient of the pipe and its diameter and the function of the pipe (foul, surface water or combined);

- the sediment bed score is then used with the Sewer Risk Manual serviceability grading to derive a pipe friction score. The SRM serviceability grading is derived either from specific CCTV of the pipe, from sample CCTV of pipes in the area or, if no CCTV data is available, a default value;

- the pipe friction. An additional score is applied for direction changes in the sewers, where these are more than 90°, to reflect the friction (local losses) that results from this; and

- the existence of stagnant flow conditions. An additional score is applied for the presence on an interceptor trap to reflect the increased friction, the reverse gradient, and the permanent presence of sitting water in the sump of the trap.

In determining the parameter coefficients, one simple approach would be to assume that each factor has an equal effect on blockage likelihood. However the literature review indicates that along with there being a number of different factors which contribute towards sewer blockages, the individual effect of each factor is highly variable. The scoring system therefore is required to reflect this variation in how influential a factor is in causing a blockage.

The coefficient values have been determined based on an understanding of the relative importance of each in influencing blockage rate. Where possible, the influence of each has been inferred from the results of physical rig testing. Where no rig testing has been available, expert judgement has been used. An outline of the coefficient values used for each, including justification and reasoning for the selection of each is outlined in Table 4.1 – 4.3. The scoring system has been developed as a series of 'questions' which act as headings to separate the model parameters. Each parameter was characterised as having either a 'moderate' or 'severe' effect on blockages, and this was used to help determine an appropriate coefficient value.

1. What are the hydraulic conditions in the pipe?			
Model Input	**Value**	**Value Range**	**Explanation of coefficient values**
Pipe Gradient	Integer Value	1:1 to 1:250	Movement of a solid requires sufficient velocity from the flow. The velocity of the flow can be estimated from the pipe diameter and the pipe gradient. The 'self-cleansing' velocity (0.7m/s) has previously been used as a benchmark to which sewers should be designed to prevent solid accumulation. The ability of a sewer to
Pipe Diameter (DN: nominal internal diameter of the pipe)	Integer value	100-300 mm	achieve self-cleaning conditions (calculated from the diameter and gradient) has therefore been used to estimate the likelihood of solid deposition. The effect of flow velocity is likely to have a *severe* effect on blockage likelihood. The following values have therefore been used. coeff = 8, for <=2.5:DN coeff = 3, >1:2.5DN and < 1:DN coeff = 1, >=1:DN
No of Connected Properties	Integer value	1-100 (properties)	The number of connected properties will determine both the volume and frequency of discharges entering the sewer. Lengths of sewer which are prone to low frequency use, i.e. where one property is connected are more likely to see frequent solid deposition and potential stranding. As the number of connections increases, the frequency of flow in the sewer increases and this reduces the chance of a stoppage forming. It is anticipated that the number of connected properties has a *moderate* effect on blockage likelihood. The following values have been used. coeff = 3, for 1 Connection coeff = 2, for Connections coeff = 1, for <2 Connections

Table 4-1 Coefficient Values Used for Estimating Flow Conditions

2. Is a sediment bed likely in the sewer?			
Model Input	**Values**	**Value Range**	**Explanation of coefficient values**
Sewer Function	Combined Foul	Combined or Foul	A study by Arthur *et al.,* (2008) reports that combined systems are 2.5 times as likely to become blocked as separate sewers. A study of a small sewer catchment (733 pipes) revealed that the 295 foul sewers suffered 11 blockages (4%) whilst the 438 combined sewers suffered 40 blockages (9%) over a 3 year period. It is anticipated that sewer function is likely to have a *moderate* effect on blockage likelihood. The following values have been used. coeff = 2.5, for Combined coeff = 1, for Foul
Self-Cleansing	Yes No	Yes No	The velocity of flow determines the transport potential and therefore the likelihood of a sediment being deposited in the sewer and forming a bed. The use of the 1:DN rule (Ackers *et al.,* 1996), has therefore been used to predict the likelihood of sediment being deposited. It is anticipated that self-cleansing conditions are likely to have a *severe* effect on blockage likelihood. The following values have been used. coeff = 1, for Self-Cleansing coeff = 8, for Non Self-Cleansing The effect of self-cleansing is considered under the hydraulic conditions. However, here as self-cleansing is used to estimate likelihood of sediment it is not considered to be 'double counting'

Table 4-2 Coefficient Values Used for Estimating Presence of Sediment

3. What is the pipe friction likely to be?			
Model Input	**Values**	**Value Range**	**Explanation of coefficient values**
Sediment Bed	Integer Value	Calculated from previous section	Rig testing of the effect of sediment on solid movement undertaken by WRc (2007) concluded that the presence of sediment in a pipe reduced the movement of a test solid in a pilot rig from 14 m to 4 m. It is therefore concluded that a sediment bed is likely to have a *severe* effect on blockage likelihood. The following values have been used. coeff = 1, for No Sediment bed coeff = 8, for Sediment bed
Serviceability grading	Integer value	1-5 (based on SRM sewer condition classification)	WRc (2007) tested the effect of displaced joints on solid mobility. It concluded that joint displacement of more than 6 mm would reduce the mobility of a test solid by around 50%. It is therefore inferred that at a condition of 1-3 solid transport would not be affected. A condition grade of 4 or 5 would have a *severe* effect on blockage likelihood. The following values have been used. coeff = 1, for 1-3 Condition Grade coeff = 4, for 4 Condition Grade coeff = 8, for 5 Condition Grade
Presence of ≥90° bends in sewer line	Yes or No	Yes or No	Rig testing was undertaken by WRc (2007) to determine the effect of short radius 90° turns in the sewer. It was determined that the presence of a bend would reduce solid mobility by approximately 30% and have a *moderate* effect on blockage. The following values have therefore been used. coeff = 3, for Yes coeff = 1, for No

Table 4-3 Coefficient Values Used for Estimating Sewer Friction

4. What is the likelihood of stagnant flow?			
Model Input	**Values**	**Value Range**	**Explanation of coefficient values**
Interceptor Trap	Yes No	Yes or No	Rig testing was also undertaken by WRc (2007) to determine the effect of interceptor traps on solid mobility. The testing indicated that the presence of a trap would result in deposition of a solid, either in or around the trap. It was therefore concluded that an interceptor trap would have a *severe* effect on blockage likelihood. The following values have therefore been used. coeff = 5, for Yes coeff = 1, for No
Network Surcharge Frequency	Numerical Value	Yes or No	Surcharging flow conditions occur when the hydraulic gradient is above than the crown of the pipe. When surcharging occurs, the movement of flow downstream is restricted and the carrying capacity of the flow is therefore reduced. This can result in solids not being conveyed through the sewer as they should, becoming deposited when the flow subsides. There was no experimental evidence to suggest what the effect of network surcharge on solid transport may be. It was therefore concluded that a surcharged network will have a *moderate* effect on blockage likelihood. The following values have therefore been used. coeff = 4, for Yes, surcharges during > 0.3 AEP storm event coeff = 1, for No, does not surcharge during > 0.3 AEP storm event

Table 4-4 Coefficient Values Used for Estimating Stagnant Flow Conditions

4.4 Creation of Look-Up Table

The parameter coefficient values outlined above form part of a scoring system. This system indicates a score of blockage likelihood based on the pipe parameters. The existing system however gives only a relative score in comparison to other sewers.

In order to be used as a decision support tool for sewerage undertakers the model required the ability to predict blockage rate for a particular length of sewer. This in turn requires a method by which a score from the scoring system can be translated into a blockage rate. This was achieved through devising a look up table which, when the parameter coefficients had been adequately calibrated, would be able to convert a score from the scoring system to a rate of blockage. A schematic overview of the model process is outlined below in Figure 4-2.

Sewer Data Entered in Model	→	Score Calculated from Scoring System	→	Look-up Table Converts Score into Blockage Rate	→	Sewer Blockage Rate
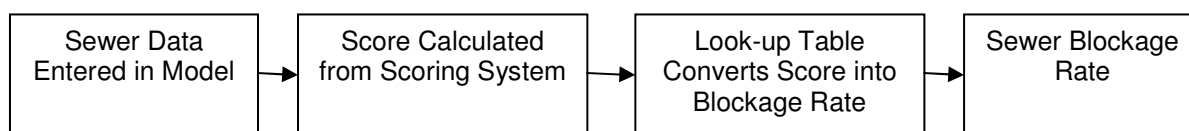
Figure 4-2 Schematic Overview of Model Process

The scores were then correlated to a blockage rate initially using a simple linear correlation. The minimum score (10) from the scoring system was correlated to the minimum observed blockage rate from a dataset of 15 sewers catchments, which was 292 blockages/1000km/yr. Similarly, the maximum possible score (50) was then correlated to the maximum blockage rate observed from the sewer catchments which was 4100 blockages per 1000 km. Based on the lower and upper values, a blockage rate for each score was inferred. The sewer catchments are later used to calibrate the parameter coefficients and were provided by Anglian Water, Northern Ireland Water, Severn Trent Water and Southern Water. A summary of the initial scoring is summarised in Table 4-5.

Table 4.5 Summary of Scoring System to Blockage Rate Inference

Calculated Score	Blockage Rate (1000km/year)
10	292
15	623
20	955
25	1432
30	1909
35	2386
40	2864
45	3487
50	4110

A calibration of the coefficient values was then undertaken. The purpose of the calibration was to ensure that the blockage rates calculated by the scoring system were reflective of actual sewer data and where necessary, the scores be adjusted.

4.5 Model Calibration

Data was collated from a total of 35 sewer catchments from the different water regions. Pipe and blockage data was extracted for each of the calibration catchments. Those catchments with higher blockage rates allowed greater confidence to be attached to their results, compared with those with smaller numbers.   A blockage rate confidence interval was quantified using the Poisson distribution method (WRc, 2012).

Table 4-6 Summary of Confidence Intervals for Number of Sewer Blockages

Number of Blockages [Nr]	Confidence Interval
1	±100%
6	±83%
10	±70%
16	±50%
20	±45%
25	±40%
30	±37%
40	±33%
50	±28%
100	±20%
150	±17%
400	±10%
1000	±6%
2000	±4%

Following the selection of 35 suitable catchments, a sequential calibration process was carried out. This consisted of three separate stages, each of which was designed to calibrate a separate component of the model. Each stage of the calibration was undertaken using a different type of catchment. An overview of each of the catchment types, plus an explanation of the parameters in the model used to calibrate is included in Figures 4-3 – 4-5.

Modern, Separate Catchment 1960's - present

These catchments are typically in good condition and built to modern design standards. They are separate and are unlikely to possess a high number of defects and do not have interceptor traps. They were therefore used to calibrate the following elements of the tool: No. of connected properties, presence of bends in sewer line

Figure 4-3 Overview of a modern separate foul sewer system and parameters calibrated

Interwar Catchment 1918 - 1945

These catchments are typically in moderate condition but not built to modern design standards. They are combined sewers and likely to contain sediment. However they are unlikely to possess a high number of defects and do not have interceptor traps. They were therefore used to calibrate the following elements of the tool: sewer function, self-cleansing conditions, flow conditions

Figure 4-4 Overview of an Interwar 1918 – 1945 sewer system and parameters calibrated

Pre 1918 Catchment

These are older sewers likely to be in poor condition and contain interceptor traps. They were used to calibrate the presence of interceptor traps and serviceability grading

Figure 4-5 Overview of a pre 1918 sewer system and parameters calibrated

For the purpose of the calibration, it is assumed that all sewers in a catchment have a uniform blockage rate, i.e. the blockage rate of any given asset was the same as the catchment blockage rate. This was required as the blockage incidents were recorded to an address rather than an asset. Therefore, whilst it was possible to calculate the catchment blockage rate, it was not possible to do this on a sewer by sewer basis.

For each type of catchment, the blockage rate predicted by the model was compared to the blockage rate calculated from the blockage records. Working sequentially through the catchment types, the parameter coefficients were adjusted to give the best fit on a trial and error basis. Only when the coefficients had been adequately calibrated using modern foul sewer catchment data did the calibration move to the inter-war combined catchment data and finally onto the pre-1918 catchment data.

The sewer and blockage data provided by each of the water companies did not include information on network surcharge, and so this parameter was not calibrated. It was however included in the model as it was deemed that there was sufficient empirical evidence used during the initial development of the scores to retain it in the model.

A summary of the calibration is included in Table 4-7.

Model Parameter	Value Range Before	Value Range After	Explanation
Pipe Diameter & Gradient (self-cleansing)	8 - 1	8 – 1	The calibration did not indicate that the self-cleansing conditions had a significantly different effect on blockage rate than the scores used.
No. of Connected Properties	3 – 1	4 – 1	It was determined that catchments with a large number of sewers with one connection had a higher blockage rate.
Sewer Function	2.5 – 1	5 – 1	It was determined that combined sewer systems were significantly more likely to block than separate systems.
Self-Cleansing	8 - 1	8 – 1	The calibration did not indicate that the self-cleansing conditions had a significantly different effect on blockage rate than the scores used.
Sediment Bed	8 - 1	8 – 1	No data was available on the presence of a sediment bed. The values were therefore not adjusted
Serviceability Grading	8 – 1	8 – 1	No data was available on the presence of a serviceability grading. The values were therefore not adjusted
90° Pipe Bends	3 – 1	2 – 1	It was determined that catchments with a large number of sewers with a 90 pipe bend did increase the chance of blockage.
Interceptor Trap	5 – 1	8 – 1	It was determined that catchments with interceptor traps were significantly more likely to block than systems without.
Network Surcharge	4 – 1	4–1	No data was available on network surcharge. The values were therefore not adjusted

Table 4.7 Modified Parameter Coefficients Following Calibration

After the calibration had been undertaken for each of the catchments the modified coefficient values were tested. Figure 4-6 indicates the performance of the model, which was measured on a catchment by catchment basis comparing actual blockage rate to observed blockage rate. The catchments used to test the initial model performance were those used in the initial calibration.
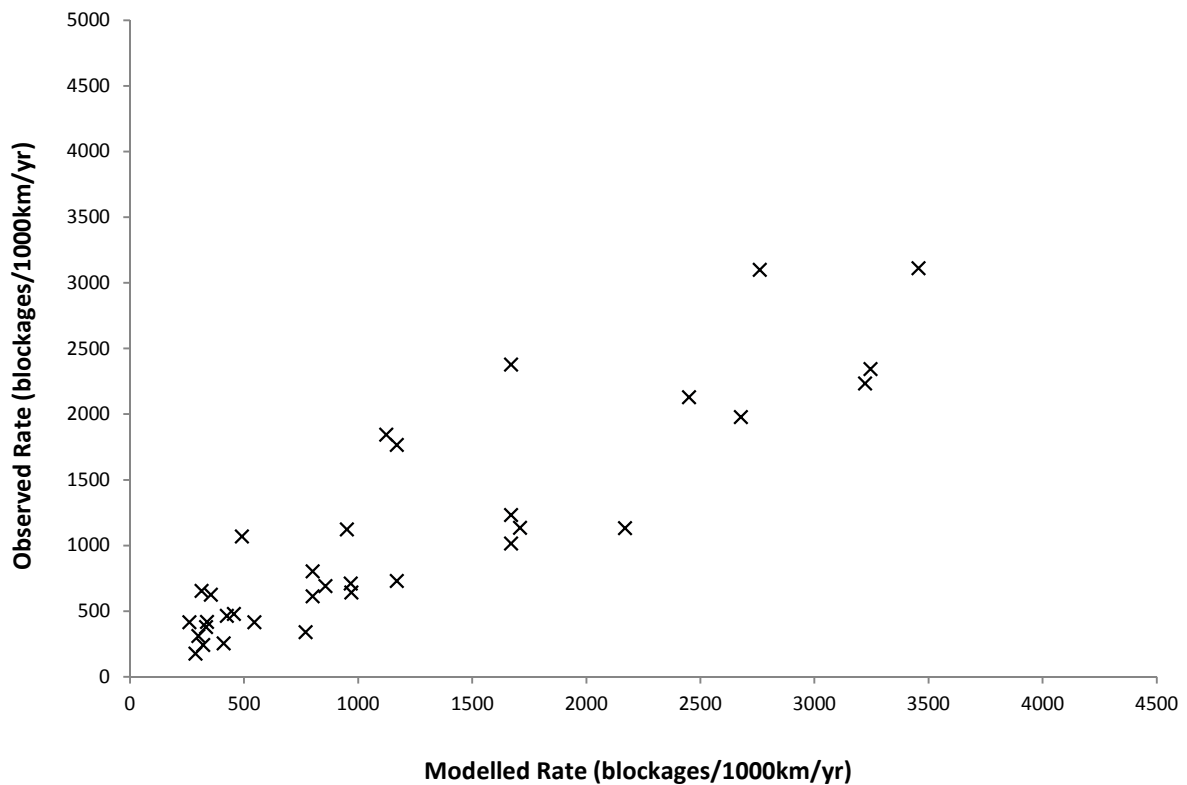
Figure 4-6 Summary of Model Performance

After an initial review of the results the model parameters were adjusted in small increments to try and improve the correlation between the observed and modelled blockage rates. This exercise would improve the correlation for some, but would severely decrease the accuracy for other types of catchments.

In terms of overall goodness of fit ($r^2 = 0.78$), the values which generated the results outlined in Table 4.7 were considered acceptable. However, it should be noted that the catchments used to test the model performance were the same as those used on the calibration. The results are therefore not indicative of the wider model performance (i.e. application to catchments not used on calibration) and further

testing of the model was required before an analysis of the model accuracy could be undertaken.

4.6   Model Interventions

Previous modelling approaches identified in the literature review have based proactive sewer intervention on historical failure records (Hafskjold *et al.,* 2004; Arthur *et al.,* 2008; Ugarelli *et al.,* 2010). Through this approach, proactive intervention is prioritised in sewer catchments where the highest number of blockages are reported. Whilst this approach may be effective in targeting the most problematic parts of the network, it does not give consideration to how cost beneficial undertaking the work may be. For example, under this approach there is no understanding of how an intervention may reduce the number of blockages and therefore how much will be saved in reactive operational costs compared to the cost of proactively removing blockages. There is therefore a requirement for a modelling approach which allows a prediction of how an intervention will impact on blockage rates so that a business case can be put forward for undertaking the intervention.

There are a number of proactive sewer interventions that can be applied. These can include very practical measures such as regular jetting but can also include more behaviour based interventions such as awareness 'bag it and bin it' campaigns. The types of interventions to be included in the modelled were determined in consultation with sewerage managers from each of the participating water companies. It was subsequently decided that a total of 3 separate interventions should be included in the model. These are:

1. Jetting of a sewer

2. Repair of a sewer defect

3. Removal of an interceptor trap

After the model has calculated a blockage rate for a specific length of sewer, there is an option for the user to calculate what the effect of an intervention may be. This function estimates what the blockage rate of the asset is after a given intervention is undertaken. The effect of an intervention is calculated based on the mechanism through which the sewer is most likely to become blocked. For example, if a length of

sewer has a particular problem with accumulation of sediment, that was in good condition and had no interceptor trap, then an intervention of sewer jetting would be effective in reducing the blockage rate. Similarly, if within that same sewer you undertook a course of repair and relining or interceptor removal, then there would be no or minimal improvement in sewer performance.

An overview of how the model interventions have been incorporated into the scoring system is outlined in Table 4-8.

Intervention	Description	Effect on Blockage Mechanism	Model Parameter Affected	Score After Intervention Applied
Sewer Jetting/Cleansing	An operative is scheduled to remove sediment accumulation within a sewer	The removal of sediment from the invert of the sewer reduces the friction acting on a solid, allowing it to be transported further by a flush wave. This reduces the chance of solid deposition and subsequent blockage.	Presence of Sediment Bed	1
Sewer Repair	An operative is scheduled to repair or reline the length of sewer to remove a defect	The removal of a pipe defect reduces the friction acting on a solid, allowing it to be transported further by a flush wave. This reduces the chance of solid deposition and subsequent blockage.	Serviceability Grading	1
Interceptor Removal	An operative is scheduled to remove an interceptor trap from a length of sewer.	The removal of an interceptor trap removes the occurrence of stagnant flow in the siphon of the interceptor. This in turn reduces the likelihood of solid deposition and subsequent blockage.	Interceptor Trap	1

Table 4-8 Approach to Model Effect of Intervention

The interventions capability of the model attempts to quantify the effect of various interventions on the performance of a sewer, specifically the rate of blockage. As there are no records on the effect of sewer interventions on blockage rate, it was not possible to calibrate or verify the effect of each. If a calibration were to take place, there is a requirement for a dataset which indicates the time of recurrence of a blockage following an intervention. The intervention values in the model are therefore based on empirical and un-calibrated values.

Notwithstanding this, the interventions are based on an empirical understanding of blockage cause, and can therefore be considered adequate to be used as a decision support in planning proactive maintenance. Furthermore, verification of the values used may take place once there is a sufficient record of the effect of each intervention on blockage rate.

4.7 Validation of Model Performance

The performance of the model was validated by applying the model to a new set of catchments, i.e. not those used in the calibration. The purpose of the validation was to ensure the model performed adequately for catchments it was not calibrated for. As discussed there was not sufficient data provided to calibrate or validate the effect of intervention on sewer blockage rate. This section only attempts to validate the model performance at estimating blockage rates of sewers.

The validation followed a similar methodology used in the calibration whereby observed catchment blockage rates were compared to the model estimated rates. A further 70 catchments were used in the validation process, each of which shared the same criteria of catchments used in the calibration i.e. homogenous. However, the catchments used in the validation were generally smaller in length, as large sized homogenous catchments were not common in the sewer record datasets provided.

The performance for the new catchments used is summarised in Figure 4-7.
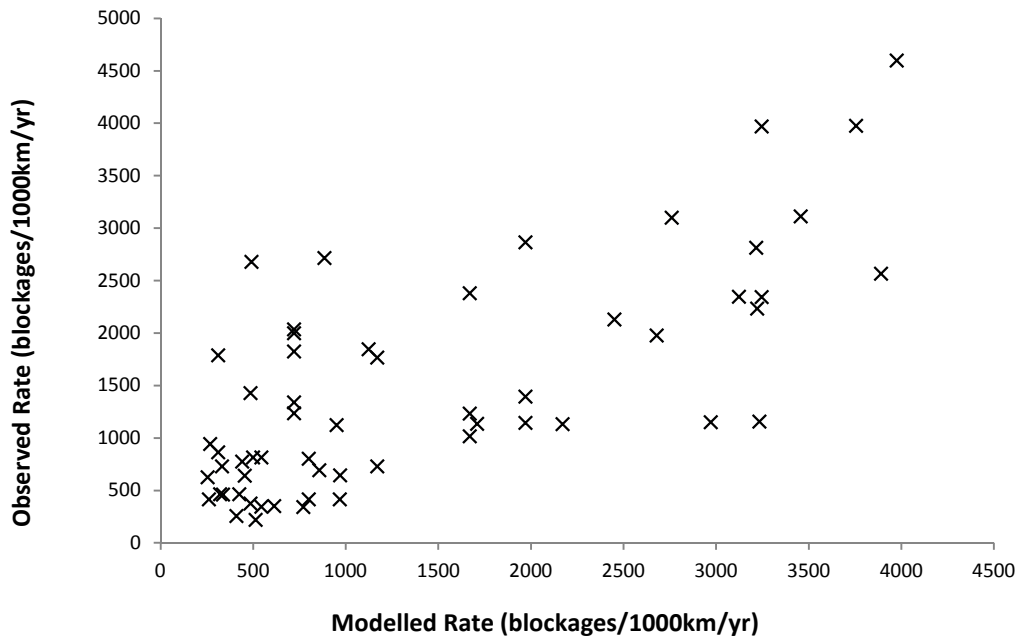
Figure 4-7 Summary of Model Performance

Figure 4-7 indicates a correlation between the observed and the modelled blockage rates. An overall goodness of fit value of $r^2 = 0.53$ was calculated. In order to understand the accuracy of the model, an analysis of the variances between the modelled rate and the observed rate was required. This is to say that an analysis is required whereby the percentage variance in score from the observed rate is most appropriate to evaluate performance i.e. a catchment with an observed rate of 1200 and a modelled rate of 1000 would give a percentage variance of 16.6%. The lower the percentage variance the more accurate the model has been for predicting the blockage rate for a length of sewer. Figure 4-8 indicates the extent of variance in the validation results.
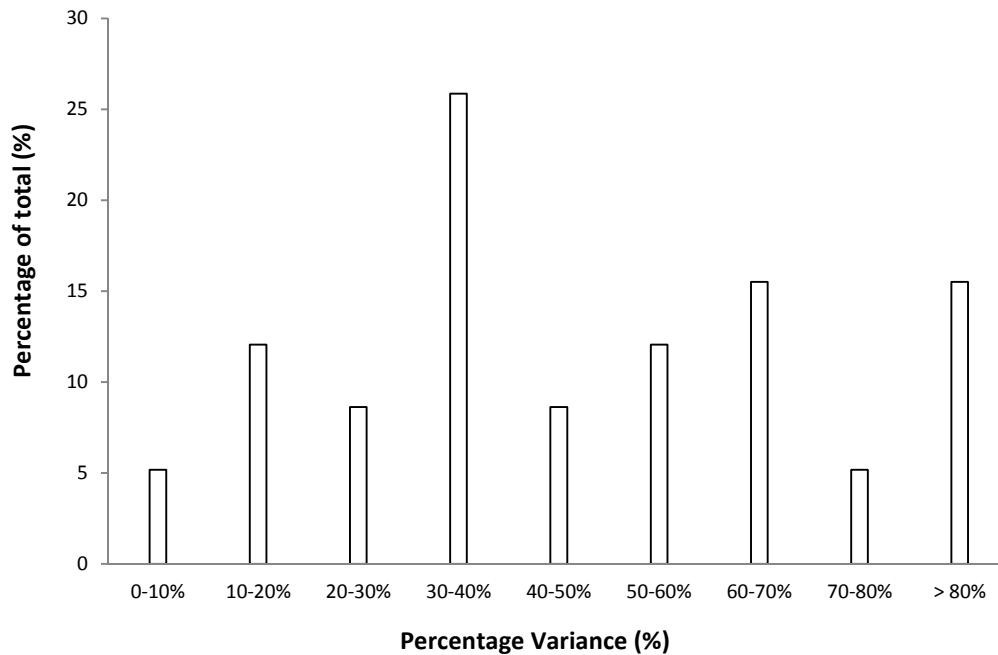
Figure 4-8 Percentage Variance in Results

The majority of the results (60%) were accurate to within 10-50% of the observed blockage rate. However just 3 catchments were within 10-20% which is 5% of the overall total. A total of 11 catchments were within 0-20% accuracy which equates to 17% of the total. A total of 28 catchments showed < 50% accuracy, with 9 catchments being < 80% accuracy, which represents 16% of the total.

There is a correlation between catchment age and the model results generated. Eight of the nine catchments which had < 80% accuracy were pre 1918. In general, the catchments from the post 1960 cohort had smaller blockage rates, and showed less variance when comparing modelled to observed blockage rates. The pre 1918 catchments had higher blockage rates and represent the catchments with the highest variance.

4.8 Discussion

The results from the model validation indicated a number of patterns in the performance of the model. The following section identifies the potential

causes of these correlations and discusses them in the context of limitations of the modelling approach. This section is of particular importance if a similar methodology is adopted in subsequent studies. Specifically what are the limitations in the approach and how these may be overcome.

The potential causes for the limitations of the model accuracy are outlined below.

- **Factors not Included in Model**

The blockages model developed based on determining the effect of a number of factors on the blockage rate of a sewer. A total of 9 factors were included in the model. However, there are a number of other potential influencing factors which were not included. This was to ensure that model did not require exhaustive data collection.

An example of a factor which was not used, but is likely to have a significant effect on blockage rates is property use within a catchment. Sewerage managers reported that blockage rates are higher in catchments with a larger number of commercial properties, specifically those associated with the preparation of hot food such as takeaways, restaurants and cafes. Such premises are more susceptible to fat, oil and grease entry into the sewer which can solidify and accumulate increasing the likelihood of a blockage.

An example of this was observed during the site work undertaken as part of the study concerned with reducing repeat blockages, as described in Chapter 3. A work order had been scheduled to attend a blockage at a fish and chip shop in Belfast. Once on-site, the operations crew observed a very large amount of fat and potato starch which had been disposed of into the sewer (*fig 4-9*).

Figure 4-9 Large amounts of Fat in a sewer at a fish and chip restaurant

Another such example is the housing demographic. Empirical evidence provided by sewerage managers suggests that higher blockage rates can be observed in areas where the demographic classification was D, working class and E, lower working class. This may result from poor kitchen habits and the disposal of fat, oil and grease into the sewer as outlined above. This however may also result from a larger number of large solid items being disposed of into the sewer due to a lack of awareness as to the operational problems this may cause.

One of the highest causal factors not included within the model is the presence of tree roots. The term 'serviceability grading' does include for the presence of tree roots, however a study undertaken in Australia by Tennekoon and Hughes (1996) suggest tree roots are the direct cause of most sewer blockages. Therefore in some catchments with a large number of trees, or in catchments with shallow sewers the model may underestimate blockage rate.

Whilst exclusion of these factors in the model may have implications on the model accuracy, the model specification was not to require exhaustive data collection. By increasing the number of factors the extent of data collection is also increased. The factors that were included in the model were selected based not only on their importance in blockage mechanisms, but also the difficulty by which obtaining the data would be. Notwithstanding this, the improvements outlined in Chapter 3 relating to data collection of blockage information will result in a better quality of blockage data being available. This will then generate the potential for more factors to be included in the model.

- **Time Taken for Blockage to Form**

The literature review and the empirical evidence used in the model development provides an account of what factors can influence blockage occurrence. There is however no understanding of how these factors impact on the rate of blockage, i.e. how long the process from an initial stranded solid to a full blockage takes to occur. Importantly, it is this length of time which will determine the rate of blockage. The mechanisms of blockage described in this chapter outline how a blockage may form, but do not provide an indication of the length through which this can take place.

From examining the historic sewer records, it is evident that the presence of certain factors can significantly the rate of blockage, i.e. catchments with interceptor traps had a much higher observable blockage rate than those without. However, there is still no evidence of the precise effect on the recurrence time of a blockage, and this therefore is not reflected in the model.

- **Size of Catchments Used in Calibration**

One of the criteria for catchments used in the calibration of the model was homogeneity i.e. the same broadly the same type of housing stock and more importantly were constructed during the same period. Sewer catchments with an adequate number of blockages to have confidence in the blockage rate (see section 4.5) which was also homogenous were not common in the data that was collected. This limited the number of catchments that could be used.

Due to the limited number of large homogenous catchments, the catchments used for the model validation were smaller. Reducing the size of the catchments essentially had the effect of reducing the number of 225 mm and 300 mm sewers, and there were therefore a larger number of smaller 150 mm and 100 mm sewers. As a result, the catchments used in the validation typically were shorter in terms of total length of sewer, but have a similar number of blockages to the larger catchments used in the calibration. This had the effect of giving a higher blockage rate and may explain why the model appeared to be underestimating blockage rates in the catchments used for the validation.

- **Effect of Unmapped Sewers**

The sewer records for each catchment showed significant variation in terms of the number of 100 mm sewers that had been mapped and included on the sewer record plans (*fig 4-10*). On most records it appeared that whilst some small sewers, formally private sewers had been mapped a large number did not appear on the sewer records.

Figure 4-10 Mapped and unmapped small connector sewers

With respect to blockage rate, the extent to which >100 mm sewers are mapped will be reflected in the overall sewer length of the catchment. For example, if catchment A and catchment B both have 750 m of >100 mm sewers, if mapping of these sewers has taken place for catchment A but not for catchment B then Catchment A will appear the longer in length. This in turn will generate a lower overall blockage rate (i.e. same number of blockages but over a smaller length of network).

One option to remove the effect of unmapped sewers would to have been to only use catchments where all >100 mm sewer were mapped. However the size of the dataset meant there were not a sufficient number of fully mapped catchments to exclude catchments on this basis. However this occurrence was the same for catchments used in both the calibration and so does not explain the higher rates in catchments used in the validation.

With respect to the results, this may have caused the modelled predicted blockage rate to differ from the observed, reducing the model accuracy.

- **Assumption of Uniform Blockage Rate**

As earlier stated it was not possible to undertake a model calibration on an asset by asset basis. This was for two reasons. Firstly, in the majority of the data collected, the blockage is designated to the address and not the asset. There is therefore no way of ascertaining which blockages occurred on which assets. This prevented a calculation of the blockage rate for an individual sewer to be undertaken. Secondly, an individual asset would not have contained a blockage record of adequate length to provide an acceptable degree of certainty when calculating blockage rate (see section 4.5).

This required an assumed uniform blockage rate in each sewer. The findings of the literature review however indicated that blockages are more likely to occur in > 150 mm sewers. By assuming a uniform rate, this will have caused an underestimation of the blockage rates for > 150 mm sewers, and an overestimation for < 150mm sewers across the catchment.

- **Comparison of Results to Existing Modelling Approaches**

The model results indicate that the presence of certain features of sewer design or deterioration can contribute to increase blockage rate. This shows general agreement with similar studies described in the literature review, which also outline a number of studies where the higher blockage rate of a length of sewer were attributed to the presence of a particular sewer feature.

However, the nature of results presented in the studies summarised in the literature review do not allow a like for like comparison, as such only a general comparison of results can be made.

A limitation of this study is the unknown effect of factors which were not included in the model. Similarly, a number of the studies reviewed as part of the literature review only examine the effect of a small number of factors, and this may cause invalid conclusions to be drawn on how influential certain sewer features are in effecting blockages rates.

4.9　Summary

There is a requirement for a modelling method which allows sewerage undertakers to effectively plan proactive maintenance on their sewer network. A literature review of previous approaches indicates that currently the majority of proactive intervention is prioritised based on an analysis of historic blockage rate i.e. catchments with the most blockages are prioritised for maintenance.

However, in order for a greater percentage of maintenance to be undertaken on a proactive basis, there is a requirement for sewerage undertakers to be able to understand what effect an intervention will have on the performance of a sewer. This will allow an economic analysis of potential intervention to be undertaken, whereby the sewerage manager can decide whether or not to undertake an intervention based on whether or not the cost will be outweighed by the benefit. The 'cost' is the outlay required to undertake the intervention whilst the benefit is the reduction in blockages and the associated costs of removing these blockages reactively.

Based on the objectives set out at the start of the chapter a predictive sewer blockages model has been developed. Unlike previous approaches to modelling sewer blockages, this modelling approach is based on an understanding of the mechanisms by which blockages are caused. This understanding is based on a large body of previous research examining solid movement in sewers and the factors implicated in solid movement. This approach has the advantage that not only can the formation of a blockage be better understood, but the effect of an intervention can also be determined.

The model was developed by first quantifying the mechanisms by which a sewer can block, starting with the stoppage of a single solid and leading to a complete impedance of the flow by solid material. This was adapted into a conceptual blockage model which maps all the potential factors involved in a blockage.

Following the development of the concept model, a scoring system was devised which attempted to quantify the effect of an individual factor on the overall rate of blockage. The scoring system was developed based on empirical evidence from previous studies along with expert judgement. The scoring system was then calibrated with sewer blockage data to ensure the scoring system was able to provide an acceptable estimation of blockage rate for a catchment.

A number of interventions were included in the model. When applied to a given length of sewer, the model estimates the effect that the intervention has on blockage rate. The effect of each intervention was estimated through examining what effect the intervention would have on the blockage mechanisms most prevalent in a sewer.

An analysis of the model performance was undertaken, and the potential causes of some of the inaccuracy of the model are discussed. The limitations identified are mostly data issues, and once there is an improvement in the quality of asset data held, a number of these limitations can be averted.

5 SUMMARY AND CONCLUSIONS

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5.1 Introduction

5.2 Summary

5.3 Conclusion

5.3 Potential for Future Research

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5.1 Summary

A study was undertaken on behalf of 6 UK water companies to enable a reduction in the number of sewer blockages suffered on public sewer networks.

In accordance with Objective 1 of this thesis, a review of the literature relating to sewer blockages was undertaken. The review determined that the majority of previous work had been concerned with allowing an increase in proactive maintenance to be undertaken. This was done through using various methods to examine historic blockage occurrence in order to predict future failures. The review also concluded that the previous methods used have limited effectiveness when being applied to < 225 mm sewers because of the lack of recorded data. The literature review identified a lack of research in considering the role of reactive maintenance, specifically ensuring that the number of repeat blockages is reduced.

In accordance with Objective 2 of this thesis, a review of the current reactive maintenance of the five (of the six) participating water companies was undertaken. Based on this review, recommendations were made as to how the operational practices of each company could be improved. Specifically, the use of best practice in blockage clearance can help reduce the number of repeat blockages caused by poor removal practices. This can be assessed through monitoring short term repeat rates of blockages i.e. the number of re-occurrences of blockages at the same or an immediately downstream location within a short period of time. Where blockage recurrence is not associated with poor clearance practices, a CCTV survey should be carried out to investigate potential causes of the blockage and to identify possible interventions to prevent re-occurrence.

In accordance with Objective 3 of this thesis, a blockages model was developed to support decision making in proactive sewer maintenance. Specifically, using the model in high blockage catchments to identify where planned intervention may be suitable. In accordance with Objective 4 of this thesis, the intervention function of the model can be used to determine what

the benefit of an intervention may be, and whether this benefit is economic in terms of cost vs. reduction in blockage.

It is anticipated that through application of the findings and methods used in this thesis, water companies can deliver a reduction in the number of sewer blockages suffered.

5.2 Conclusions

In order to reduce the number of blockages that occur on public sewer networks, an initial approach should be targeted at reducing the number of repeat blockages. This includes ensuring that a right first time approach is applied where the blockage is completely removed from the sewer. This also covers ensuring that sewer faults which are responsible for blockages are identified and repaired to reduce the chance of recurrence. A greater emphasis should also be placed on correctly recording the blockage information so that a meaningful analysis of historic blockage records is possible.

Alongside improving reactive maintenance, proactive maintenance should be better targeted at locations where the consequences of blockage are more severe. This may include locations particularly susceptible to internal flooding or pollution events. The blockages model provides a method whereby blockage likelihood in small sewers can be estimated. When applied to a sewer catchment, the model can estimate the effect of a particular intervention on sewer performance, which in turn will allow the decision to be supported on an economic basis.

In summary, the main conclusions from the research are:

1. Addressing the current limitations in reactive maintenance would yield significant benefit in terms of reducing blockages. Specifically, encouraging blockage crews to observe best operational practice, and supplying them the necessary training and equipment to do so;

2. Generally, the current data held on blockages in small sewers is not sufficient to act as a decision support for small diameter < 225 mm,

particularly when a business case for undertaking proactive intervention is required;

3. By understanding the mechanisms through which blockages form, the likelihood of a sewer to suffer a blockage can be modelled to an acceptable degree of accuracy. However, a larger dataset is required whereby the tool can be properly tested, an necessary improvements to the calibration made;

4. All decisions regarding proactive maintenance of sewers should be supported by an economic analysis, to ensure that all intervention made is targeted at parts of the system where blockages cause the highest consequences;

5. A framework is required through which reactive and proactive maintenance is   implemented to deliver the highest possible reduction in blockage numbers.

6. Implementation of an improved method for data collection would deliver improvements in the quality of blockage records. This in turn would in turn would allow analysis of historic blockage records to be used in planning future maintenance

7. The improved data collection should be prioritised based upon:
   - ensuring a blockage is recorded to an asset rather than a customer address;
   - ensuring the cause of the blockage is properly recorded; and
   - recording and analysing the effect of various sewer interventions on the long term rate of blockage.

5.3   Direction for Further Research

To progress the methods applied within this thesis further, the following should be considered.

1. Laboratory testing of solid movement and blockage formation, to provide a better account of the mechanisms on which the model is founded;

2. Calibration of the effect of each intervention on the sewer performance;

3. Calibration with a greater number of sewer catchments, some of which should be heterogeneous;

4. Establish whether a separate scoring mechanisms for each catchment type would yield a better model performance;

5. Investigate what further factors could be included in the model to help improve accuracy. Specifically:

   • the effect of tree roots on blockage likelihood;

   • the effect of housing demographic and land-use on blockage likelihood; and

   • the number of model interventions should be increased to include 'bag it and bin it' campaigns' which represent a large percentage of the current proactive intervention undertaken.

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